

Ecosystems for water and food security



Ecosystems for
water and food
security



CREDITS

Scientific Editor: Eline Boelee (IWMI)

Main authors: Sithara Atapattu (consultant), Jennie Barron (SEI-SRC), Prem Bindraban (ISRIC), Stuart W. Bunting (iCES), David Coates (CBD), Katrien Descheemaeker (IWM-ILRI), Nishadi Eriyagama (IWMI), Max Finlayson (ILWS), Line Gordon (Stockholm Resilience Center), Elizabeth Khaka (UNEP), Gareth James Lloyd (UNEP-DHI), David Molden (IWMI), Catherine Muthuri (ICRAF), Sophie Nguyen-Khoa (CPWF), Don Peden (ILRI), Petina Pert (CSIRO), Fergus Sinclair (ICRAF), Elaine Solowey (AIES), Luke Sanford (consultant), David Stentiford (consultant), Lamourdia Thiombiano (FAO).

Contributors: Tilahun Amede (IWM-ILRI), Marc Andreini (IWMI), Stefano Barchiesi (IUCN), Malcolm Beveridge (WorldFish), Luna Bharati (IWMI), Marta Ceroni (GIEE), Thomas Chiramba (UNEP), Floriane Clement (IWMI), Karen Conniff (consultant), Jan de Leeuw (ILRI), Kristina Donnelly (AIES), Pay Drechsel (IWMI), Alexandra Evans (IWMI), Renate Fleiner (UNEP), Mark Giordano (IWMI), Delia Grace (ILRI), Mario Herrero (ILRI), Devra Jarvis (Bioversity), Robyn Johnston (IWMI), Tim Kasten (UNEP), David Lehrer (AIES), Clive Lipchin (AIES), Abby Lutman (AIES), Matthew McCartney (IWMI), Bertha Nherera (Pelum), An Notenbaert (ILRI), Asad Qureshi (IWMI), Sara J. Scherr (EcoAgriculture Partners), Katherine Snyder (IWMI), Rebecca Tharme (TNC), Martin van Brakel (CPWF), Jeanette van de Steeg (ILRI), Gerardo E. van Halsema (WUR), Kees van 't Klooster (WUR), and others.

Language editor: Helen Cousins

Layout: Jennifer Odallo

Cover photo: Karen Conniff (rice field and forest gardens at Arankele monastery, Sri Lanka)

Boelee E (ed) 2011. Ecosystems for water and food security. Nairobi: United Nations Environment Programme; Colombo: International Water Management Institute.

/ ecosystems / agroecosystems / water management / food security/ ecosystem services / sustainability

ISBN: 978-92-807-3170-5

Job Number: DEP/1392/NA

Copyright © UNEP 2011

Disclaimer

The contents of this report do not necessarily reflect the views or policies of UNEP or contributory organizations. The designations employed and the presentations do not imply the expression of any opinion whatsoever on the part of UNEP or contributory organizations concerning the legal status of any country, territory, city, company or area or its authority or concerning the delimitation of its frontiers or boundaries.

CONTRIBUTING ORGANIZATIONS

<p>Arava Institute for Environmental Studies (AIES)</p> 	<p>Bioversity International</p> 	<p>CGIAR Challenge Program on Water and Food (CPWF)</p> 
<p>Commonwealth Scientific and Industrial Research Organisation (CSIRO)</p> 	<p>The Secretariat of the Convention on Biological Diversity (CBD)</p> 	<p>EcoAgriculture Partners</p> 
<p>Gund Institute for Ecological Economics, University of Vermont (GIEE)</p> 	<p>Interdisciplinary Centre for Environment and Society (iCES), University of Essex</p> 	<p>Institute of Land, Water & Society (ILWS), Charles Sturt University</p> 
<p>International Livestock Research Institute (ILRI)</p> 	<p>International Union for Conservation of Nature (IUCN)</p> 	<p>International Water Management Institute (IWMI)</p> 
<p>ISRIC – World Soil Information</p> 	<p>Stockholm Environment Institute (SEI)</p> 	<p>Stockholm Resilience Centre (SRC)</p> 
<p>The Nature Conservancy (TNC)</p> 	<p>United Nations Environment Programme (UNEP)</p> 	<p>UNEP-DHI Centre for Water and Environment</p> 
<p>Wageningen UR</p> 	<p>World Agroforestry Center (ICRAF)</p> 	<p>WorldFish Center</p> 

TABLE OF CONTENTS

PREFACE	vi
FOREWORD	vii
ACKNOWLEDGEMENTS	viii
EXECUTIVE SUMMARY	ix
1. INTRODUCTION	1
1.1. Background and justification	1
1.2. Scope	2
1.3. Relationship between ecosystems, water and food	3
2. FOOD SECURITY	5
2.1. Introduction: hunger, access, and ecosystem impacts	5
2.2. Drivers and future prospects	7
2.2.1. Demographic drivers	8
2.2.2. Climate change and other shocks	10
2.3. The necessity of ecosystems and water for food security	11
2.4. Conclusion: challenges for food security	14
3. ECOSYSTEMS	15
3.1. Introduction: concepts and definitions	15
3.1.1. Ecosystems and agroecosystems	15
3.1.2. Ecosystem services	18
3.2. Challenges to agroecosystem management	21
3.3. Examples of agroecosystems	24
3.3.1. Arid agroecosystems	24
3.3.2. Wetlands	27
3.3.3. Dry rangeland	32
3.3.4. Aquatic ecosystems	35
3.3.5. Tree ecosystems	36
3.4. Sustainable management of agroecosystems	37
3.5. Conclusion: recognizing agroecosystem services	39

4.	WATER	41
4.1.	Introduction: water in ecosystems	41
4.2.	Assessment of current and future water use	41
4.2.1.	Water vulnerability, food security and poverty	42
4.2.2.	Water use in agriculture.....	43
4.2.3.	Water-soil-plant interactions	44
4.2.4.	Tension between water for ecosystems and water for food.....	45
4.3.	Increasing water productivity in agriculture	47
4.3.1.	Increasing crop water productivity	48
4.3.2.	Increasing water productivity in agroforestry systems.....	52
4.3.3.	Increasing livestock water productivity	52
4.3.4.	Increasing water productivity in aquaculture.....	54
4.3.5.	Policy options	56
4.4.	Conclusion: tackling water scarcity in agroecosystems	57
5.	MANAGING WATER IN AGROECOSYSTEMS FOR FOOD SECURITY	59
5.1.	Introduction: the role of water in ecosystem services	59
5.2.	Managing agroecosystem services	60
5.2.1.	Ecosystem services in agriculture.....	60
5.2.2.	Decision making over ecosystem services.....	61
5.2.3.	Payments for ecosystem services.....	63
5.3.	Managing water efficiently for ecosystems and food production.....	64
5.3.1.	Efficient water management	64
5.3.2.	Integrated Water Resources Management (IWRM).....	65
5.3.3.	IWRM and ecosystem services.....	68
5.3.4.	Practical approaches to water management in agroecosystems	71
5.3.5.	Water for nature: environmental flows	71
5.4.	Water management in agroecological landscapes.....	74
5.5.	Conclusion: managing agroecosystem services for food security	77
	GLOSSARY	81
	REFERENCES.....	85
	APPENDICES.....	109

PREFACE

Overcoming hunger and meeting the nutritional needs of almost 7 billion people, rising to over 9 billion people by 2050, is a central challenge for this generation. Equally critical will be to achieve this in a way that keeps humanity's footprint within planetary boundaries.

Water scarcity is self-evidently one of the key factors that will limit food production. This is especially the case in South Asia and sub-Saharan Africa, where malnutrition and food insecurity are already widespread. In these areas, the livelihoods and well-being of poor communities are critically dependent on their farm produce and the ecosystem services from the local landscape that support their livelihoods and income.

This background document and synthesis on *An Ecosystem Services Approach to Water and Food Security* is part of UNEP's contribution to the global food crisis, pledged to the United Nations Secretary-General and developed in collaboration with the International Water Management Institute (IWMI) and other partners. Together, we identified and explored the links between ecosystems, water and food, and illustrate how resilient ecosystems can support and increase food security.

It is clear that enormous opportunities exist to increase food production in ways that make optimal and sustainable use of water and other resources. This means that we can feed a global population without massive and irreversible damage to our ecosystems. It also means that ensuring food security, managing water resources and protecting ecosystems must be considered as a single policy rather than as separate, and sometimes competing, choices.

This approach calls for a fundamental shift in perspective and a deeper understanding of the enormous economic importance of ecosystems and the broad suite of services they provide. For example, well-managed agroecosystems not only provide food, fiber and animal products, they

also generate services such as flood mitigation, groundwater recharge, erosion control and habitats for plants, birds, fish and other animals.



It also requires intersectoral collaboration, because only then can policies and practices change. The overarching recommendation of this synthesis is that future sustainability requires an integrated approach to managing multipurpose agroecosystems in a landscape or river basin setting.

These ecosystems—whether they are wetlands or forests, arid pastoral lands or rice fields—represent the future of food security and resilience against shocks while offering a way towards achieving the Millennium Development Goals (MDGs) and beyond.

This document does not come in isolation. It is also a contribution to UNEP's wider work and partnerships on *The Economics of Ecosystems and Biodiversity (TEEB)* and a transition to a low-carbon, resource-efficient Green Economy.

Together they are all part of the urgency to evolve the sustainable development agenda forged in a previous century to reflect the new challenges and also the emerging opportunities of the 21st century.

A handwritten signature in black ink that reads "Achim Steiner". The signature is fluid and cursive, with a long horizontal stroke at the end.

Achim Steiner
UN Under-Secretary-General and Executive Director

FOREWORD

By 2050 the world will need to produce approximately 70% more food than at present to cope with growing population and dietary changes. This is going to put agricultural production systems and the environment under ever increasing pressure. Competition for the water that we use to grow our food is also increasing. In fact we are facing a paradox of having to grow more food with less water. Additionally, we will have to do this causing less environmental impact than we do now. These critical issues define a critical challenge for the next 30 years or more. Achieving food security is the product of many variables, including management of water, land, aquatic resources, crops and livestock. Lasting food security – a food supply system that can stand up to environmental and economic shocks – requires a holistic approach, with healthy ecosystems as a foundation. The recent world food crises demonstrated the vulnerability of our food supply and the need to improve its sustainability and resilience. Too little attention has been paid to the importance of healthy ecosystems as key components of our food production systems. More resilient ecosystems can support a wider range of ecosystem services, including water management functions that are crucial for stable food security, and become more diverse and more productive.

Thus water management for food security cannot be sustainable without paying attention to ecosystems, their functions and services as part of the natural resource base supporting agriculture. Overcoming natural resource management problems and adapting to climate change will only be achieved by understanding and managing the dynamics of water across the whole landscape of interlinked ecosystems. Ecosystems provide food both in their natural state and in managed landscapes. Climate change and overexploitation, especially of water resources, threaten the productivity of ecosystems. Given that the majority of the world's poor are directly dependent on ecosystems for food, they are the most vulnerable to environmental degradation and climate-related shocks.

Ecosystems also provide a host of services that underlie food and water security. In particular, many ecosystems provide water management functions that are crucial to a stable food supply – these include water storage, purification and regulation functions as well as flood control. Ecosystems also need water to support their functioning, but currently ecosystems are not considered a priority water user or even a water user at all in many countries. One of the main factors limiting future food production will be water. Water underlies many ecosystem services, including biomass and crop production, as well as supporting and regulating services. It is also a key ingredient in enhancing food production – not just through irrigation, but through better management of rainwater and water for livestock and aquatic food sources.



Solutions to water access, land degradation, nutrient management and ecosystem services have to be developed with a view to what works for communities across landscapes, not just what works on the farm. The International Water Management Institute (IWMI) aims to improve the management of land and water resources for food, livelihoods and the environment and targets water and land management challenges faced by poor communities in the developing world. In the new CGIAR strategic research program Water, Land and Ecosystems, IWMI and partners focuses on three critical issues: water scarcity, land degradation and ecosystem services. The current document on Ecosystems for Water and Food Security is an important contribution to assessing the important role of ecosystems in increasing resilience and providing food in a sustainable way to future generations.

Colin Chartres
Director General
International Water Management Institute

ACKNOWLEDGEMENTS

Throughout the process of drafting, reviewing and editing this document, various people have provided valuable advice. As much as possible, these people

have been recognized as main author or contributor. In addition we would like to thank all others who have given their support and assistance behind the scenes.

EXECUTIVE SUMMARY

Challenges for Food Security

With a growing global population expected to reach 9.1 billion in 2050 and the increasing impacts of climate change, sustainable use of water and ecosystems for food security is a great challenge. It is important to gain a better understanding of the functioning of terrestrial and aquatic ecosystems and their interrelation with the availability and quality of water. This calls for a shift in the management of ecosystems and the water within them for food security. Agricultural production systems have to be recognized and managed as a landscape of interlinked agroecosystems with the potential for multiple functions

Climate change impacts on ecosystems and thereby on water and food security are highly uncertain, and most forecasting scenarios suggest greater vulnerability to damage, reduced ecosystem services, and undermined resilience. Building resilience to climate change and other shocks needs to be mainstreamed into agricultural planning to ensure food security targets. This is especially important for vulnerable populations with low adaptive capacity: poor women and marginal social groups in geographical areas at risk, with limited resources, poor social networks, and low access to education, health care and other services.

Many drivers of global change affect water availability and thus agroecosystems and food security, by limiting or taking away the water necessary for maintaining ecosystem functions. This is a challenging development since ecosystem functions and food security go hand in hand: healthy ecosystems enhance food security while degraded ecosystems decrease food security. Healthy ecosystems are particularly important for the poor who predominantly directly rely on ecosystem services. Water is the important link between agroecosystems and food security and it is important that the right balance of water is

provided to each of these needs in order to sustain both functions.

Recognizing Agroecosystem Services

Recognizing the multiple functions of agroecosystems and the many services they provide is essential to fostering an integrated approach to natural resources management, agricultural production, and food security. The sustainable management plans of various agroecosystems ranging from hyper-arid and dryland agroecosystems to wetlands and aquatic ecosystems require strong policy support and incentives for users. The services provided by ecosystems can be optimized through appropriate land use planning that takes into account the limits of each ecosystem's carrying capacity, while multiple users need to be brought together in common management arrangements to sustainably reconcile the needs of food production and ecosystems services for a growing population. Thus food production can be made more sustainable; more productive in terms of producing more food, services, and benefits per unit of land and water; more resilient to climate change and other shocks; and more compatible with sustaining other ecosystems and their functions and services, such as wild biodiversity.

The ecosystem services framework provides a useful umbrella for this endeavor as this can only be achieved by healthy agroecosystems. Inter-sector collaboration at ministerial level is essential to ensure good ecosystems care while providing the necessary food and services to communities. The situation now calls for a more balanced approach in managing food security and its interrelation with ecosystem services: worldwide, ecosystem services are in a poor state and agroecosystems have lost their capacity to recover from stress. Food security is further threatened by reduced yields associated with depleted water quantity, reduced water

quality, and degradation of other natural resources. These factors also negatively impact on a range of provisioning, supporting, regulatory, and cultural ecosystem services.

However, solutions are available. Policy makers can help to safeguard ecosystem services. Accounting for the benefits and costs of the full range of ecosystem services in policy-making and greater emphasis on natural resources and water use efficiency in food production will promote better decision making towards more sustainable farming. In arid regions, new or local cultivars and appropriate land and water management practices can increase productivity and restore degraded lands. In other areas the provision of livestock herders with incentives can help to keep and improve the environmental services of semi-arid rangelands. The integration of crop, tree, livestock, and in some cases aquaculture farming, can enhance resource recovery and reuse of resources for feed or soil fertility

Wetlands across the world play a critical role in the provision of freshwater for human consumption and agriculture, while both fresh and saline waters provide food security by supporting fisheries, aquaculture, and other related activities. Urgent steps are needed to protect the rich wetland ecosystems with their multitude of functions and services, as well as the livelihoods and well-being of the dependent communities. Monitoring of wetland functions and services is crucial to ensure the continuation of wetland ecosystems and their important role in flood protection, biodiversity, food provision, as well as many other critical ecosystem services.

Tackling Water Scarcity in Agroecosystems

To share a scarce resource and to limit environmental damage, it is imperative to limit future water use. Important pathways to growing enough food with limited water are to increase the productivity of water in irrigated and rainfed areas, in animal husbandry and in aquaculture; improve water management in low-yielding rainfed areas; change food consumption patterns; and (possibly) through enabling trade between water rich and water scarce countries and areas. Increasing water use efficiency of crop, livestock, and aquatic production,

while preserving the functioning of water bodies in a context of increased demand for food and energy, is a real challenge. Consideration of the various ecosystem functions in irrigated and rainfed agroecosystems is crucial, as is effective water governance at different and appropriate scales to help ensure sustainable use of water resources.

Water storage options along the continuum, from soil and groundwater to natural wetlands and dams, can make water more accessible at different spatial and temporal scales. This is especially important in rainfed agriculture, where other water management options and appropriate farming practices can help increase agricultural and water productivity through various water management options. Support should be given to systems and approaches that ensure high water productivity as well as gender and social equity and contribute to closing the water cycle to the benefit of many ecosystem functions.

Sustainable livestock production systems should be encouraged in order to respond to changing diets and the increased demand for animal products while maintaining environmental flows and ecosystem services. The resulting improved livestock water productivity would allow more animal products and food to be produced without increasing the volume of water depleted.

For aquaculture, various practical approaches and policies for enhancing water use have been developed in different geographical settings all of which have potential to be useful elsewhere. Greater awareness of these amongst producers and policy-makers could encourage more cost-effective water management strategies that would concomitantly reduce animal, environmental and public health risks.

Managing Agroecosystem Services for Food Security

To ensure food security it is important for decision makers to support the management of agroecosystem services by taking appropriate policy measures that encourage the use of technologies and approaches such as sustainable land management, integrated water resources management, and more sustainable agricultural practices by female and male farmers.

For sustainable water use, water managers must consider agriculture as an ecosystem with all its services, and in turn consider how these services may be impacted by water. Agroecosystems are huge providers of food, animals, products, services, and incomes and, if they are well managed, in sustainable ways, to maintain ecosystem functions and benefit from the full range of ecosystem services could ensure food security.

This calls for a shift in the management of water from water for food to water for multifunctional agroecosystems, considering the whole ecosystem base of provisioning, regulatory, cultural, and supporting services. More research is needed on tools to analyze the potential at various spatial scales and over time in order to define an appropriate and practical management approach.

Many of the recent synthesis assessments on environment and water suggest that concerted global actions are needed to address the root causes, while local efforts can reduce human vulnerability to shocks and chronic food insecurity. There is scope for actions at all levels: local, national and river basin levels. Recognizing the multiple ecosystem services of agroecosystems, coupled with elements of Integrated Water Resource Management (IWRM) at the basin scale, considering all sources of rain, surface and groundwater, can be a powerful and sustainable response to freshwater scarcity. Because agriculture accounts for more than 70 percent of global water use, agroecosystems are a logical target for water savings and demand management efforts.

To ensure that we have enough water for food and for a healthy planet, we must go beyond implementing the known improved techniques, incentives and institutions, and invest in understanding the various ecosystem functions and services, as well as their interaction, in the agroecosystems, that cover so much of the earth's surface. An ecosystem services perspective to agriculture can also help in the consideration of agronomic questions such as crop choices and soil fertilization, but institutional and market issues need to be addressed in these choices too.

Water plays a significant role in the support and regulation of various other services provided by agroecosystems. These uses of water in the

landscape can be hampered if agricultural activities are viewed in isolation and receive disproportionately more water. The capacity of multipurpose agroecosystems will be enhanced, when the water quantity and quality are adequate for the whole range ecosystem services, which will lead to greater environmental sustainability, more equity and result in higher economic efficiency in the long term.

Key Recommendations

Integrated water resources management can contribute to long-term food security by providing water for agroecosystems and for non-agricultural ecosystems. More resilient ecosystems can support a wider range of ecosystem services, including water management functions that are crucial for stable food security, and become more diverse and more productive. This requires the following changes in the valuation and management of ecosystems, water resources, and food security:

- *Valuation of ecosystem services* from agroecosystems and non-agricultural ecosystems, so that these can be used to understand incentives and trade-offs.
- *Management of agriculture as a continuum of agroecosystems* that not only produce food, but also deliver a whole range of other ecosystem services necessary for long-term food security, in a larger and diverse, tree-rich landscape. The integration of crop, tree, livestock, and aquaculture production can lead to resource recovery in the form of manure for soil fertility and fish feed, as well as crop residues and tree fodder for livestock feed.
- *Management of all rain and runoff water sources for multifunctional agroecosystems* at river basin level to support the widest range of ecosystem services. With higher water productivity in terms of ecosystem services (water for agroecosystems), ecosystems will in turn be more efficient in terms of regulatory and supporting services for water (agroecosystems for water).
- *Application of adaptive Integrated Water Resources Management* supported by capable

and empowered institutions to provide water for non-agricultural ecosystems (water for nature/environmental flows) and agroecosystems (water for food).

- *Collaboration between sectors:* multiple services from agroecosystems require support from authorities and experts in, for instance, agriculture, environment, water, aquaculture, forestry, fisheries, livestock and wildlife management. This is required at local, basin, national and international scales.

Specific opportunities to enhance food security and increase water productivity include:

- *Strategic placement of multipurpose trees* in agricultural landscapes to tighten water, nutrient and carbon cycles that sustain soil and water productivity, thereby reducing pressure on the remaining forest resources.
- *In dryland agroecosystems* with locally adapted cultivars, the holistic utilization of water and nutrients, provisions for herds and integrated tree-crop-livestock management are all crucial to guarantee ecosystem services in the long term.
- *In wetland ecosystems* the development of synergies with fisheries, aquaculture, livestock grazing, and horticulture and strategic enhancement of tree cover without compromising the water regulating functions and other ecosystem services of the wider catchment, including groundwater utilization.
- *In crop systems*, where the highest potential is in increasing rainfed crop production, yield increases can be obtained over vast cropland areas with targeted surface water and ground-

water management to bridge dry spells, careful nutrient management, innovative field practices and adapted cultivars. More ecosystem services could be provided by crop-tree-agroecosystems, if (a) diversity within the cropping system as well as in landscapes is promoted, (b) habitat integrity and connectivity are maintained, (c) the right infrastructure is selected, and (d) effective supporting institutions are in place for water management and collective action.

- *In aquaculture and fisheries* the provision of healthy aquatic ecosystems with clean and oxygenated water for physical support and respiration, seed and feed. If managed well, such aquatic ecosystems need, and in return will also provide, regulation of detritus, waste, nutrient cycling and carbon sequestration. In capture fisheries, maintaining migratory routes and breeding habitats as well as sustainable fishing practices are important. More ecosystem services can be provided in multipurpose aquatic ecosystems such as livestock-aquaculture integration, rice-fish culture, aquaculture in irrigation and water management systems, and wastewater-fed aquaculture.
- *In livestock systems* animal management strategies to improve animal health and survival can reduce herd sizes, while feeding strategies such as the use of crop residues and other waste products, tree fodder, proper selection of fodder crops and implementation of grazing management practices can increase livestock water productivity, while water quantity and quality can be conserved by, for instance, water point management. More ecosystem services can be provided in, for instance, mixed crop-livestock systems with multipurpose crops and by integrating livestock in irrigation systems.

1. INTRODUCTION

1.1 Background and Justification

Globally, about one billion people, mostly from developing countries are under-nourished. Most of these people live in countries that are not self-sufficient in food production, in particular in South Asia and sub-Saharan Africa. The livelihoods and well-being of these people is critically dependent on their farm produce, and on the local landscape with its ecosystem functions, to provide ecosystem services that sufficiently support their livelihoods and income. Water is a key driver of several ecosystem functions, including biomass and crop yields, as well as various supporting and regulatory ecosystem services. It is also a principal input in enhancing food production, irrigation being a well-established method of improving yield in many parts of the world. Use of irrigation in sub-Saharan Africa is still at a low level while rainfed agriculture remains the dominant mode of subsistence agriculture. Ninety-five percent of agriculture in sub-Saharan Africa and sixty percent in India is rainfed (CA 2007). Productivity from rainfed agriculture remains low due to limited soil nutrient availability, occurrence of pests and diseases, and spells of minimal or no precipitation at critical growing periods. Several of these factors are related to degradation of ecosystems. In key parts of the tropics, agriculture has continued to expand into forest and woodland areas, reducing tree cover and compacting soil, causing higher run-off (Ong and Swallow 2003). With the impact of climate change, spatial and temporal variability in production is expected to increase, while overall food production is projected to decrease, especially in sub-Saharan Africa, because an increase in magnitude and frequency of drought and floods (Parry et al. 2007). Improving water productivity in sub-Saharan Africa and in other vulnerable regions of the world is one key avenue to gaining food security for these regions. Maintaining healthy ecosystems to ensure water availability and the continuance of other regulatory

ecosystem services can be an essential contribution to the sustainable improvement of food security.

The understanding of linkages between ecosystems, water, and food production is important to the health of all three, and managing for the sustainability of these connections is becoming increasingly necessary. In many places, changes in the global water cycle, caused largely by human pressures, are seriously affecting ecosystem health and human well-being (MA 2005). Widespread land degradation driven by bad agricultural practices is seriously limiting food production (Bossio and Geheb 2008). Forest clearing or deforestation for agriculture has hydrological consequences and can lead to land degradation through salinization, soil loss, and waterlogging (Falkenmark et al. 2007). Fisheries and aquaculture, major sources of protein in many developing countries which provided more than 2.9 billion people with at least 15 percent of their average per capita animal protein intake in 2006 (FAO 2009a), are threatened by ecosystems degradation caused by over-fishing, habitat degradation, pollution, invasive species, and disruption of the river flow by dams. These pressures have caused a severe decline in fish species and production particularly in inland fisheries, thus threatening an important food and nutrition source for poor rural men, women, and children (UNEP 2010). Beef, poultry, pork and other meat products provide one-third of humanity's protein intake, but also consume almost a third (31%) of the water used in agriculture globally (Herrero et al. 2009). Furthermore, pro-poor initiatives to ensure equal access to land, water and other natural resources and to their benefits have become crucial in the context of increasing commercial pressures on land. Whereas the question of rights is essential to ensure food security for future generations; ecosystems, water, and food production also have to be managed wisely to prevent irretrievable losses in ecosystem services and overall food production (Falkenmark 2008).

Over the last few years, the international community has released several publications which highlight the need to improve water management for food production (crops, livestock, fish etc.). Some of these have been summarized in an Appendix and include the UNEP report on Ecosystem management and the environmental food crisis (Appendix 1), FAO's work on Water, Food and Ecosystems (Appendix 2), Millennium Ecosystems Assessment (Appendix 3), GEO 4 (Appendix 4), Comprehensive Assessment of Water Management in Agriculture (Appendix 5), World Water Development report (Appendix 6), International Assessment of Agricultural Knowledge, Science, and Technology for Development (Appendix 7), and the Inter-governmental Panel Climate Change reports. Each of these reports has played a significant role in developing the understanding of policymakers, scientists, and the international community on the environment and water. Each report has a specific focus, which creates a lens that it uses to view the interactions between water and the environment. The publications have focused on issues such as efficient irrigation, ecosystems, climate change and now there is a need to review all these reports, complement them with new publications, and produce a consolidated message assessing the importance of ecosystems in managing for sustainable water use in food production. Global change, with driving factors including population growth, increasing wealth and increased variability, e.g. due to climate change causing shocks, needs to be addressed in view of the integrated relations between ecosystems, water, and food production. This document draws from the tools and ideas expressed in the above reports, which have since been complemented by international publications, and seeks to synthesize their results and transcend the information contained therein.

As predicted by the various reports, the timely supply and availability of food, fuel and water, and the deterioration of ecosystem services, are growing concerns. The recent global food shortage and other simultaneous shocks that hit the world resulted in soaring food prices leading to increased attention worldwide to food security. This trend is continuously aggravated by population growth. Feeding a world population of 9.1 billion people in 2050 will require raising overall food production by

some 70 percent over the period from 2005/07 to 2050 (nearly 100% in developing countries) (FAO 2009b), in addition to global and national mechanisms ensuring equitable access to land and agricultural products. Adding ecosystem restoration makes the challenge even more complex as the cost of restoration is generally extremely high compared with the cost of preventing degradation and not all services can be restored (MA 2005a). Increasing food production translates into significant increases in the production of several key commodities. This will not be possible with the current agricultural, livestock, forestry, and fisheries practices which are limited by insufficient amounts of renewable freshwater per capita and ecosystems degradation. Hence one way of securing sufficient and affordable food for all is a revisit of our current agricultural, livestock and fisheries practices, as water scarcity and ecosystems degradation may jeopardize the world's ability to meet the needs of its people and their health. The rapidly increasing and potentially infinite demand for natural resources, trees, land, and water for the production of biofuels may put a severe burden on ecosystems, whereas climate change may contribute to more frequent and more intense global shocks. These challenges could be addressed by recognizing that agriculture provides ecosystem services beyond food production and making policy and management decisions that act upon that. In practical terms this would mean improving agricultural management, linking to downstream aquatic ecosystems and creating and managing multi-functional agroecosystems (Gordon et al. 2010).

As part of its contribution to the global food crisis, UNEP pledged to the UN Secretary-General to produce a policy document on Ecosystems for Water and Food Security, to which this publication provides background and further reading.

1.2 Scope

The target group of this publication consists of high and mid-level professional staff in Ministries of Environment and other relevant government and inter-governmental bodies, as well as other professionals in other institutions e.g. NGOs, bilateral organizations, and UN Agencies.

The purpose of this document is to show how sustainable ecosystems, explicitly including agroecosystems, are essential for water management and food production. This document provides background evidence illustrating the 3-way interdependence between ecosystems, water and food security, demonstrating how ecosystem management can be improved to ensure water availability and to avoid future food crises. By looking at the world as a range of ecosystems (from pristine nature to highly intensive agriculture) and recognizing their variety of ecosystem services, agroecosystem functions can be managed sustainably for current and future food security. It has become widely accepted that food security is not only a matter of food production but also an issue of equal and secure access to the means of production and to food products (FAO 2010). This document focuses primarily on how to achieve sustainable food production from a biophysical perspective and does not address *per se* the key social and institutional issues related with food security¹. Several of those are however highlighted throughout the text in order to remind the reader that these remain a critical component to ensure food security for the poor and socially-disadvantaged groups.

It is hoped that this document will help policy makers to understand agriculture in terms of ecosystem functions and services and provide background and guidance for sound decision making in order to create efficient ecosystems for water management and for food production. In this, it builds on the new paradigms or views on the environment and the water sector as developed in various recent assessments (MA 2005; CA 2007; UNEP 2007, 2009b, 2010; McIntyre et al. 2008; WWA 2006, 2009; Nellemann et al. 2009). Central to these new paradigms or views are:

- *Ecosystem Services* – ecosystems provide important services to the agriculture sector and society. When ecosystems are viewed in terms

¹ Similar considerations hold true for water security or water safety, more commonly addressed in drinking water supply literature. In addition, another topic that is relevant but will not be discussed in much detail here is the concept of carbon sequestration and the role of ecosystems in storing carbon.

of the services that they provide (regulatory, supporting and cultural ecosystem services in addition to provisioning services such as food production), it shows their economic and political significance, thus the ecosystem service approach is more likely to generate an understanding of why and how ecosystems need integrated management and some require protection.

- *Environmental Flows* – Stemming from the concept of ecosystem services, environmental flows in the context of this report are the water flows – at the right time, with the right amount and of the right quality – necessary to sustain certain ecosystem services, in particular those related to downstream wetlands and aquatic habitats.
- *Agriculture as an ecosystem: agroecosystems* – This idea views agriculture as a set of human practices embedded in and part of its own ecosystem that has certain ecosystem needs, functions and services and interacts with other ecosystems. It moves away from viewing agriculture as an isolated activity towards regarding it as a part of many interconnected landscape elements.
- *Climate change as a water sector driver* – Because climate change has experienced a meteoric ascent in public awareness and in funding for study, all of these reports include an aspect of the effects of climate change on the water sector (see Chapter 2 for more details).
- *Food security as outcome of sustainable ecosystem management* – By applying the ecosystem services framework to agroecosystems, water can be managed in a more sustainable way, increasing food security and livelihood benefits while minimizing (or ideally reversing) environmental deterioration.

This report on ecosystems for water and food security will take an ecosystem perspective, where agroecosystems are seen as providers of food security and of water, contrary to other studies that place ecosystems more at the receiving end.

1.3. Relationship between Ecosystems, Water, and Food

This document is structured to show the relationships between ecosystems, water, and food (Figure 1). Hence it starts with chapters on food security (2), ecosystems (3) and water (4) that each provide more insight into the reasons why an integrated ecosystem

approach is required and what this should entail. These are also the three main areas (separate sectors in some countries) that require change: food production (crops, fish, livestock), environmental protection and sustainable management, and water resources management, respectively. The synthesis chapter (5) then explains how agroecosystems provide water and other services for food security. There is some deliberate overlap between chapters so they can be read independently.

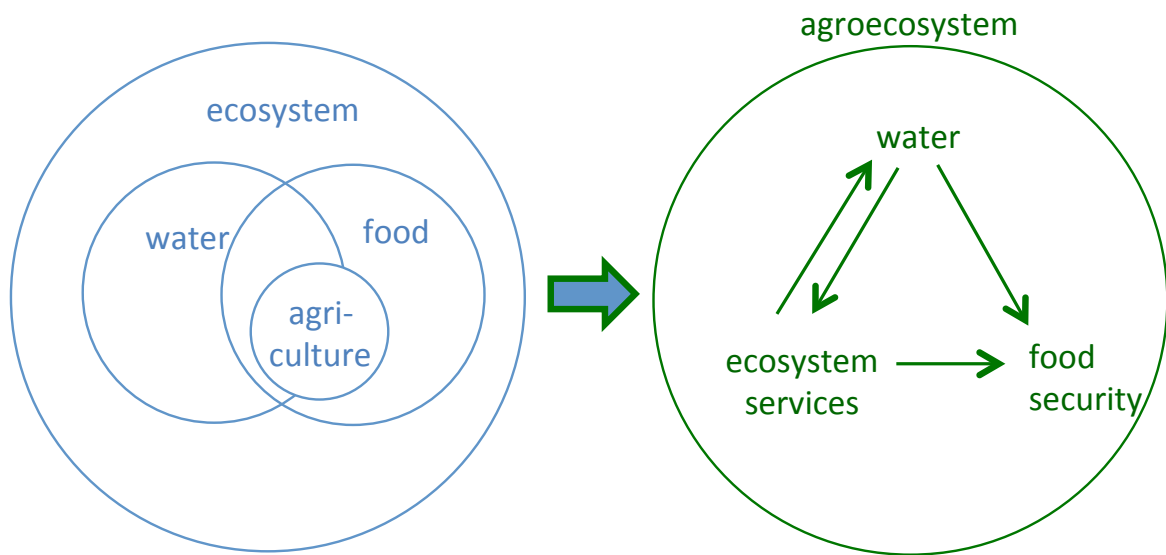


Figure 1. Water and food as dimensions of ecosystems (left), with agriculture as subset of food (production), and the role of water for food security and other ecosystem services in an agroecosystem (right).

2. FOOD SECURITY

2.1 Introduction: Hunger, Access, and Ecosystem Impacts

Food security, meaning access to adequate food for all, at all times, requires *inter-alia* sustainable and increased production and productivity in the agricultural sectors well as more equitable distribution of food produced. Hence food security is the product of many variables including physical factors such as climate, soil type and water availability; management of these and other natural resources (water, land, aquatic resources, trees and livestock), at the level of fields, landscapes and river basins; and losses and waste along the value chain. It also requires adequate policies and institutions in the many sectors that influence the ability of men and women to produce and purchase food, and the ability of their families to derive adequate nutrition from it.

According to the FAO High Level Experts panel on Food Security (FAO 2009b), “agriculture in the 21st

century faces multiple challenges: it has to produce more food and fiber to feed a population expected to grow by over a third (or 2.3 billion people) between 2009 and 2050, more feedstock for a potentially huge bioenergy market, contribute to overall development in the many agriculture-dependent developing countries, adopt more sustainable production methods and adapt to climate change”. The latest FAO estimates indicate that over the same period agricultural production needs to grow by 70% to feed this population, because of a shift in demand towards higher value products of lower caloric content, and an increased use of crop output as feed for the rising meat demand (FAO 2009b). At the same time the adaptation of the agriculture sector to climate change will be costly but is necessary for food security, poverty reduction, and the maintenance of ecosystem services. In such a context sustainable use and management of water and biodiversity resources in agroecosystems play a decisive role in providing food and income for a growing population (Nellemann et al. 2009; FAO and PAR 2011).



Harvesting fish in peri-urban Ho Chi Minh City, Vietnam.

A sustainable increase in food production has to be coupled with pro-poor policies which give to men and women the rights and means to access the resource base for sufficient and adequate food production or the rights and means to access food products. More than 40 countries already have the right to food entrenched in their constitutions (McClain-Nhlapo 2004). A rights-based approach to food security requires identifying men and women more at risk of hunger and creating the enabling environment for them to produce or access food, through targeted policies.

Despite 10 years of global commitment to reduce hunger, the number of hungry (as measured through MDG target 1A) remains more or less the same as estimated during the base year of 1990 (Figure 2). Significant gains have been achieved in the past twenty years, as the relative share of hungry people has decreased from around 20% of developing country populations in 1990 to a current 15% (FAO 2010), though according to other sources this seems to be rising again. Still, about 925 million people do not have sufficient food and 98% of these live in developing countries (Figure 3). Sixty-five

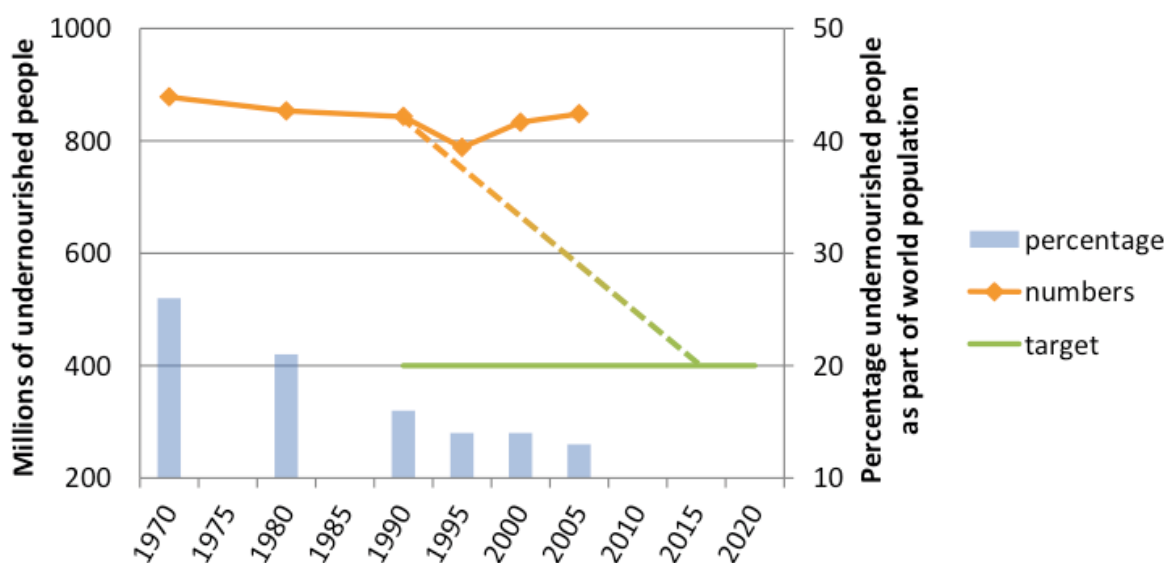
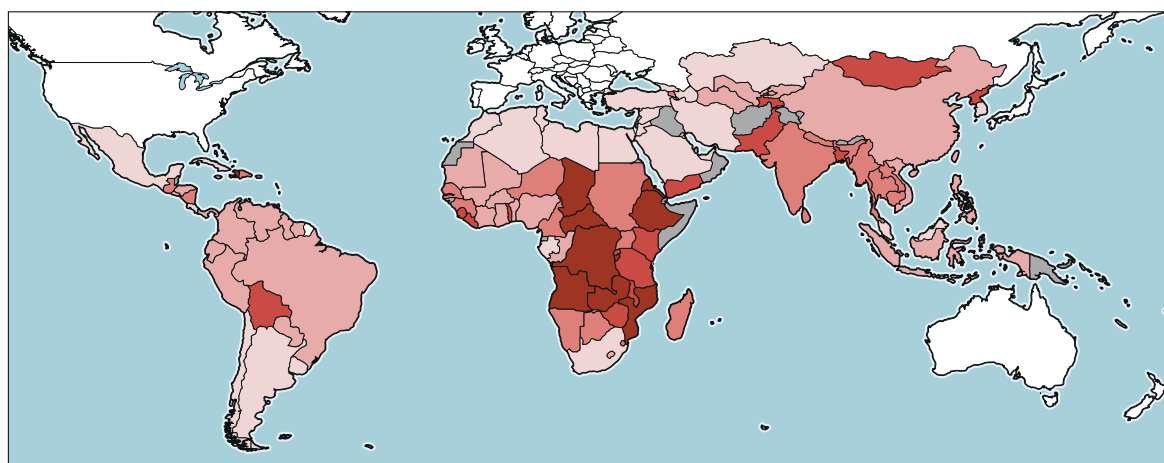


Figure 2. Trends in numbers and percentages of undernourished people in the world for the period from 1969 to 2009, compared to the MDG target of halving the number of hungry people (based on FAO 2010).



Source: FAOSTAT 2010 (www.fao.org/hunger)

Prevalence of undernourishment in developing countries (2005-07)

- Very high (undernourishment 35% and above)
- High (undernourishment 25-34%)
- Moderately high (undernourishment 15-24%)
- Moderately low (undernourishment 5-14%)
- Very low (undernourishment below 5%)
- Missing or insufficient data

Figure 3. Prevalence of undernourishment in developing countries (2005-2007) (FAOSTAT 2010; www.fao.org/hunger).

percent of the world's hungry live in India, China, Democratic Republic of Congo, Bangladesh, Indonesia, Pakistan, and Ethiopia. Women account for about 60% of global hunger. Malnutrition and hunger-related diseases cause the death of about 7 million children annually. Child malnutrition costs developing countries 20 to 30 million USD per year. Apart from lack of calories, diets deficient in zinc, vitamin A, iron, and iodine impair the health of up to 2 billion people. Achieving food security for all is necessary and vital for human well-being globally (WFP 2010).

The sudden increase in food prices that 2006/07 brought, was largely unanticipated, and has become a driver in water and food sectors (von Braun 2007). It was caused by a variety of factors including "rising demand, shifting diets, droughts, increased cost of agricultural inputs, and policies that encourage use of agricultural land and output for bioenergy production" (WWA 2009). This has resulted in an increased burden on the poor, who already spend one half to three quarters of their income on food. Major food producing countries have restricted exports of food to keep costs down domestically, which has raised international food prices even more. While increased food costs will likely push governments to invest more in agricultural productivity, this will take years to offset the current high food prices (WWA 2009).

Efforts to meet the MDG of halving hunger (compared to 1990) in 92 developing countries by 2015 will have significant impact on water flows, possibly on water quality and most likely on water-dependent ecosystem services. Global estimates on the water needed for meeting the MDG target on hunger suggest that the current appropriation of circa 4,500 km³ annually for food, needs to increase to 6,700 km³ annually by 2015 and to 8,660 km³ by 2030 (Rockström et al. 2007). Some of this additional water needs may be mobilized through water savings such as improved water productivity, in particular in currently low yielding agroecosystems. The distribution pattern of water is uneven and inequitable. There are fundamental differences in opportunities between as well as within countries, depending on whether they are projected to be under absolute water stress, with limited opportunity to develop either rainfed or

irrigated food production systems to meet in-country food demand, or potentially have opportunities in either rainfed agricultural management, or in irrigation development (Rockström et al 2009). Access and control over land, water and produced capitals (e.g. financial capital, technologies) are also key factors to achieve the MDGs and increase water productivity in a way that will benefit the poor, notably women (UN 2009). These different opportunities for the appropriation of water for food security may have quite different impacts on water resource appropriation in different countries, as well as on downstream flows, ultimately affecting various water-related ecosystem services and functions. A comprehensive analysis of the need for water for food, and the potential impacts on water-dependent ecosystem services in various landscapes is not yet available on aggregated global level.

2.2 Drivers and Future Prospects

Demand for the world's increasingly scarce water supply is rising rapidly, affecting its availability for food production and putting global food security at risk (Rosegrant et al. 2002). The increasing world population and their improving wealth as major drivers of future change will continue to increase pressure on the natural resource base (Godfray et al. 2010b). Inequities in access to land, trees and water are likely to increase in the absence of policies ensuring equitable rights for all. The average availability of land, forest resources and water per person will continue to decline, especially for the poor men and for women, which in turn compels us to increase equitably the efficient use of natural resources. Another major driver is climate variability that causes shocks to the food and other systems, such as finance, energy and health systems. The poor, women and marginal groups are particularly vulnerable to loss of livelihood and assets and hunger in the face of climate variability and change (Cannon et al. 2003). Variation in climate vulnerability is place-based, depending on social inequality, unequal access to resources, poor infrastructure, lack of representation, and inadequate social security, early warning or planning systems (Ribot 2009).

In the Millennium Ecosystem Assessment, drivers were defined as any natural or human-induced

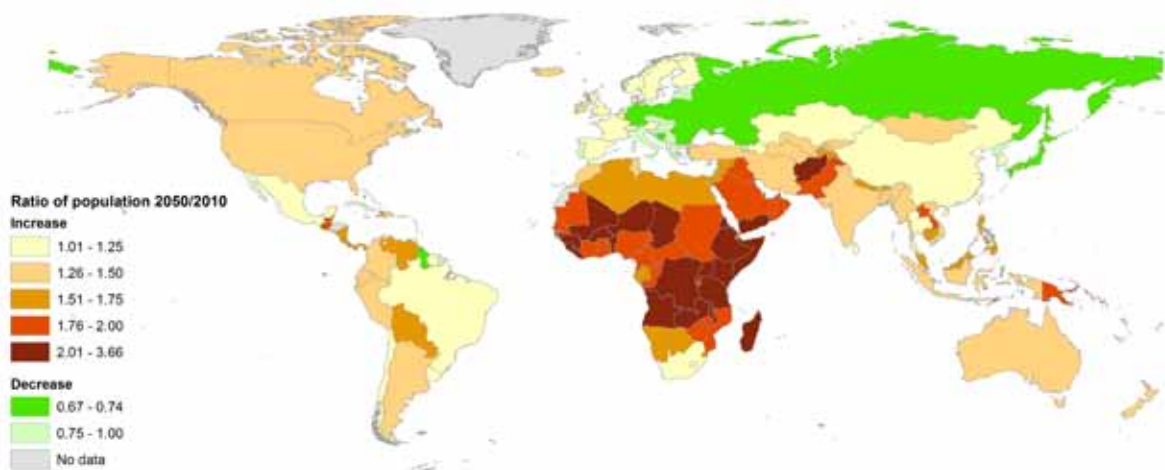


Figure 4. Expected areas of population growth and decline 2010-2050 (IWMI, based on UNFPA 2010).

factor that directly or indirectly causes a change in an ecosystem (Carpenter et al. 2006). Such drivers can be observed at global and local scales, ultimately putting direct or indirect pressure on the management of our natural resources (Nelson et al. 2006). Key global drivers discussed in this section center around food security, and, to a limited extent, energy, as major influences affecting water demand and increasing pressure on ecosystems.

2.2.1 Demographic drivers

Obviously, the main driver relating to food security is demographic pressure: in order to feed 9 billion people by 2050, food production has to increase. Since a higher number of people means the consumption of more resources and population growth under current scenarios will lead to reduced food security, increased water use, more pollution of the natural resources and ecosystem degradation. This will result in destruction of natural habitats such as forest, in favor of land for people and crops. As access to forest resources declines there is pressure on rural people to derive forest products, such as fuel, fodder and timber from farm land, often meaning that these products compete with food crops if not tightly managed (Muthuri et al. 2005). Agroecosystems tend to use more water than natural ecosystems, and higher production is often associated with higher water use, so that increased food requirements for a growing population put a huge stress on water resources (CA 2007). The challenge is therefore to improve water productivity at the landscape or river basin level, especially for the rapidly growing populations in the drier areas of many developing countries (Ong et al. 2006).

In the developing world, populations are rapidly increasing, reducing food security and nutrition (von Braun 2007). In Europe and East Asia, populations are aging rapidly², and in much of the developed world, populations are stable or declining (WWA 2009). Water resources development cannot keep up with population growth and hence water scarcity, defined as less than 1000 cubic meters available water resources per capita per year, is increasing (Khosh-Chashm 2000). Unfortunately, most of the population increases will occur in water stressed areas with fragile ecosystems—in Africa and the Middle East, hence further increasing local water scarcity (Figure 4).

One of the traditional coping strategies to deal with environmental stress has been migration, another important demographic driver. While earlier reports suggested that climate change would be a main driver of migration, in reality socio-economic circumstances are the key determinants (Tacoli 2011). Hence migration could be defined as an adaptive response to diversify sources of income. As people become more vulnerable to variability in natural resources, mobility patterns may change with regard to distance, duration and type of migrants. International migrants have an impact on urbanization in their country of origin, as they tend to invest in small and medium towns, attracting local, often seasonal, migrants (Tacoli 2011).

² While aging populations might appear to be outside of the drivers affecting the water sector, older people require more medical help, and water that is better sanitized (WWA 2009). This will increase the water needs of aging populations slightly, though this effect is most likely marginal as compared to that of global population growth.

In 2008 the world's population was split evenly between urban and rural dwellers. By 2030 there will be 1.8 billion more urban dwellers, and 100 million fewer rural inhabitants (WWA 2009). Urbanization, foreseen to continue at an accelerating pace, is expected to account for 70 percent of world population in 2050. As people move to cities, their energy needs increase as urban middle and upper classes begin to use personal cars for transportation, use more electricity at home, and consume more energy-intensive diets (more meat and processed foods) (Kearney 2010). Demand for aquaculture products like fish and shrimp continues to rise (CA 2007), endangering the health of aquatic ecosystems in many areas (Hoanh et al. 2010). Wealthier urban inhabitants are likely to consume both more calories and higher protein diets (especially dairy and meat products that have higher water requirements per calorie) than their rural counterparts (von Braun 2007; de Fraiture and Wichelns 2010). This will increase and concentrate food demands (Cirera and Masset 2010). Urbanization also increases the reliance on sanitation and water storage as more people need water in one place. This in turn will increase water pollution and increase the amount of pollutants that the water is exposed to. In addition, large urban areas covered with impervious surfaces will increase the risk of flood disasters. Increases in energy consumption will put more pressure on the environment to generate more energy (e.g. hydropower). People living in cities also produce more waste in higher concentrations than those in rural areas. They tend to use products that require more processing, and consume food that needs to be transported longer distances, both of which cause more pollution. Urbanization and the increase in the world's population both lead to increased trade. Trade of agricultural commodities has impacts on ecosystem services at the production end, distant from the point of consumption of the products. Trade will grow in importance, both between rural and urban areas and internationally between countries.

While in certain parts of the world, sheer population growth and aggravated social inequities lead to reduced food security, in the wealthier parts of the world, higher consumption per person further increases food demand (von Braun 2007). In terms of grain equivalent (GE), consumption generally

varies between 1–1.5 kg GE/person/day for a vegetarian diet (using 1000–1500 liters of water) and 4–5 kg GE/p/d in wealthy societies (meat rich diet; using 4000–5000 liter). Under current agricultural practices this would also result in an increasing demand for land (up to 200 million ha additional by 2030) (Bindraban et al. 2010b). This does not even consider the impact of people's need for fibers and fuel in the light of generally declining forest area. Since 2000, production of biofuels, particularly ethanol and biodiesel for use in the transport sector, has tripled and is projected to double again within the next decade (FAO 2008a). This increase has been driven largely by policy support measures in the developed countries, seeking to mitigate climate change, enhance energy security, and support the agricultural sector. If the world switches from fossil fuels to the production of biofuels, this will have immense impacts on ecosystems and water availability (de Fraiture et al. 2008; Bindraban et al. 2009a). Currently biofuels account for 0.2% of total global energy consumption, 1.5% of total road transport fuels, 2% of global cropland, 7% of global coarse grain use and 9% of global vegetable oil use (FAO 2008b).



In parts of Ethiopia, manure is not used to enhance soil fertility, but for cooking.

These shares are projected to rise over the next decade. While two thirds of the world's poorest people still rely on fuel wood and charcoal as their major source of heat and cooking, representing over 40% of wood removal from forest globally (FAO 2006), biofuels have contributed to higher food prices, with adverse effects on consumers (von Braun 2007).

2.2.2 Climate change and other shocks

While there is increased pressure due to human population increases, additional uncertainty is due to other factors such as weather variability caused by climate change and other external shocks (e.g. sudden rise in food prices, or epidemics). The United Nations Framework Convention on Climate Change defines climate change as "a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods" (Pachauri and Reisinger 2007). The Fourth Assessment Report of the IPCC concluded that current global climate change was primarily anthropogenic and likely to result in profoundly negative consequences for a majority of the world's population (Pachauri and Reisinger 2007). While the effects of climate change on food security, ecosystems and water may be overtaken by the impacts of population growth, the two may reinforce each other and worsen the vulnerability of many poor people in the world. This may be further aggravated by other external shocks such as local food shortages, sudden increases in food prices and financial crises, and the ability of poor people to cope may be undermined by chronic vulnerability, low education, and exposure to disease.

Predicting the effects of global climate change is a process that is daunting in scale and uncertain at best in its application. Several predictions are generally agreed upon however: first, that the average global temperature will increase at an accelerated rate, and second, that weather events will become less predictable, more severe, and probably more frequent as well. Some ecosystems are more vulnerable to these changes than others, but in many cases their resilience will be exceeded, leading to irreversible losses of biodiversity and various ecosystem services such as the regulation of pests and water flows

(Fischlin et al. 2007). Climate change is predicted to affect agriculture and forestry systems through higher temperatures, elevated carbon dioxide (CO₂) concentration, precipitation changes and increased pressure from weeds, pests and disease (FAO 2009d). In the short term, the frequency of extreme events such as droughts, heat waves, floods and severe storms is expected to increase.

Water links earth's atmosphere, land masses, and oceans through the global hydrological cycle. Aside from providing one of the key ingredients of life on planet earth, the hydrological cycle has a great many other important functions, which include energy exchanges, erosion, climate regulation, and the transference of bio-active chemicals. The effects of climate change on the hydrological cycle are nearly impossible to predict on a local scale, but certain global changes are likely (Jung et al. 2010). There is consensus among climate scientists that warming will accelerate the global hydrological cycle, resulting in changes in stream flow, precipitation, atmospheric water content, soil moisture, ocean salinity, and glacier mass balance.

As agriculture is mostly dependent on the hydrologic cycle, food production will be greatly affected by changes in precipitation, soil moisture, and evapotranspiration. Local agricultural production may increase or decrease under conditions of climate change, depending on geographic features such as elevation, latitude and other circumstances. However all current quantitative assessments indicate that climate change will adversely affect food security in developing countries, particularly Africa, and increase the dependency of many of these countries on food imports. It is estimated that climate change will reduce Africa's potential agricultural output by 15–30 percent by the 2080–2100 period (FAO 2009d). Poor female and male farmers have a low ability to cope with extreme climatic events and climatic variability due to small landholding, less control over water, lack of access to capital, reduced participation in decision-making and less access to adequate information.

Climate change will have a variety of effects on the water sector. Water planners will be less able to use historical data to plan, design, or operate hydrological systems, though new prediction models are under

development, which will enable policy solutions (CA 2007). Additionally, extreme hydrologic events such as floods, droughts and storm surges will become more common, appear in new places, and appear with increased intensity and frequency (Solomon et al. 2007). In most places, unpredictable weather variability will decrease the availability of water, even if it is more abundant: drought-flood cycles may result in increased annual precipitation, but decrease the ease of access to water. Under these circumstances, it becomes highly important to capture and store the water so that it can be used for food production. Otherwise, more crops and livestock may be lost through floods and drought (Bates et al. 2008). Coupled with impacts on water quality, fresh water systems are particularly vulnerable to negative impacts of climate change (Bates et al. 2008). The increase in the average temperature may benefit some areas, but on the whole reduce the arable land area leading to decreased food production (Parry et al. 2007). Furthermore, this will disproportionately affect Sub-Saharan Africa (de Wit and Stankiewicz 2006), where food production per capita is already lowest (McIntyre et al. 2008). In general, arid and semi-arid regions are predicted to experience significant temperature increases and reduced precipitation (Sivakumar 2005). Climate change will also adversely affect ecosystems by changing the climatic conditions that they rely on, which may result in decreased biodiversity, decreased ecosystem services and reduced human well-being in many areas of the world (UNEP 2007). On the other hand, while climate change can be seen as a driver of food and water security, agricultural food production also has its own effects on climate change. There is also increasing evidence for linkages between reduction in tree cover and rainfall, that may extend much further than previously thought (Makarieva et al. 2010). For example, the reduction of forest areas in East Africa is one of the main causes of more frequent droughts, which currently affect large parts of the region (UNEP 2006b). More examples of the impact of agriculture on climate change are given in Appendix 8.

Other than food crises, economic crises have large impacts on food security, ecosystems and the efficiency of water use. The recent world-wide financial crisis increased the occurrence of protectionist policies, decreasing world-wide food trade and reducing the amount of money devoted to development projects and technological research

and development. It has also focused people's attention away from environmental and hydrological issues, and much more towards financial issues, a change in attention which in turn tends to have negative consequences on food security. The recent rise in world food prices has driven 110 million more people into poverty. Over the next several decades, food prices are predicted to rise by another 30–50% due to the inability of food production to keep up with growing demand (Nellemann et al. 2009). Development aid to agriculture decreased by some 58% between 1980 and 2005, even though total official development assistance increased significantly by 112% over the same period (FAO 2009c). This meant that the share of aid funds going to the agricultural sector fell from 17% in 1980 to 3.8% in 2006, with the same downward trend observed in national budgets.

2.3 The Necessity of Ecosystems and Water for Food Security

Ecosystems provide food both in their natural state (for instance through capture fisheries and forest products) and in the form of managed landscapes (such as in crop systems, through agroforestry, livestock keeping and aquaculture). To feed a growing population, food production has to grow too, which in turn means that more water is needed to sustain agricultural, aquaculture and livestock production systems. Water is one of the main factors limiting future food production, particularly in the poorest areas of the world where access to water, and its timely availability, is a problem. Over 1.6 billion people live in areas of physical water scarcity and without changes in management this figure could soon grow to 2 billion (Figure 5). With the same practices, increased urbanization and changed diets, the amount of water required for agriculture to feed the world population would have to grow from 7,130 km³ (today's amount)³ to between 12,050 and 13,500 km³ by 2050, representing an increase of 70–90% (CA 2007).

The Millennium Ecosystem Assessment (www.maweb.org) sought to catalogue the state of the

³ This is more than the 4,500 km³ for food as estimated by Rockström et al. (2007) in Section 2.1.



Rice is an important crop for food security that needs a lot of water.

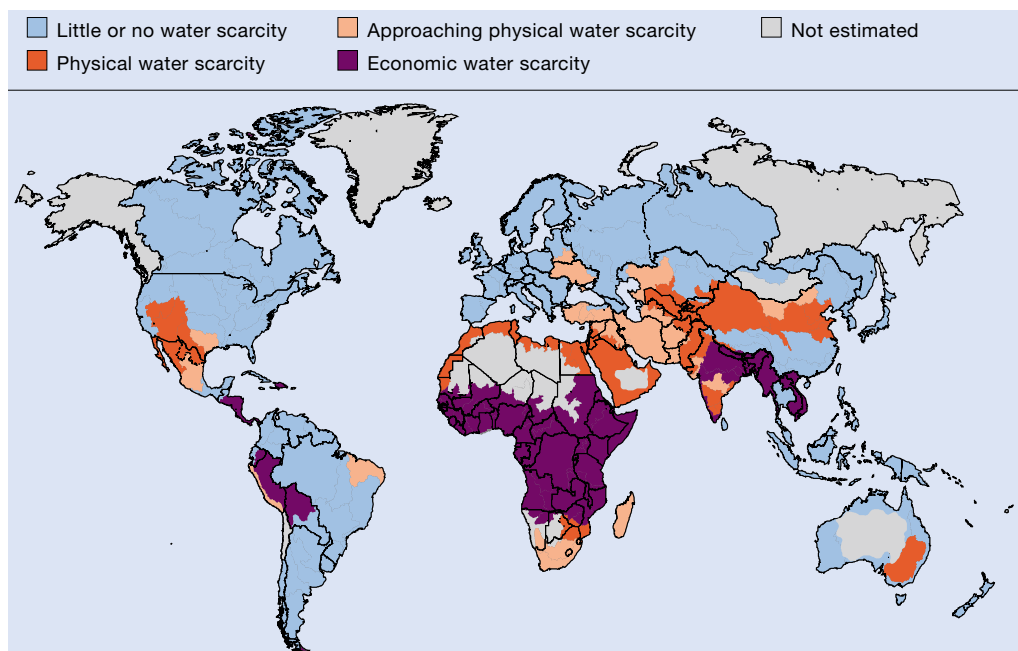


Figure 5. Areas of physical and economic water scarcity (CA 2007). *Little or no water scarcity* means that water resources are abundant relative to use, with less than 25% of water from rivers withdrawn for human purposes. *Physical water scarcity* means that water resources development is approaching or has exceeded sustainable limits: more than 75% of river flows are withdrawn. *Approaching physical water scarcity* means that more than 60% of river flows are withdrawn and these basins will experience physical water scarcity in the near future. *Economic water scarcity* means that water resources are abundant relative to water use, with less than 25% of river flows withdrawn, but lack of human, institutional, and financial capital limits access to water and malnutrition exists.

environment⁴ and assess the consequences of ecosystem change on human well-being (Appendix 3), including its effects on food production. The MA points out that the significant increases in provisioning services (largely the goods used by people) achieved in recent times, and in particular food production through agriculture, to a large extent has been achieved at

the expense of reductions in other ecosystem services, such as those supporting or regulating other things that people need (such as drinking water, flood and drought protection, nutrient recycling and regulation of pests and disease). We are thus facing a tremendous challenge where we need to develop agriculture to feed the world, use water and allocate water to agriculture much more efficiently, and develop new

4 More on ecosystems, agroecosystems, and ecosystem services in Section 3.1.

water resources while ensuring that ecosystems continue to provide environmental services.

The rural poor and marginal groups have a greater direct reliance on ecosystem services. They also have less capacity to cope with degraded ecosystems services and therefore are more and more immediately vulnerable to ecosystem degradation (WRI 2005). However, food production does not necessarily have to come at the expense of other services (Bennett et al. 2009) and cases exist where investments in sustainable agriculture can actually raise food production while also benefitting ecosystem processes (Pretty et al. 2006). Hence there is a need for a better managed and balanced delivery of ecosystem services. This means that in some places and cases you might have to reduce some services at the expense of others, while in other cases you might be able to find win-win situations. The ecosystem services approach (Section 3.1 and Appendix 1) is useful both in focusing attention on, and in finding better ways to manage, the wide range of processes that an agricultural system or landscape can generate and could help better identify beforehand what the services are that will be impacted by a specific intervention (Section 5.2).

The current situation of ecosystem degradation from the impact of over-withdrawal of water for agriculture is already one characterized by dried-up and polluted rivers, lakes and groundwater. For example, more than 50% of wetlands have been lost during the last century (IUCN 2000). If the same practices continue to be used it would result in inevitable degradation or complete destruction of the terrestrial freshwater and coastal ecosystems that are vital to life itself. Instead, appropriate strategies, safeguards, options and technical solutions need to be developed in order to ensure that water can provide for diversified incomes and food security. These strategies should be based upon a better understanding of the functioning of ecosystems, be they terrestrial, aquatic, or marine, and their interrelation with the availability and the quality of water.

For agriculture to feed the world water allocated to agriculture (crops, fish, livestock) must be used more efficiently and new water resources must be developed while ensuring that ecosystems continue

to provide environmental services. More specifically as it is essential to take the following measures (based on FAO Netherlands 2005):

- *Increasing water productivity and ecosystems preservation:* Efforts to improve food security and rural livelihoods must focus on raising water productivity in both rainfed and irrigated agriculture and on increasing the availability of affordable, environmentally acceptable water, especially for the poor, women, and marginal groups, in a way that generates maximum socio-economic returns.
- *Harnessing new water supplies:* Surface and groundwater supplies for agriculture and water storage capacity will have to increase significantly to meet growing food and energy requirements in the context of climate change.
- *Ensuring access to food and improving nutrition:* Access to food at the individual, local and continental levels should be ensured through pro-poor policies. Domestic development policies (including subsidies and implicit taxes), international assistance programs and international trade agreements will have to acknowledge and support the centrality of agriculture-based development in these policies.
- *Increasing investments:* Gender sensitive investments are needed to meet the demand for food, to increase the productivity and development of water, preserve the ecosystems services and to improve the livelihoods of rural women and men.
- *Increasing ecological food production in/for cities:* Environmental regulations and parallel investments in municipal and industrial waste treatment are needed to improve the quality of river water and their related ecosystems, ensuring better quality water for food.
- *Developing more consistent, comprehensive water, ecosystems and food policies:* Governments need to intensify efforts to prepare medium and long-term water, ecosystems and food policies at the local, national and regional levels, which integrate the differentiated needs, interests and perceptions of communities, and especially poor men and women.

- *Increasing research:* More research is required to develop new and situation-adapted technologies that maximize water productivity, ecosystems management and poverty alleviation in irrigated and rainfed areas. This should be accompanied by integrative disciplinary and sector-specific knowledge and gender-sensitive approaches to help understand and develop institutions for management, operation, and maintenance.

2.4 Conclusion: Challenges for Food Security

With a growing global population expected to reach 9.1 billion in 2050 and the increasing impacts of climate change, sustainable use of water and ecosystems for food security is a great challenge (Section 3.2). It is important to gain a better understanding of the functioning of terrestrial and aquatic ecosystems and their interrelation with the availability and quality of water (Section 3.3). This calls for a shift in the management of ecosystems and the water within them for food security. Ecosystems have to be safeguarded and used wisely as they provide the backbone of all environmental services needed in achieving food security and are particularly important for the poor, women, and marginal groups. Agricultural production systems have to be recognized and managed as a landscape of interlinked agroecosystems with the potential for multiple functions (Section 3.4). Land management and tree cover in catchment areas play a critical role in water yield and sediment flow (Carroll et al. 2004). Trees could play a strategic role in agricultural landscapes to increase infiltration and penetration of water, but appropriate species and management options must be used.

Climate change impacts on ecosystems and thereby on water and food security are highly uncertain, and most forecasting scenarios suggest greater vulnerability to damage, reduced ecosystem services, and undermined resilience. Building resilience to climate change and other shocks needs to be mainstreamed into agricultural planning to ensure food security targets (FAO 2009b). This is especially important for vulnerable populations with low adaptive capacity: poor women and marginal social groups in geographical areas at risk, with limited resources, poor social networks and low access to education, healthcare and other services. Efforts to improve their ability to deal with

current rainfall variability and extreme climate events through increased water storage, early warning systems, and better post-harvest processing and food storage will improve the capacity of vulnerable groups to adapt to future climate change, especially when this is done through an ecosystem services approach. Policy makers have a role to play in safeguarding ecosystem services and food producing systems from climate change uncertainties.

Efforts to improve food security and rural livelihoods must focus on giving the capacity to female and male farmers to raise water productivity in both rainfed and irrigated agriculture (Section 4.3) and on increasing the availability for all of affordable, environmentally acceptable water that generates maximum socio-economic returns (Section 5.3). This means considering access to water, land, technologies and inputs, and looking at increasing productivity and broadening the scope from local food production to food security. At the same time there is pressure from global drivers such as urbanization, change of diets, and climate change. Many drivers of global change affect water availability, which in turn affects agroecosystems and food security by limiting or taking away the water necessary for maintaining ecosystem functions. This is a challenging development since ecosystem functions and food security go hand in hand: healthy ecosystems enhance food security while degraded ecosystems decrease food security. Healthy ecosystems are particularly important for the poor who predominantly rely directly on ecosystem services (sub-section 3.1.2). Ecosystem services and food production both rely on water and it is important that the right balance of water is provided to each of them is negotiated in order to sustain both functions (Section 5.1).

The continuous provision of food under global change at the individual, local, national and regional levels can only be ensured by targeted investments and adaptive national and international policies. Domestic development policies (including subsidies and implicit taxes), international assistance programs and international trade agreements will have to acknowledge and support the central role of ecosystem services, agricultural development and water management. Investments are needed to meet the demand for food, to increase the productivity and development of water, preserve the ecosystems services and to improve the livelihoods of rural people.

3. ECOSYSTEMS

3.1 Introduction: Concepts and Definitions

The concepts of nature, ecosystem, agroecosystem and ecosystem services are often interpreted differently by various interest groups. For easy reference, a glossary with short definitions is included at the end of this document (before the references), while this section provides some additional details.

3.1.1 Ecosystems and agroecosystems

An ecosystem is a dynamic complex of plants, animals, microorganisms and their nonliving environment, of which people are an integral part (UNEP 2009a). The benefits that we as humans derive from nature, such as timber and food, or water and climate regulation, are all ecosystem services. There are several types of ecosystems that provide these services: mountain and polar, forest and woodlands, inland water, drylands, cultivated, urban, coastal, island, and marine (MA 2005d). In this document, we consider a continuum of ecosystems ranging from pristine ('nature'), not subjected to any human intervention, up to those highly impacted by people, such as intensive agriculture that can take place in entirely artificial environments. Currently, there is actually very little left of pristine areas, some argue as little as 11% of the terrestrial surface can be called "wild", and most of this is actually barren land or deserts (Ellis and Ramankutty 2008).

Agriculture is thus also an ecosystem, with plants, animals, microorganisms interacting with its non-living environment, and from which primary and secondary products are appropriated by humans (Fresco 2005). In this document we therefore refer to these agricultural ecosystems as 'agroecosystems'. In this continuum from pristine to heavily human impacted ecosystems, certain types of ecosystems are particularly relevant to our scope

of water and food security. These include inland water areas competing with agriculture over water, and impacted by agricultural use of e.g. fertilizers and pesticides; drylands with the limited availability of water and often lack of nutrients and organic matter; and cultivated land, but largely restricted to those used for agriculture. Natural forest and forest management are hardly discussed in this document, while forest-like plantations such as coffee and rubber are considered as agroecosystems and thus included in the continuum. Each type of ecosystem has its own particular issues of vulnerability and management related to specific ecosystem services (Table 1). In addition, ecosystems throughout the range of more or less anthropogenic influences can play a role in food security.

Table 1. Various services provided to human populations from three types of ecosystems (after MA 2005d).

INLAND WATER Rivers and other wetlands	DRYLANDS	CULTIVATED
Fresh water	Food	Food
Food	Fodder and grazing	Fiber
Pollution control	Fiber	Fresh water
Flood regulation	Fuel wood	Dyes & resins
Sediment retention and transport	Medicines	Timber
Disease regulation	Local climate regulation	Pest regulation
Nutrient cycling	Bee pollination	Biofuels
Recreation and ecotourism	Cultural heritage	Medicines
Aesthetic values	Recreation and ecotourism	Nutrient cycling
	Spiritual values	Aesthetic value
		Cultural heritage

Freshwater is considered as the bloodstream of the biosphere (where land and soils would be the bones), driving critical processes and functions in forests, woodlands, wetlands, grasslands, croplands, and other terrestrial agroecosystems (Figure 6), and maintaining them, while keeping them resilient to change (Costanza et al. 1997). The presence and absence of water in the landscape very often determines the characteristics of several supporting and regulating functions, e.g. preserving nutrients

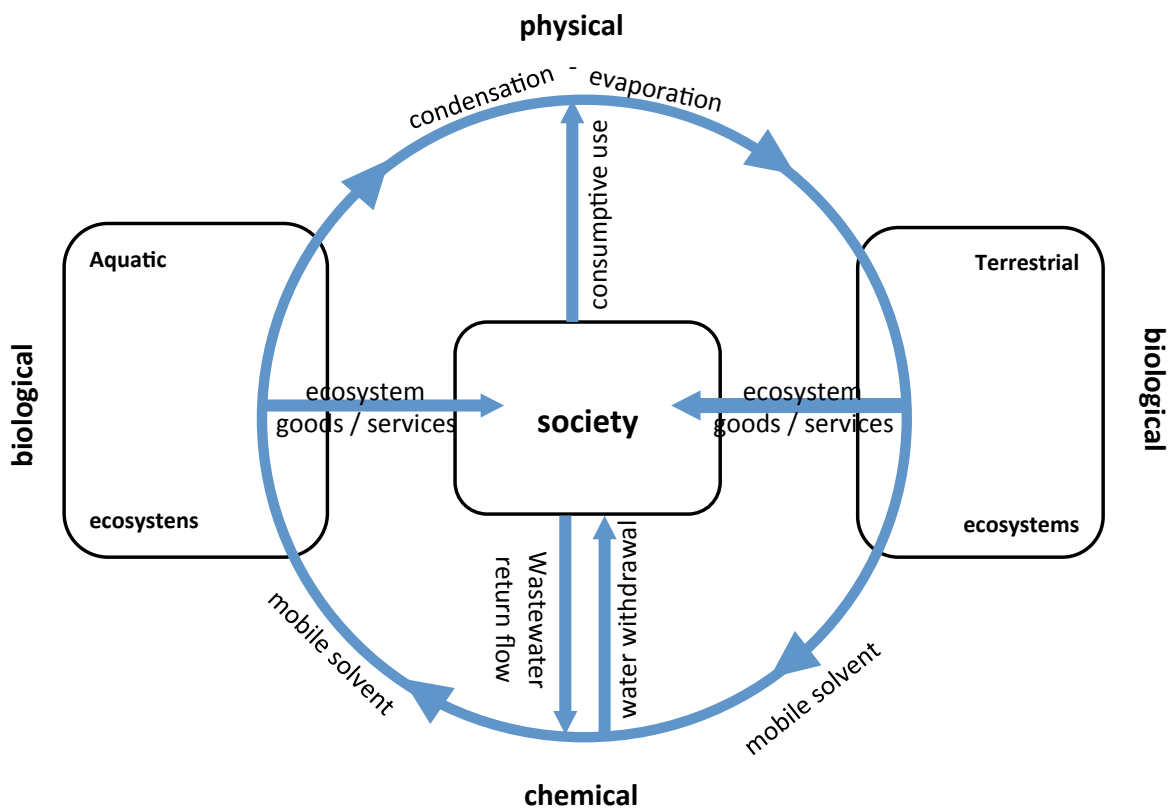


Figure 6. Water as the blood stream of the biosphere (adapted from Falkenmark 2003a).

and removing pollutants, just like blood does in the human body (Falkenmark 2003a). Physical processes like evaporation (creating clouds) and condensation (precipitation) influence chemical interactions with soils by dissolving and transporting salts and solids, thereby providing terrestrial and aquatic ecosystems with water and nutrients (Figure 6).

Ecosystems are shaped by water flows and therefore ecosystem services are also shaped by water flows. In any given landscape the characteristics of the landscape and its location determines water flow paths, quantities and qualities, which in turn determines vegetation, habitats and fauna (Figure 7). Seasonality in rainfall combined with temperature and the landscape characteristics (slope, soil, bedrock) affects water availability and the resulting ecosystem services. In this document we consider water as a crucial part of ecosystems and in particular will make an attempt to define ecosystem water services (Chapter 5). Water plays various, but always crucial, roles in agroecosystems. The importance of water quality is notably clear in aquatic ecosystems, obvious habitats where fish and other aquatic animals are caught. Terrestrial

ecosystems and catchment land-use practices influence – at various spatial and temporal scales – the hydrology and quality characteristics of water resources. In turn, these water resources are critically important in governing which types of species can survive in certain habitats.

An agroecosystem perspective also helps to give value to ecosystem services (see below). According to FAO, agroecosystems are ecosystems in which humans have exercised a deliberate selectivity and modified the composition of existing living organisms (OECD 2003). Together these agroecosystems cover over a third of total global land area. Agroecosystems are different from unmanaged systems as they are intentionally altered and often intensively managed for the purpose of providing food, fiber and other products and services. Agroecosystems both provide and rely upon important ecosystem services (Zhang et al 2007).

There is a large amount of overlap between the services provided by agroecosystems traditionally considered as ‘natural’ and those traditionally

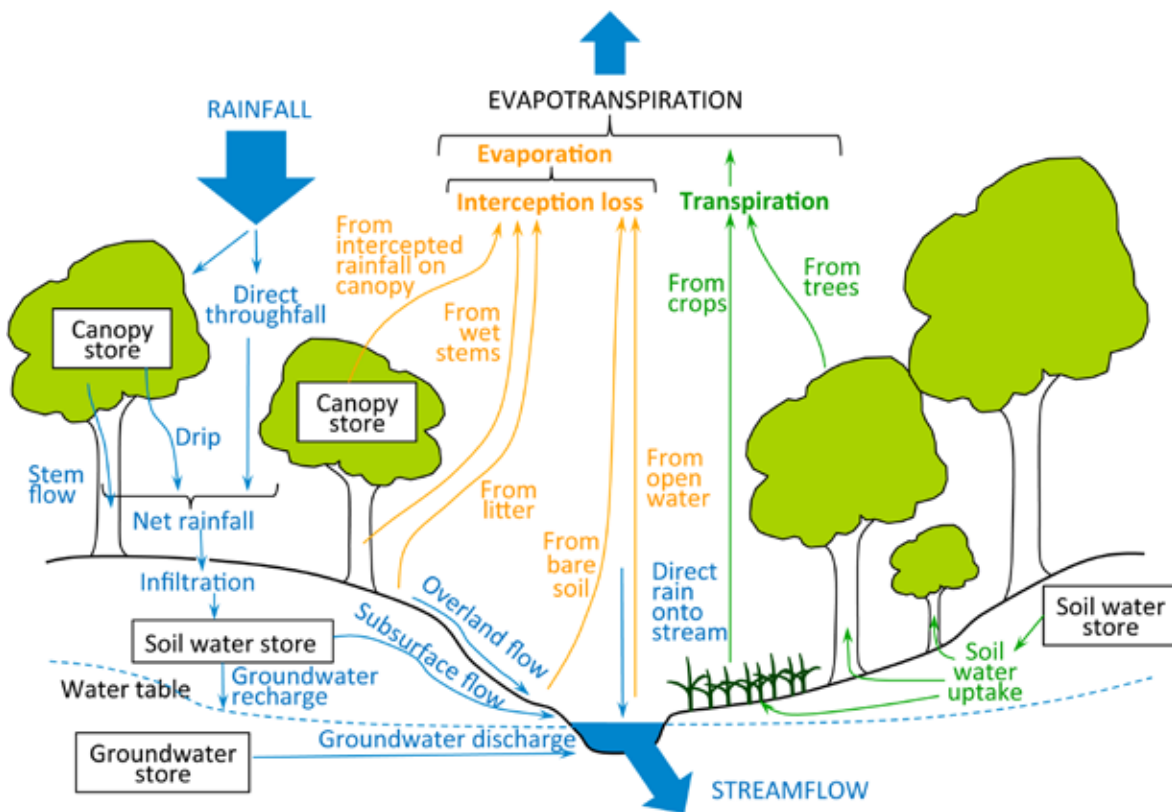


Figure 7. The hydrologic cycle in an agroforest ecosystem.

considered as agriculture. For example, planted forests or tree plantations are sometimes classified as ‘forests’ whereas in terms of ecosystem services they are simply long standing mono-cultures with a high level of provisioning services (e.g. timber, fruits, rubber). On the other hand, planted trees may bring a wealth of additional ecosystem services in to agricultural production systems. Recent assessments suggest that almost half of all agricultural land has more than 10% tree cover, indicating that trees outside forests are a mainstream component of agricultural landscapes (Zomer et al. 2009) that may provide forest functions to some extent. Tree cover in farming landscapes can have a large impact on infiltration and penetration of water and hence catchment hydrology (Carroll et al. 2004). But when tree cover is changed, other ecosystem services besides water flow may also be affected such as forest habitat connectivity for some species, pollination, carbon storage, and even agricultural productivity (Harvey et al. 2006). The impact of changing tree cover on various ecosystem services depends on its amount, spatial configuration, species composition and management, so there is a need to get beyond generalizations and look at

tree cover at the landscape scale in order to meet specific objectives, including the consideration of trade-offs and synergies amongst the ecosystem services affected (Pagella et al. 2011).

Also grasslands are normally managed by people, hence far from ‘natural’ particularly if livestock are grazing. In fact, almost all so-called natural ecosystems are influenced by people as hunters, gatherers and foragers actively manage the landscape to facilitate their harvesting of food and other useful products (Bharucha and Pretty 2010). At the other end, heavily human-managed systems can provide many ecosystem services. For example, sustainable paddy-aquaculture systems provide more ecosystem services (not only provisioning services) than the production of rice and fish alone.

The idea of agriculture as an ecosystem has been explored in detail by the International Assessment of Agricultural Knowledge, Science, and Technology for Development IAASTD (Appendix 7; McIntyre et al. 2008). In addition to providing food, agriculture delivers fiber, fuel, fodder, a variety of other goods and ecosystem services, and fulfills

various social and cultural roles. Aquaculture has been an integral part of many agroecosystems for hundreds of years, producing additional food and cash crops to supplement grain and livestock production, making more efficient use of feed and fertilizer inputs and facilitating nutrient retention and recycling from manure, agricultural and food processing by-products and domestic wastewater. Agriculture is a major employer; globally 40% of livelihoods depend on it (McIntyre et al. 2008). It is especially crucial for poor women who have fewer other income-earning opportunities (UNFPA 2009). The various types of agroecosystems are determined by the environment (e.g. climate and soil type) in which they are situated, but also by the farming system used (Appendix 9.1, 9.2). Agroecosystems are continuously evolving due to changing external conditions (Appendix 9.3).

3.1.2 Ecosystem services

Ecosystems and their multiple services provide the fundamental basis for human well-being, society and economy (WRI et al. 2008). Ecosystem services are thus the key also to local and global development opportunities and all people, worldwide, are dependent on ecosystem services for their survival and quality of life (UNEP 2009a). The global community can only fare well if the functions and production capacity of the ecosystem services of our environments can be maintained. As stated in MA (2005) most landscapes (and seascapes) on earth are affected directly or indirectly by human actions. Very few areas (or any, if you take into account atmospheric pollution) can be defined as un-disturbed by human interventions (Appendix 9.4), which is another reason for considering a continuous range of agroecosystems in this document. As the size of the human population increases, demand for ecosystem services is projected to increase as well. At the same time, the sustainable production of most services is under threat and, in many places, in decline (Brauman et al. 2007). Their access is also constantly reshaped under increasing commercial pressure on land and forests. Because many of the world's ecosystems are already highly degraded, restoring their productive capacity requires revegetating the planet. In many cases fencing and no-grazing strategies can greatly support vegetation recovery, but during the first couple of years the new

vegetation needs to be irrigated, which will compete directly with the water demand for food production (Fresco 2005). Revegetation or restoration of natural ecosystems is complex and requires good planning. Even under humid conditions and with significant investments, success is not guaranteed if monitoring is not carried out properly. In Australia, efforts to revegetate tropical rainforest lacked success mainly due to lack of frequent monitoring and maintenance with only half the area that had been designated to be reforested actually forested six to 11 years into the program (Kanowski et al. 2008).

In this document we adopt the categorization of ecosystem services as proposed by the Millennium Ecosystem Assessment (2005) and used by UNEP (2009a) and other organizations in their policies. Ecosystem services can be grouped into four different types and these services might be of different importance to local livelihoods depending on gender, age, caste, religion or social group:

- *Provisioning services* are perhaps the most recognizably valuable in terms of human use and are thus most frequently monetized. These include food, freshwater, fiber and fuel, biochemicals, and genetic materials, e.g. fish harvested from an ocean or other body of water (Appendix 10).
- *Regulatory services* are slightly less tangible and therefore can be more difficult to assess economically. These include climate regulation, water regulation (i.e., hydrological flow), water purification and waste treatment, erosion regulation, pollination and natural hazard regulation; e.g. the protection a mangrove provides a city from storm surges. In some instances, these systems can be replaced by technology but often at a higher cost than maintaining the original service (Cairns 1995). Regulatory services can be brought into markets and evaluated in financially driven decision-making processes by exploring the costs of substituting for them. For example, a watershed's purification functions can be monetized and compared to the cost of substituting a water treatment facility to fulfill these needs for a community (Appendix 11). Some ecologists, however, have argued against this logic, suggesting that humans cannot fully substitute for the functions of these regulating

systems, especially as they contribute to multiple services and biodiversity (Ehrlich and Mooney 1983). This dilemma is one of the central issues of debate on the valuation of ecosystem services (Ehrlich and Mooney 1983; Heal 2000; Pimentel et al. 2001; MA 2005; Kremen and Ostfeld 2005). Nevertheless, in many cases the costs of replacing services has been shown to exceed the costs of restoring or sustaining them, particularly with regards to water.

- *Cultural services* can be spiritual and inspirational, recreational, aesthetic, and educational, e.g. the recreational benefit of a lake for fishing. Some are relatively easy to value (e.g. recreation) but others are less-tangible and often difficult to quantify or monetize. In the case of pastoral livestock, cultural values are often singled out as a separate livelihood asset class, overriding economic valuation in terms of development and land management, and taking into account “antiquity, role in the agricultural systems, farming techniques, role in landscape, gastronomy, folklore and handicrafts” (Gandini and Villa 2003).
- *Supporting services* are functions that operate on a long-term time-scale. They include soil formation, and nutrient cycling. All of these services can be divided into direct market goods (such as water for domestic use) and nonmarket goods (such as soil formation) (Wilson and Carpenter 1999). Some non-marketed goods and services can accumulate or increase on large or global scales; in these cases, individuals may need minimal incentives for maintaining production of such

goods and services. Groundwater recharge and climate regulation are examples where an individual’s benefits from these services is not directly linked to the cost of using them (MA 2005). By estimating the value of an ecosystem’s market and nonmarket goods, hidden social and environmental cost and benefits can be made visible (Wilson and Carpenter 1999). This might also apply to regulatory services.

Now, instead of considering agricultural food production as one of many (provisioning) ecosystem services, we propose in this document to consider agroecosystems as providing their own ecosystem services. Hence if the agroecosystem is degraded, the various ecosystem services will decline, affecting current and future agricultural productivity and livelihoods. In agroecosystems, the system is managed currently to enhance specific desirable ecosystem functions, for example the provision of crop yields, fuel, fodder, or fibers, sometimes at the expense of other types of ecosystem services (Gordon et al. 2010; Figure 8). For example highly mechanized intensive agroecosystems can yield 10–20 tons of maize per hectare with large inputs of agro-chemicals and sometimes irrigation. These inputs may be associated with depleted water for other users, be it humans or ecosystems, and agro-chemicals may have negative downstream impacts on soil and water quality. Other systems such as aquatic systems, grasslands for grazing and tree plantations may be managed at larger spatial scales to provide a suitable landscape and habitat for the maximum harvest of a particular species. The provisioning capacities of a landscape rely on the supporting and regulating characteristics.

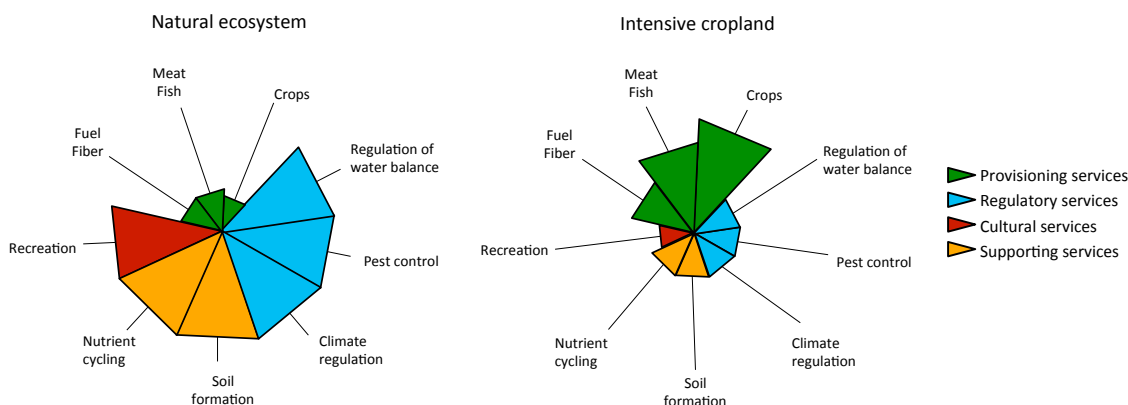


Figure 8. In most agricultural systems (right), provisioning ecosystem services are increased at the expense of regulatory, cultural and supportive ecosystem services, as compared to natural ecosystems (left) (adapted from CA 2007 and Gordon et al. 2010).

While many ecosystem services are known to be important to agriculture, the mechanistic details of their provision, or reduction, remain poorly understood (Kremen 2005) and we lack ways to measure the quantities of many ecological services in a manner similar to measures of marketed goods and services in the economy (Dale and Polasky 2007). However, the provisioning services that we can measure depend upon a wide variety of supporting and regulatory services, such as soil fertility and pollination (MA 2005; NCR 2005), that determine the underlying biophysical capacity of agricultural ecosystems (Wood et al. 2000). Agroecosystems also receive an array of ecosystem disservices, i.e. costs (to the environment or the users) rather than benefits of ecosystems, such as herbivory and competition for water, which reduce productivity or increase production costs (Zhang et al. 2007).

While figure 8 is a visually powerful qualitative comparison between two different types of land use and their ecosystem services, economists have tried to value ecosystem services in monetary terms for more detailed quantitative comparisons. UNEP hosts The Economics of the Environment and Biodiversity

(TEEB), an international initiative to draw attention to the global economic benefits of biodiversity (<http://www.teebweb.org/>). Valuing ecosystem services is an important tool when considering the costs and benefits of different options for achieving water and food security. Many goods and other provisioning services come from non-agricultural land. When making decisions on water allocation or land use, the whole range of ecosystem services, their benefits (values) and costs (social, financial, water) have to be taken into account (TEEB 2010). Well-balanced decisions can then be made about trade-offs and, ideally, ecosystem services can be enhanced (Bennett et al. 2009).

While focused on biodiversity, TEEB assessed other ecosystem services as well (Table 2). For example, wetlands in particular make for highly valuable ecosystems, yielding high benefits by providing and regulating water. This is even clearer in a recent detailed evaluation of the ecosystem services provided by different land cover types in the Mississippi Delta (Batker et al. 2010). The study shows the total economic value of ecosystem services in wetlands range from 7,121 to 31,762 USD per hectare per year, much higher than values

Table 2. Estimation of the average value of ecosystem services of terrestrial biomes (in Int. \$/ha/year- 2007 values, adapted from van der Ploeg et al. 2010). Empty cells mean insufficient data.

Ecosystem services	Tropical forests	Other forests	Woodland	Grass	Wetlands	Lakes and rivers
Provisioning						
Food production	121	496	68	54	709	94
Water supply	300	152		378	1,598	3,361
Other provisioning ^a	1,466	45	291	22	433	
Cultural	373	25		4	3,218	1,337
Regulatory^b						
Water flow regulation	19	1			4,660	
Extremes	92				1,569	
Other regulatory	1,711	143	432	686	1,460	2,642
Supporting^c	1,008	399		99	2,104	
Total (Int.\$/ha/year)^d	5,088	1,261	792	1244	15,752	7,433

^a Other provisioning services include raw materials, and genetic, medicinal and ornamental resources.

^b Regulatory services include water flow regulation; waste treatment and water purification; moderation of extreme events such as floods, droughts and storms; and other regulatory services such as influence on air quality, climate regulation, erosion prevention, pollination, and biological control.

^c Supporting services include nutrient cycling, habitat services and maintenance of genetic resources.

^d Total (van der Ploeg et al. 2010) may differ from calculated sum because of rounding.

for open water or wooded areas, while agriculture has the lowest values, by a considerable margin (see Appendix 12.1 for more details).

Another important finding from TEEB is the contribution of forests and other ecosystems to the livelihoods of poor rural households, only partly reflected in the values for provisioning ecosystem services of natural ecosystems in Table 2. There is significant potential to contribute to poverty reduction through conservation efforts. While agriculture, forestry and fisheries together do not usually make out a large proportion of a country's GDP (e.g. 6, 11 and 17% in Brazil, Indonesia and India, respectively), ecosystem services can contribute more than half the GDP for poor households (89, 75 and 47%, thus benefitting 18, 25 and 165 million people in Brazil, Indonesia and India, respectively) (TEEB 2010).

Non-agricultural ecosystems are also important in food security, especially for the poor. In addition to fisheries, a host of other wild animals and plants play an important role as many vulnerable communities obtain a significant amount of food from the ecosystems that surround them (Foresight 2011; Appendix 10). Estimates on the importance of these 'wild foods' vary from 1 billion consumers to 20% of protein in at least 60 poor countries (Bennett and Robinson 2000). These are probably underestimated as consumed non-cultivated plants and animals persist in agroecosystems as well, providing important supplementary food, particularly for the very poor at times of food stress. At the same time, many 'natural' ecosystems are actively managed to facilitate hunting and gathering (Bharucha and Pretty 2011).

3.2 Challenges to Agroecosystem Management

The impacts of population growth and other demographic changes on ecosystems are substantial and vary over time. Population growth is one of the largest drains on the environment, simply because more people mean the consumption of more resources. This results in the conversion of natural ecosystems into land that is more habitable and arable. Increasing populations put more pressure

on ecosystem services causing those ecosystems to break down. Migration has the potential to further over-stress ecosystem services as large groups of people temporarily reside in areas where they will gather firewood, hunt game, and produce large amounts of waste, such as happens in cases of war refugees. Migration in response to degradation is undertaken most frequently by men; leaving women with more responsibilities in the absence of men. Degradation further compounds the work necessary in the traditional sphere of women's activities such as in firewood and water collection.

Greater understanding and appreciation of the role of the services provided by a variety of ecosystems, including agroecosystems, could help break the cycle of declining food production, increasing degradation, increased expansion of crop and grazing land, and further diversion of water to agricultural production, all of which further decrease resilience and increase vulnerability. UNEP (2009a) promotes an ecosystem approach to the integrated management of land, water and living resources that provides a sustainable delivery of ecosystem services in an equitable manner. For food security in the short term, provisioning services are crucial, but to secure access to food for all in the future and long-term, regulatory and supporting services are as important. The ecosystem approach requires adaptive management, as its implementation depends on local, national or even global conditions. Hence, the UNEP Ecosystem Management Programme (Appendix 1) is working towards a cross-sector approach that integrates landscape elements in agroecosystems and non-agricultural ecosystems, and manages these towards delivery of the full range of ecosystem services.

Agroecosystems have an important role to play in food security but also in their impact on other ecosystems. When compared to other groups of ecosystems, or biomes, the total value of ecosystem services from cropland is relatively low, even for food production alone. For example, in the Mississippi Delta the total value of agricultural land ranged from 195 to 220 USD/ha/year, 85 USD/ha/year of which was from food production, which fell behind most other ecosystem types (including forest and in particular wetlands where food production was valued at 145 to 3,346

USD/ha/year) (Batker et al. 2010; Appendix 12.1). Other studies found higher values for food production in cultivated systems: 667 USD/ha/year in South Africa, 1,516 in El Salvador and as high as 3,842 and 7,425 USD/ha/year in Israel (van der Ploeg et al. 2010). However, it is not clear how this would compare to the average values of other biomes as listed in Table 2. Also reported in the TEEB studies, wetlands had very high values per unit of land for food production as well as for other ecosystem services. Previously, Costanza et al. (1997) had suggested that wetlands provide so much more valuable food per hectare annually, that the total global value of food from wetlands was estimated at 84.5 billion dollars, while four times the area in cropland was calculated to produce 75.6 billion dollars (Appendix 12.2). This can only partly be explained by the difference between high value fish and shrimps versus low value grains. The discrepancy is also a reflection of the relatively low number of studies done on the value of ecosystem services in agriculture. Still these various estimates do point at a real underestimation of the benefits of non-agricultural ecosystems for food production and possibly food security.

These distortions in economics occur, in part, because land and water use planning are based on limited sector-based considerations which do not factor in the overall values of all services that any ecosystem delivers. Hence agricultural land has such a low value in terms of output because it tends to be managed for a single service (food production) and often with significant negative consequences on other services (e.g. through pollution). Another reason might be that the value of food production is measured in terms of market prices whereas the value of other ecosystem services often reflects avoided societal costs that are normally much higher but for which there are not market places (with the exception of carbon). Nevertheless, food production, irrespective of its relative economic value, will always remain a priority as people also need lower value staple crops for food security. But the limits to what the land can produce using contemporary methods and ways of thinking have been reached and land degradation, partly driven by poor agricultural land and water management practices, further limits productivity gains (Bossio and Geheb 2008). Consequently, crop yields could

fall 5–25% short of demand by 2050 (Nellemann et al. 2009) pushing food prices up as a result.

Managing agricultural land to deliver multiple services considerably improves values derived. For example, added value can be obtained from improved services such as carbon storage, erosion control, water retention, waste treatment, and cultural and recreational values including tourism. Most of these added services do not conflict with agricultural production but in many cases can improve both its productivity and sustainability (Sections 3.4 and 5.4), with beneficial impacts on surrounding ecosystems as well. For instance, the on-site costs of nutrient depletion (including soil loss through erosion) of the agricultural sector in sub-Saharan Africa varies between countries from less than one to more than 20% of the agricultural gross domestic product (Drechsel et al. 2004). The off-site costs, especially of erosion, can be much larger, affecting a variety of non-agricultural ecosystems and their services (Enters 1998). Protecting these services by reducing soil, water and land degradation appears to be a cost-effective investment. Payments for environmental services (PES; sub-section 5.2.3) and other finance mechanisms could be good incentives to use to stop these off-site costs, but have to be explored in each context.

Over the years agricultural systems have evolved into diverse agroecosystems, some of which are rich in biodiversity and provide ecosystem services in addition to food production (for example rice-shrimp farming systems). Water management for agroecosystems can create competition with wider environmental requirements. Water use decisions invariably involve trade-offs and require mechanisms in which the needs of both the farmers and the ecosystem services are provided for. Such mechanisms could include, for example, buying irrigation water from farmers to sustain or rehabilitate ecosystems and their services (Molden and de Fraiture 2004). These decisions need a broader consideration of ecosystem services in agroecosystems; this consideration should take into account for example which services are enhanced at the expense of which other ecosystem services (Figure 8) and which services benefit mostly poor men, women, and other vulnerable groups. Agroecosystems provide most essential services

to mankind in the form of food and drink, where food production is again underpinned by a reliable availability of water. Tools are being developed that allow quantification of trade-offs and synergies amongst impacts of land use interventions on different ecosystem services, such as the polyscope tool (Appendix 12.3).

Agriculture is already the main human use of water accounting for about 70% of total global withdrawals and in many areas exceeding 90% (CA 2007). Yet food production needs to increase by at least 50%, and probably almost double, by 2030 in order to meet the needs of a growing population and changing consumer preferences for more water intensive crops. Based on current practices this implies almost a doubling of water use by agriculture worldwide. But the environmental sustainability of water use, and in many places limits to its absolute availability, has already been reached globally – and even surpassed locally (CA 2007). Agriculture, therefore, is faced with significant challenges regarding water use and availability. There are solutions, which are based largely on the more efficient use of water in agriculture (Section 4.3), but agriculture can also be managed differently, in a way to enhance ecosystem services and increase the capacities of the poor male and female farmers (CA 2007). This change in thinking and in the way that agroecosystems are managed is crucial for food security.

Livestock is the single largest agricultural use of land globally either directly through grazing or indirectly through consumption of fodder and feed grains. Livestock production therefore has important implications for ecosystem services. Trade-offs associated with livestock production systems include environmental issues such as impacts on water scarcity, nutrient cycling, climate change, and land degradation, though human impacts such as public health and the exclusion of smallholder producers are also often mentioned (Appendix 13). Livestock production can have important environmental impacts by producing large amounts of methane, a greenhouse gas (GHG) (Steinfeld et al. 2006; Appendix 8), though this is still less than that attributable to crop production. However, these estimates apply mostly to industrialized animal production and do not take into account the

history of pastoral areas; i.e. that even before the industrialized animal production began there would have been high levels of GHG emissions due to the termites and wild ungulates that occupied the lands before animal production began. They also do not apply to many mixed crop-livestock systems in developing countries that are food insecure. For example, cattle are kept primarily for draft power in countries such as Ethiopia, and meat is a by-product of cattle keeping. Forest is also directly cleared for growing mono-crops like soybeans to feed pigs and poultry in industrial systems and to provide a high protein source for concentrates of dairy cattle (0.4–0.6 million ha/year) (Steinfeld et al. 2006). Globally manure contributes 14% of nitrogen, 25% of phosphorus and 40% of potassium nutrient inputs to agricultural soils. However, nutrient surpluses from livestock waste and fertilizer use for feed production may result in eutrophication of surface waters and groundwater contamination. Another disservice to the ecosystem is the health hazard posed by water contamination from livestock excreta and drug residues (Herrero et al. 2009).

Likewise, important fisheries that depend on healthy aquatic ecosystems are endangered. Since fish provide 21% of animal protein in Africa, and 28% in Asia (WCD 2000), a loss of fisheries can be detrimental for food security. The link with management on inland aquatic ecosystems is clear as almost 50% of the global fish consumption comes from aquaculture and in Africa almost half is from inland fisheries (UNEP 2010). In order to avoid further degradation, fundamental changes are required to establish an ecosystem-based catchment management approach (IUCN 2000). A common problem with fisheries is over-exploitation of target species and by-catch of other species. Destructive practices such as poisoning and explosives are also employed in some circumstances, with major impacts on ecosystems and habitats. Where fisheries have declined, stock enhancement and establishment of culture-based fisheries are increasingly viewed as a potential means to bolster catches, however, potential negative ecological and social impacts of such initiatives demand comprehensive and rigorous assessment, with appropriate mitigation and control measures, prior to implementation. For example, conventional aquaculture practices might also be considered for development on existing wetlands

or newly established water-bodies and reservoirs. However, aquaculture appropriates a range of environmental good and services that may lead to adverse environmental impacts and affect the ability of stocks and flows of ecosystem services to sustain other productive activities, which could again result in disputes and conflict.

3.3 Examples of Agroecosystems

The wide range of issues associated with ecosystems for water and food security can be illustrated by looking at agroecosystems at the extremes of water availability. Seasonality and amounts of rainfall limit both natural and agroecosystem vegetation production, thus setting limits to the provisioning capacity of landscapes by determining the habitats and species that can persist. Some of these are extremely vulnerable, either because their natural resource base is limited, or because they are threatened by on-site or upstream over-exploitation. Arid ecosystems can still be used for food production despite frequent droughts. On the other hand, wetlands need a relative abundance of water to sustain their wide range of ecosystem services, while inland aquatic ecosystems are entirely based on the services provided by a freshwater system. In between is a wide range of different ecosystems with various degrees of potential for agriculture. A special case here is dry rangeland, as it is a mix of natural and man-made and is especially prone to over-exploitation and degradation.

3.3.1 Arid agroecosystems

Physical water scarcity (Figure 5), probably the most prominent constraint in dry environments, is worsening, with per capita water flows reducing. Physical water scarcity is tied to reduced rainfall intensity, uneven distribution of rainfall and poor soil water holding capacity of the landscapes and leads to low soil moisture contents, low plant productivity, low nutrient availability and poor soil development. This results in a relatively high susceptibility to soil erosion, salinization, and land degradation in general (MA 2005). Physical water scarcity in arid areas is mostly linked to climate variability and recurrent droughts, causing variations in primary production. Climate change, with decreasing

rainfall amounts and increasing rainfall variability (Burke et al. 2006) is believed to exacerbate these constraints, especially for those who do not have a secure access to irrigation water. High population growth rates in dryland areas, especially in the tropics, lead to land use changes that might trigger land degradation if supportive institutional and socio-political mechanisms are not present.

Desertification, defined as resource degradation (land, water, vegetation, biodiversity) is a major environmental problem in dryland areas, impairing various ecosystem services. It is related to the inherent vulnerability of the land and caused by a combination of social, economic and biophysical factors, operating at varying scales. The direct effects of desertification include soil nutrient losses, decreased infiltration and soil water holding capacity and impaired primary productivity. These in turn result in the disruption of various ecosystem services, including nutrient cycling, water regulation and provisioning, and climate regulation (MA 2005). Also biodiversity, key to the provisioning of various dryland ecosystem services, decreases because of land degradation. According to the desertification paradigm, which is based on the assumption that natural systems are in an equilibrium state that can be irreversibly disrupted (MA 2005), desertification leads to a downwards spiral of productivity loss and increasing poverty. However, evidence of recovery of areas that were previously thought to be irreversibly degraded (e.g. greening of the Sahel: Hermann et al. 2005; Olsson et al. 2005), led to the emergence of counter-paradigms. One argues that dryland agroecosystems are better described as non-equilibrium systems, where large variability from place to place and from year to year is common, related to irregular events like droughts, impeding the establishment of equilibriums (Ellis and Swift 1988; Behnke et al. 1993). Another suggests that "triggers" must be found to enable the rapid rehabilitation of degraded areas. For example, in Northern Uganda Mugerwa (2009) found a solution to overcome the tendency for termites to keep degraded rangelands in a state of non-productivity. There is an emerging consensus that both dryland ecology (Scheffer et al. 2001; Washington-Allen and Salo 2007) and people's livelihoods (Folke 2006) in dry areas respond to key drivers of change in a non-linear way, so that systems have multiple

states displaying some sort of stability, separated by thresholds. State and transition models (Stringham et al. 2003) have begun replacing those based on equilibrium concepts and diagnostic tools for detecting thresholds using remote sensing are being developed and applied (Washington-Allen et al. 2008).

The main objective of sustainable agriculture in arid and semi-arid areas is in producing crops that utilize the limited water resources efficiently, do not use harmful methods of cultivation and do not endanger fragile marginal lands. Arid and semi-arid areas are found on all continents and there is evidence to support the idea that the actual land mass that can be considered arid or semi-arid is growing (UNCCD 2010). Irregular precipitation, frequent drought cycles and overgrazing are some of the main causes of environmental degradation and the growth of arid zones (Noy-Meir 1973). Conventional agriculture, from milder climates, that requires expensive inputs to produce fruits and vegetables is not sustainable in arid zones. In fact, conventional agricultural methods in arid zones greatly contribute to soil loss by wind and water erosion, vegetation depletion, the loss of potentially valuable species of plants and the loss of fertility and productivity in marginal areas under cultivation. Therefore, more appropriate methods for cultivating and protecting dryland must be found, such as replanting the degraded areas with plant species tolerant or resistant to drought and salinity, cultivation in soil and water-thrifty modes, or managing grazing and collection areas with an eye to conservation and future use (Kirkby et al. 1995). In addition, a broader approach to agroecosystem management increases the options for livelihoods and employment at the local level, especially for women, by creating opportunities for trade, processing and by increasing the amount of usable materials for the dryland household.

With increasing population pressure, traditional agriculture may no longer be sufficient to maintain productivity of these arid ecosystems. Sustainable agriculture in arid and saline areas must be based on maximizing opportunities for the development of specifically desert-adapted crops, soil fertility improvement, protecting fragile desert soil, integrating local crops and animals and mobilizing

underutilized water sources. The synergy of such a combined strategy will greatly increase the use efficiency of the resource base. The expert use of local inputs, local knowledge and indigenous crops with an eye to the conservation of desert soil and the thrifty use of all appropriate water resources can enhance certain local agricultural systems and increase the ability of these systems to support local women and men. Enhancing existing systems or introducing new systems requires integrating the different needs, interests and perceptions of local male and female farmers, and particularly of marginal groups who are more vulnerable to environmental degradation. Agricultural changes might trigger different impacts on the livelihoods of men and women, and small and large landholders, which diversity needs to be taken into account. New crops, new technologies, and external inputs such as soil fertilization may be required to optimize the agroecosystem and produce food sustainably. Where feasible, this can be fitted carefully around traditional agricultural practices to make more water available, which can lead to the synergistic integration of agriculture, animal husbandry, conservation planting and agro-forestry. Appendix 14 provides examples of sustainable agroecosystem management in arid environments.

There is a desperate shortage of fresh water in the Middle East and all over the world. More water resources must be reserved for drinking each year while growing populations also increase the demand for agricultural products. In an effort to supply the needs of the populations of various countries for water, food and produce, run-off water, wastewater including grey and black water, treated and untreated, and saline water resources are being used for farming. Saline or brackish water, often of a quality that precludes drinking, is a commonly underutilized water resource in many areas. However, it can only be used for carefully selected crops and agricultural strategies such as the cultivation of halophytic perennials, local grass or green manure crops that are salt tolerant or halophytic annuals. This type of water can also be filtered by successive layers of stone filters and biological filters or can be desalinated but these two possibilities are expensive and time consuming. In areas lacking reservoir sites or ponds for natural water storage, soil based storage of moisture is an

interesting possibility, which could be done by, for example, improved in-situ water management and groundwater recharge (McCartney and Smakhtin 2010).

The use of wastewater is highly controversial but is often done out of necessity in both a planned context, in which wastewater is treated to the desired quality, or informally where wastewater pollutes existing water streams or is used directly from drainage channels. Estimates of wastewater use vary but some 23 countries use untreated wastewater, 20 use treated wastewater and a further 20 use both (Jiménez et al. 2010). Much of this wastewater irrigation, is in arid areas, for example Israel, which is a world leader reclaiming more than 60% of its sewage effluent, and Jordan, which reuses more than 20% of the wastewater from Amman, i.e. 50 million m³, mainly for irrigation (Hamilton et al. 2007). There are of course concerns over the use of untreated wastewater for irrigation and as a result several guidelines have been written, the most widely accepted being the World Health Organization's 2006 *Guidelines for the safe use of wastewater, excreta and greywater in agriculture* (WHO 2006). These offer solutions that can be applied to protect health irrespective of the level of sanitation in the country and are based on assessment of human health risks and the introduction of barriers to those risks along the pathway from wastewater production to crop consumption.

However, irrigation is not necessarily the cure for the deterioration that leads to desertification. Inadequate design, construction, and management of irrigated areas can lead to water logging, salinization, alkalization and sedimentation, all of which cause soil degradation and drastic yield decline. Well-managed and well-kept irrigation systems can revolutionize agriculture in dryland areas but systems that are poorly designed and poorly maintained can damage fragile soils, cause minerals prevalent in desert soil to contaminate areas downstream and accumulate salts in the soils until they are no longer suitable for agriculture. These impacts can have significant negative effects on rural livelihoods. Drip irrigation systems have slowed these processes but cannot protect the soil unless combined with measures that prevent surface

evaporation and capillary rise. Areas with ground cover, shade and good soil structure suffer from neither problem. It is wise then when creating a drip system to design a system that can be used effectively with living ground covers such as low growing plants, skillful mulching and adequate protection from drying winds and sun in the form of windbreaks and shelter belts. This also helps manage soil fertility.

Erosion is one of the biggest problems in dry and saline areas as it causes topsoil loss, encourages soil salinization and makes life much harder for farmers and herders living in dry lands (Clemings 1996). Water erosion causes formation of gullies and can ruin entire fields if unchecked. A specific risk is the development of impermeable clay crusts when the clay, normally dispersed throughout the soil profile, is dissolved by excess (run-off) water and floats to the top when water pools and later, when the water evaporates, hardens to hard ceramic-like plates on the soil surface. Wind erosion moves vast quantities of soil away and up into the air causing choking storms, burying plants and crops, contaminating food and water. Entire communities can disappear in eroded areas under layers of sand and dust. Examples from recent history include the infamous Dust Bowl in the United States, caused by inappropriate agricultural practices, the past land degradation in the Sahel (now moving towards reversal by laborious planting of windbreaks, shelter belts, planting of resilient plants as well as field texturing; see e.g. Hermann et al. 2005 and Reij et al. 2009) and the serious encroachment of the sands of the Gobi on agricultural land in China. The strategies that best address the problems of erosion are those that slow and hold the water so it can be used and those that lessen the force of the wind. Measures to combat both types of erosion entail a certain amount of field texturing (such as making berms and limans) and the planting of especially hardy types of plants and trees (Appendix 14.2). Rational use of combined interventions from modern and traditional desert agriculture can offer new ways to cultivate the desert in a sustainable manner. The oasis, the xiji and the indigenous acacia grove can serve as ecosystem models for the dry lands of the world. Because of the extreme aridity of many of the areas under discussion, water is most efficiently and best used on plants that become multifunctional

features in the landscape, part of a new ecosystem. Every plant must be a multipurpose species, capable of breaking the wind, absorbing water but also of producing food, fruit, oil, fodder, firewood, fixing nitrogen, hosting useful or edible insects or providing building material, hence providing a multitude of ecosystem services. New technologies, new cultivars, and enhanced utilization of sources of water can be combined to strengthen ecosystem services and increase water efficiency for the cultivation of local plants, desert-adapted plants, and arboreal pastures. Mechanisms for more sustainable models of arid lands agriculture include the efficient collection of run-off, soil based storage of moisture and nutrients and strategic planting of local and desert-adapted cultivars to increase the resource base and the provision of ecosystem services. These mechanisms must take into account the differentiated needs and capacities of local men and women and of different social groups.

3.3.2 Wetlands

Globally, wetlands cover at least 6% of the Earth's terrestrial surface (Finlayson and D'Cruz 2005), of which some 125–130 million hectares occur in Africa, and 200–280 million hectares in Asia (Table 3; Figure 9). Common inland and coastal wetlands comprise lakes, rivers, marshlands, mangroves, estuaries and lagoons, groundwater and shallow water coral reefs and sea grass beds. These ecosystems host a wealth of biodiversity and account for about 45% of the total value of all global ecosystem services, including those supporting food

security and reducing rural poverty (MA 2005c; Appendix 1.5). Their supply of freshwater to human populations is recognized as one of the foremost natural benefits (MA 2005c). Simultaneously, fisheries (and in some cases aquaculture) provide highly valuable food. For instance in the Mississippi Delta, the value of food production per hectare of wetland is estimated at 1.7 times to almost 40 times that of agricultural land (Batker et al. 2010; Appendix 12.1). Other important functions of wetlands include their base flow release in dry seasons, their capacity to provide off-season biomass (fish, crops) and their role as local or even global biodiversity 'hotspots'.

Table 3. Estimates of global wetland area (for the six geopolitical regions used by the Ramsar Convention on Wetlands).

Region	Estimates of global wetland area (million ha and percentage area)	
	Global lakes and wetlands database (Lehner and Döll 2004)	Global review of wetland resources (Finlayson et al.1999)
Africa	131 (14%)	125 (10%)
Asia	286 (32%)	204 (16%)
Europe	26 (3%)	258 (20%)
Latin America	159 (17%)	415 (32%)
North America	287 (31%)	242 (19%)
Oceania	28 (3%)	36 (3%)
Total	917 (100%)	1,280 (100%)

For this document, the most important role of wetlands is in the hydrological cycle, where wetlands contribute towards a complex series of hydrological regulative functions, including water storage (i.e. water holding, ground water recharge and discharge and flood prevention by

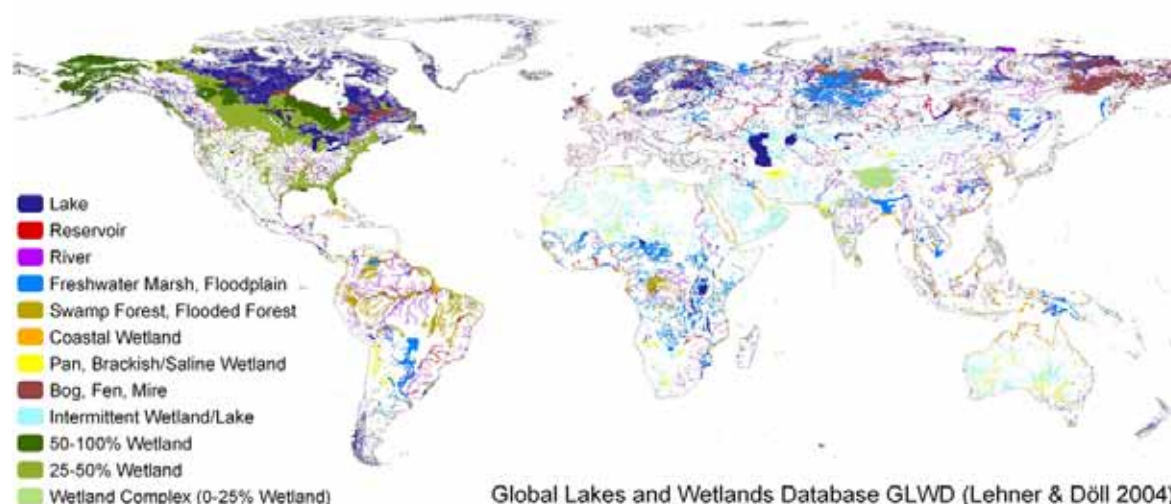


Figure 9. Spatial distribution of wetlands and lakes across Africa and Asia (see <http://www.worldwildlife.org/science/data/item1877.html>)

flow regulation and mitigation), water purification and retention of nutrients, sediments and pollutants (MA 2005c). For example, the Hadejia-Nguru wetlands in northern Nigeria play a major role in recharging aquifers which provide domestic water supplies to approximately one million people (Hollis et al. 1993). The quantity of water stored globally in wetlands amounts to about 11.5 thousand km³ (Shiklomanov and Rodda 2003), though it is important to note that most of this is recycled: reducing the extent of the wetlands, or their storage capacity, does not necessarily increase water for direct human use; in many cases it can reduce it. Inland wetlands in particular play a major role in providing water for agriculture.

Wetlands, in particular river floodplains, are often regarded as functioning as natural sponges; they expand by absorbing excess water in time of heavy rain and they contract as they release water slowly throughout the dry season to maintain stream flow (MA 2005c). In reality the hydrological functions of some wetlands are not that simplistic, vary considerably, are quite complex and tend to be highly site-specific (McCartney et al. 2010). With agricultural expansion into wetlands and the growing need for more food, it is important that the functions of these agroecosystems are seriously considered and managed in terms of their contribution to environmental services (Wood and

van Halsema 2008). Wetland agroecosystems are common in less developed countries across the world; however, they have often been managed in isolation – disconnected from the river basin system.

Another important function of wetland agroecosystems is the detoxification of wastes, but there are intrinsic limits to their waste-processing capability. Aquatic ecosystems “cleanse” on average 80% of their global incident nitrogen loading, but this intrinsic self-purification capacity varies widely and is declining due to the loss of wetland areas (MA 2005c).

The most common wetland-agroecosystems are rice fields. These are important wetland ecosystems that support a wide range of biodiversity, including fish, amphibians and insects, and play a significant role in water bird flyways and the conservation of water bird populations (Matsuno et al. 2002). Large numbers of rice farmers in Asia keep fish in their rice fields (Appendix 16.1). These fields also provide natural drainage systems and help in flood control. The loss of these agroecosystems can have telling effects on the hydrological functions maintained by the wetlands. For example, continued expansion of agriculture, cattle-raising and the establishment of shrimp aquaculture in the coastal humid regions of Latin America have resulted in mangrove destruction on a large scale (MA 2005c). In Thailand and Vietnam, the recent trend, started in the early



Wetlands are important for birds, such as these pelicans at Lake Nakura in Kenya.

1990's, of expansion of brackish water pond aquaculture at the expense of rice cultivation has given rise to competing demands of both users while causing dynamic changes in these wetland ecosystems (Szuster et al. 2003; Dung et al. 2009). In other areas, intensive integrated land-based marine systems have been developed for fish cultivation (Appendix 16.2). In Tanzania, wetlands are extensively used for rice farming and cattle grazing; in certain parts these agroecosystems contribute up to 98% of the household food intake (McCartney and van Koppen 2004; McCartney et al. 2010).

Fisheries and aquaculture are very important sources of food and use wetland systems such as inland lakes (UNEP 2010). They provide synergies with rice cultivation, increasing water productivity as well as biodiversity. Variability and diversity within and among species and habitat is important for supporting this aquatic ecosystem service and for increasing resilience (CA 2007). Culture-based fisheries, stocking fish and other aquatic organisms in water bodies to grow for harvest with little further intervention, have been established mainly in the seasonal wetlands, lakes and reservoirs, including water bodies in upland and highland areas of South and Southeast Asia. Often developed to sustain livelihoods in fishing communities and enhance food security in poor and vulnerable rural communities, culture-based fisheries have also been proposed to increase employment and income from tourism and angling or to enhance food fish production to alleviate fishing pressure on wild stocks. Fish stocking and their subsequent harvest with the objectives of reducing invasive macrophyte communities (as well as harmful mosquito populations), increasing water clarity or sequestering nutrients have been proposed as potential strategies to facilitate the bio-manipulation of water bodies to enhance water quality characteristics. However, the stocking of juvenile fish constitutes a major cost and there are ecological, social and economic risks associated with culture-based fisheries (Gurung 2002).

Wetland ecosystems are particularly vulnerable as changes in water quality and quantity may damage their physical, chemical and biological properties (Alegria et al. 2006; Tuan et al. 2009; Dong-Oh Cho 2007; Gregory et al. 2002; UNEP 2006a). In

turn this can result in river desiccation, groundwater depletion, water pollution and sedimentation, salinization and salt water intrusion, soil erosion and nutrient depletion (Dugan et al. 2007; Atapattu and Kodituwakku 2008). Problems relating to water imbalances in agroecosystems have dramatically changed the capacity of wetland ecosystems in the humid tropics to provide ecosystem services (Foley et al. 2005). Agriculture has been a major driver of wetland loss worldwide both through water use and direct conversion. By 1985, an estimated 56–65% of inland and coastal marshes (including small lakes and ponds) had been drained for intensive agriculture in Europe and North America, 27% in Asia, 6% in South America, and 2% in Africa (MA 2005c). For example, in Asia, more than one-third of mangroves have been lost since the 1980s, mainly to aquaculture (38% to shrimp farming and 14% to fish farming), deforestation (some 25%) and to upstream water diversions (11%) (MA 2005a). Such practices have not only undermined the processes which support ecosystems but also the provision of associated services essential for human well-being (MA 2005c; Hoanh et al. 2006; CA 2007; Atapattu and Kodituwakku 2008). Sub-Saharan Africa alone contains more than a million km² of wetlands, a large part of which are freshwater marshes and flood plains (Rebelo et al. 2010). Out of more than 500,000 km² Ramsar sites, an estimated 93% support some form of fisheries or agriculture and 71% are facing threats due to these activities (Rebelo et al. 2010). Indirectly, irrigation can threaten wetlands, not only by diverting freshwater, but also by reducing the capacity of rivers to transport sediments.

Excessive nutrient loading from fertilizers causes poor water quality and eutrophication of inland and coastal wetland systems (CA 2007; Lukatelich and McComb 1986; Falconer 2001). For example, in India, the Chilka Lagoon is affected by anthropogenic stresses as a result of agricultural practices and drainage in the catchment, thereby affecting water quality (Panigrahi et al. 2006). Globally, in the coastal regions, agrochemical contamination is well documented to result in bioaccumulation and have dire consequences on the many species that reside or feed in wetlands (Atapattu and Kodituwakku 2009). In some cases, urban wastewater has been turned into an asset.



Photo: Stuart W Bunting

Wastewater-fed fishponds in the East Kolkata wetlands.

The wetlands east of Kolkata in India turned salty and brackish water into freshwater and now form the world's largest collection of sewage-fed fisheries, providing up to 80% of the fish in Kolkata (McInnes 2010).

While recognizing the threats to wetlands caused by agriculture as discussed above, we must also recognize the importance of wetlands for agriculture (cultivation, livestock and fisheries) in developing countries and the important role that wetland agriculture provides for livelihoods (Wood and van Halsema 2008; McCartney et al. 2010). One of the ways of doing this could be by emphasizing multiple ecosystem services of agro-wetlands and their value for livelihoods. In higher income countries, there is increasing realization of the importance of the wetland services which have been lost; a realization that is often felt first amongst the farmers themselves. For example, wetlands in the prairies of Canada have been drastically converted into agricultural land but many farmers have now realized that they suffer from decreased water availability as a result and are moving towards wetlands restoration (Canada's fourth national report to the CBD).

Likewise, the flood mitigation services of wetlands are particularly valuable – especially where they reduce flood risk to infrastructure. In many countries there is a move away from artificial flood control

approaches (e.g. embankments) towards wetlands rehabilitation because it is often cheaper and more sustainable. Male and female farmers are often integral to this process either because they too have an interest in better flood protection of their assets or through receiving incentives (compensation) from urban areas for reinstating flood protection on their farmland and reverting to more traditional floodplain pasture cropping or grazing. In New Zealand formal protection of the Whangamarino Wetland led to reduced costs for flood protection while conserving water for irrigation during the dry season (Department of Conservation 2007).

On the other hand, wetlands are further threatened by climate variability. The findings of the IPCC third and fourth assessment reports confirm that the changing water cycle is central to most of the climate change-related shifts in ecosystems and human well-being (Pachauri and Reisinger 2007). By 2050 climate change is also anticipated to have significant impacts on coastal wetlands through both changing hydrology and sea level rise. The future use of water and land for agriculture will further constrain the ability of the wetland system to respond to climate change. Coupled with ever-increasing human pressures, such as high-density populations and associated needs, wetlands and their ecosystem services are seriously threatened unless the issues are urgently addressed

and managed effectively. Hence, when water resource issues are to be addressed in climate change analyses and climate policy formulations, changes in the water cycle have to be considered as important starting points for interventions. Climate change variability will increase the need for improved water storage and the role of wetlands and other water-based ecosystems in this should be recognized (McCartney and Smakhtin 2010). In view of the importance of wetlands in delivering ecosystem services, including the achievement of water and food security, the implication of most climate change scenarios is that it is more urgent than ever to achieve better management of wetland ecosystems in order to sustain water supplies and the other ecosystem services they provide.

Various agricultural practices can be advocated which promote the wise use of wetland ecosystems while ensuring sustainable development. Adoption of strategies (i.e. relevant provisions of the Conventions on Biological Diversity and Wetlands) that work towards the environmental management of these ecosystems would link the environmental stewardship directly to poverty alleviation, food security and quality water in the wetlands (MA 2005c). If better management is sought, the development, assessment and diffusion of applicable technologies which increase the production of food per unit of water,

without harmful trade-offs, is both feasible and essential. Though such technologies have already been identified and are available, most countries (it is mostly less developed countries that are grappling with these issues) lack the financial resources to improve their capacity to adopt this approach (MA 2005c). However certain strategies can be adopted in order to realign policies on agriculture and wetlands (Wood and van Halsema 2008; McCartney et al. 2010):

- Improve the agricultural practices of female and male farmers in ways that positively influence wetlands, while at the same time not compromising livelihoods: this can be done by increasing agricultural productivity (intensification) without expanding land area or water use, thereby not compromising the water regulative functions of wetlands; shifting from irrigation to rainfed agriculture; and improving soil management.
- Adopt supporting strategies which maintain and improve wetland ecosystem services so that a broader range of stakeholders, including the rural poor men and women, receive the benefits.
- Assess water use by the surrounding agroecosystems and adapt its use to be in harmony with a sustainable supply using trade-off analyses.



Cultivating a wetland in Mozambique.

- Improve land and water management techniques after a comprehensive evaluation of the social and ecological products and services supported by the wetlands for women and men.
- Provide alternate livestock drinking sites away from sensitive wetland areas not only for the benefit of the wetlands but also as a means to reduce animal health risks (Peden et al. 2005).
- Improve awareness among all stakeholders who are involved in agricultural water management and improve their understanding of ecosystem services.
- Improve the inventories, assessment and monitoring of interactions with agro-ecosystem change and of changes to the surrounding wetland. Apply environmental monitoring and decision support systems which involve the affected local communities.
- For each water use activity, identify who are the winners and losers among men and women and affected social groups; and determine the costs and benefits incurred by each and look for ways to transfers costs into incentives to farm more sustainably.
- Adopt an integrated approach to water management that considers the whole catchment, its land use and the water and wetland ecosystems within it in a way that balance the multiple water requirements for livelihoods along with the needs of the different ecological processes of wetland ecosystem services.

3.3.3 Dry rangeland

Roughly all of the Middle East, half of India, and about 70% of Africa is considered as semi-arid or arid dryland (including the millet-based Sudano-Sahelian zone, the maize-ground nut belt of southern Africa and the Maghreb), defined as areas where evapotranspiration is exceeding rainfall for some part of the year but conditions still allow for crop-livestock production enterprises. Dry rangelands support about 50% of the world's livestock population (MA 2005) and are of huge importance for often poor livestock keepers in these regions.

The most important livestock production systems in dry areas are grazing systems, occupying 77% of the dryland area worldwide, followed by mixed rainfed systems with a share of 17% (Appendix 9.2). Livestock-dominated and mixed crop-livestock systems in arid and semi-arid areas cover about 11.9 and 6.9 million km² respectively or about 15% and 9% of the 80.8 million km² comprising Latin America, Africa and South and Southeast Asia (Thornton et al. 2002; Table 4). In 2002, the livestock-dominated areas were home to about 116 million people while about 595 million resided in the mixed crop-livestock systems.

Table 4. Distribution of land and people in mixed crop-livestock and livestock dominated systems in arid and semi-arid lands in developing countries (Thornton et al. 2002).

	Livestock dominated systems	Mixed crop-livestock systems
Land area (million km ²)	11.9	6.9
Land area as % of developing country	15	9
Number of people (million)	116	595
Density (people/km ²)	9.7	86.2

The importance of rangelands for livestock grazing is highest in the arid agroecosystems, whereas in the semiarid and sub-humid areas grasslands are being converted into shrublands and cultivated land (MA 2005). In the tropics, this is driven by increasing human populations, resulting in the expansion of croplands at the expense of grazing areas (Kristjanson et al. 2004). As a result, in the sub-humid and semiarid tropics, traditional pastoral practices are often being replaced with agropastoralism and mixed farming in which livestock increasingly depend on crop residues as feed.

Historically, pastoralism with its defining attribute of mobility was a resilient and sustainable livelihood activity. The key threat to pastoralism comes from reduced mobility and loss of dry season watering and grazing areas that result from the expansion of cropping. Livestock mortality is a key challenge for the development of viable livestock systems in the drylands. This is reflected as lack of supply of goat, sheep and cattle juveniles to the market, but also greatly contributes to loss in water and land productivity as the animals die after eating all the feed and depleting the water.

The transition from grazing to agro-pastoralism to mixed crop-livestock production is also often accompanied by the migration of people, an increased human population also puts enhanced pressure on fuel sources such as charcoal further aggravating land degradation. While livestock production in arid and semi-arid areas has been effective and sustainable for centuries, expansion of cropping to feed a growing population has placed these dryland ecosystems under new pressures that threaten continued animal production and livestock based livelihoods. In many cases the degradation of land and water resources is well advanced. The future may require limits to be placed on the expansion of cropping into arid areas and for rangelands to be rehabilitated in order that the world's needs both in terms of animal production and in terms of ecosystem services in the form of carbon sequestration are catered for (Peden et al. 2009b).

Livestock are kept in most places where crops are grown as well as in pastoral areas that are not suitable for cultivation. Herding can be viewed as a form of water harvesting in the sense that grazing animals capture the benefits of sparsely distributed rainfall by grazing pastures (Bindraban et al. 2010a). Mobility is the primary and requisite characteristic of pastoral agroecosystems. Grazing by domestic and wild ungulates is the means for maintaining extensive grasslands that provide important ecosystem services

including maintenance of biodiversity and carbon sequestration. Arguably, pastoralism has proven to be one of the most enduring and sustainable land-use systems dating back as much as 10,000 years. In recent decades expansion of cultivation and the establishment of international boundaries and barriers across traditional migratory routes has diminished mobility forcing herders toward a more sedentary livelihood strategy that has often resulted in severe land and water degradation, aggravated poverty, poor health, and food insecurity. Small areas of encroaching cultivation can have a multiplier effect and reduce livestock production over much larger land areas. In arid regions, the expansion of cropland, inappropriate grazing practices (Geist and Lambin 2004) and newly imposed barriers to pastoralists' mobility may even increase trends in desertification. Policies directed at sedentarizing nomads often have adverse effects as they reduce the traditional ability of pastoralists to respond to climate shocks, resulting in a downward spiral of poverty, conflict and social exclusion (IIED and SOS Sahel UK 2010). Where population growth leads to increased migration of people, this may cause conflict over access to natural resources, such as water resources that are used by livestock keepers for drinking, but also claimed by farmers to irrigate their crops. However, the increased interaction between pastoralists and farmers may also lead to increased exchanges and closer collaboration (Turner 2004).



Strategic placement of watering points for livestock can support pastoralists in selecting appropriate migration routes and reduce pressure on fragile areas.

Inappropriate livestock grazing practices are often seen as the culprit for rangeland degradation and desertification (Asner et al. 2004). But traditional pastoral practices are often very well adapted to make use of the spatially and temporally variable feed resources in rangelands (IIDE and SOS Sahel UK 2010). However, when these are disrupted or pressurized due to demographic, climate or land use changes, livestock grazing may threaten the provision of ecosystem services. Overgrazing is an important cause of land degradation in arid drylands, tropical grasslands and savannas worldwide. It leads to soil compaction, reduction in long-term grazing productivity, loss of topsoil and disruption of the hydrological cycle. Extensive cattle enterprises have been responsible for 65–80% of the deforestation of the Amazon at a rate of forest loss of 1.8–2.4 million ha/year (Herrero et al. 2009). When the carrying capacity of the land is exceeded or not well managed, the vegetation is put under pressure, resulting in a chain reaction of interlinked effects, finally leading to soil and vegetation degradation, reduced productivity and food insecurity (Asner et al. 2004). In such degraded rangelands, most water is lost as runoff and unproductive evaporation, so that water use efficiency is dramatically reduced. Increased runoff and the trampling of the soil by livestock lead to erosion and thence to siltation of downstream freshwater resources.

Although reports from drylands often paint a grim picture of poverty, drought and conflicts over resources, dryland populations could avoid degradation by intensifying agricultural production and safeguarding pastoral mobility (MA 2005). Due to their large area, rangelands can be a global sink of a roughly similar size to forests (Herrero et al. 2009). However, there is a real need for research on how this large potential can be untapped through technologies and policies for carbon sequestration. These rangelands could even be the source of significant regional increases in water productivity by judiciously using rangelands as a feed source, at the same time as taking care to avoid overgrazing (Herrero et al. 2009). Solutions for breaking the downward spiral of water scarcity, decreasing productivity and disrupted ecosystem services should take on board technical, socio-political, and institutional issues (Amede et al. 2009b). They should secure property rights, be risk adverse, take into account the labor constraints of women, men, and children, and enable their access to input and output value chains and market information (FAO et al. 2010). In particular, securing the mobility of herds for accessing natural resources, trade routes and markets is essential to avoid degradation and conflict (IIED and SOS Sahel UK 2010). This can be achieved through appropriate policies that take into account trans-boundary herd movements, enable



In many parts of the world, children are responsible for herding animals. If livestock management needs to change, this group has to be targeted specifically.

the creation of corridors and the establishment of water points and resting areas along routes, etc. The strategic positioning of drinking water points is instrumental in balancing feed availability with livestock numbers, so that feed resources can be used optimally (Peden et al. 2009b). In addition, the provision of sufficient watering points is important to avoid the concentration of too many animals around one watering point, causing soil and vegetation degradation, and water contamination (Brits et al. 2002; Wilson 2007). At farm level and on larger landscape scales, the integration of crop and livestock production can create synergies. These bring about mutual benefits in terms of manure for soil fertility replenishment and crop residues for feed, in addition to benefits in terms of land allocation and the exploitation of spatial and temporal variability in feed availability, for instance, growing crops in fertile areas and grazing livestock in less fertile areas. These synergies and complementarities lead to more a productive use of natural resources, including water.

3.3.4 Aquatic ecosystems

Inland capture fisheries landings, including fish, mollusks, crustaceans and other aquatic animals exceeded 10 million tons in 2006, with the majority occurring in Asia (67.9%), followed by Africa (23.5%), Americas (5.9%), Europe (3.5%) and Oceania (0.2%) (FAO 2009a). More recent numbers are even more impressive, with an estimated 14 million tons caught annually in small scale fisheries in developing countries only (Mills et al. 2010), providing livelihoods for 60.4 million people, 33 million of which are women (UNEP 2010). A wide range of aquatic ecosystems are important for fisheries, perhaps most obvious being habitats where fish and other aquatic animals are caught. Breeding and nursery sites which may be quite distant from fishing areas also play a critical role in the lifecycles of exploited stocks and these could be managed better in the wider landscape of agroecosystems. Stocking aquatic animals in predominantly aquatic agroecosystems, with interconnected field and pond systems, may make a significant contribution to household farming and local community food security and nutrition. Similarly, terrestrial ecosystems and catchment land-use practices influence the hydrology and

quality characteristics of water resources, which in turn are critically important in governing which types of species that can survive in certain habitats (Welcomme et al. 2010). Appropriate management and governance arrangements are required to ensure costs and benefits are distributed equitably and that any proposed changes in access arrangements consider the needs of poor and landless groups (FAO et al. 2010).

Both aquaculture development and fisheries depend on the appropriation of various environmental goods and services from aquatic ecosystems, including, clean and oxygenated water for physical support and respiration, seed, feed and detritus inputs, waste removal, nutrient assimilation and carbon sequestration (Beveridge et al. 1997). Failure of many apparently promising aquaculture ventures has occurred when the capacity of ecosystems to meet the cumulative demand, for environmental goods and services from rapidly growing numbers of farms and culture units, has been exceeded (Bostock et al. 2010). Early assessments concerning appropriation of environmental goods and services by aquaculture systems intimated that ecological footprints⁵, expressed as m² of supporting ecosystem per m² of culture facility, were larger for more intensive production systems (Berg et al. 1996; Folke et al. 1998). Subsequent reassessment, however, has shown that some goods and services are used more efficiently in intensive production, as compared to semi-intensive systems (Bunting 2001).

Provisioning ecosystem services from aquatic ecosystems are often under-valued and assumed only to comprise fish catches. However, a wide array of other aquatic animals and plants are exploited by various groups at various times, often by the poor in times of need (WVRI et al. 2008).

⁵ Assessments of ecological footprints have the potential to highlight disparities between the demand and supply of ecosystem services for particular culture systems but care is needed in the calculation and interpretation of footprints, especially with respect to geographical and temporal differences in the location and availability of goods and services. Appropriation of goods and services by other sectors also needs to be considered and environmental stocks and flows maintained. Approaches to supplement ecological goods and services in certain cases have been proposed but it is difficult to replicate natural processes in ecological engineered systems. Moreover, the development of such systems may cause further environmental and financial impacts and, being ecologically-based, the operation and performance of such systems will be highly influenced by prevailing environmental conditions, notably temperature and light levels, and vulnerable to other natural occurrences such as storms, pests and diseases.



Women cooperative active in aquaculture.

Artificial water-bodies and wetlands also sustain provisioning ecosystem services and, with the proliferation of water storage reservoirs for irrigation and hydroelectric power generation, are emerging as a major source of food and income in remote and highland areas (Welcomme et al. 2010).

Ecologically sustainable water management in humid agroecosystems often involves multiple uses of water by men and women and can be further enhanced by considering the whole range of ecosystem services through a gender-sensitive approach. Some good examples are the integration of aquaculture into various agroecosystems, such as livestock-aquaculture integration, rice-fish culture, aquaculture in irrigation reservoirs and water management schemes, and wastewater-fed aquaculture (Appendix 16). Evaluation of the full range of provisioning ecosystem services from aquatic ecosystems, not only fish, is vital if the true value of such 'eco-aqua-systems' in the livelihoods of men and women, and in local and national economies is to be accounted for and safeguarded. Current appropriation of aquatic ecosystem services is in many cases not sustainable; this is the case with fishing in most waterways and wetlands and with the majority of aquaculture practices used around the world. As with the assessment of marine capture fisheries, however, there must be concern

over introducing shifting-baselines (Pauly 1995) and setting overly generous limits or inappropriate conservation goals. It is critical to maintain a balance between fisheries, often the most obvious benefit derived from aquatic ecosystems, and the continued provision of stocks and flows of other ecosystem services, that may actually benefit more people and make a more significant contribution to the well-being and resilience of poor women and men and marginal groups, local communities or regional populations (Welcomme et al. 2010). Moreover, assessment and allocation of water resources must also account for environmental water requirements (Gichuki et al. 2009).

3.3.5 Tree ecosystems

Tropical forest ecosystems host at least two-thirds of the Earth's terrestrial biodiversity and provide significant local, regional, and global human benefits through the provision of economic goods and ecosystem services (Gardner et al. 2009). Only 9.8% of the entire tropical forest biome lies within strictly protected areas (Schmitt et al. 2008), and the long-term viability of existing reserves is strongly affected by patterns of human activity in adjacent areas (Wittemyer et al. 2008). Gross forest cover loss was estimated to be 1,011,000 km² from 2000 to 2005, representing 3.1%

(0.6% per year) of the estimated total forest area of 32,688,000 km² in the year 2000. The boreal biome experienced the largest loss, followed by the humid tropical, dry tropical and temperate biomes (Hansen et al. 2010).

On the other hand, it was estimated that the area under agroforestry worldwide was 1,023 million ha in 2009, suggesting that substantial areas of unproductive crop, grass, and forest lands as well as degraded lands could be brought under agroforestry (Nair et al. 2009). Agroforestry offers a promising option for productive and sustainable use of land and water as it involves combining managed trees with productive agricultural activities. Agroforestry thus provides opportunities to reverse negative impacts of deforestation and intensive cropping through tighter water, nutrient, and carbon cycling (Ong et al. 2006). There are also opportunities to use agroforestry to prevent or reverse land degradation in the humid tropics (Cooper et al. 1996). Such systems may provide numerous potential benefits ranging from diversification of production to improved exploitation of natural resources, such as soil conservation (protection against erosion); improvement or maintenance of soil fertility; water conservation and more productive use of water; and provision of environmental functions required for sustainability. The concept of agroforestry is based on the premise that structurally and functionally more complex land use systems capture resources more efficiently than either crop or tree monocultures (Schroth and Sinclair 2003). Trees enhance belowground diversity that supports local ecosystem stability and resilience (Barrios et al. in press), and also provide connectivity with forests and other features at the landscape and watershed levels (Harvey et al. 2006). Nearly half of agricultural land globally has more than 10% tree cover, indicating trees outside forests are an important mainstream component of man-made landscapes (Zomer et al. 2009).

A key challenge for agroforestry is to identify which combination of tree and crop species optimize the capture and use of scarce environmental resources such as light, water, and nutrients, while fulfilling farmers' needs for timber, fuel, mulch, fodder, and staple food (Sanchez 1995; Muthuri et al. 2009). The most critical tree characteristics with

regard to water include deep rooting, leafing phenology (evergreen or with seasonal loss of leaves) and its timing, as well as growth rate and age. The complementary aspects of trees in relation to crops can be enhanced by selecting trees with characteristics that minimize competition; and by managing to limit their competitive impact (Schroth 1999). Management options to minimize competition include root and shoot pruning (Siriri et al. 2010), increasing tree spacing within the crops (Singh et al. 1989), and matching the trees and crops to appropriate niches within the farm (van Noordwijk and Ong 1996).

Trees are important landscape elements that help regulate water flows and even a small change in tree cover can have a large impact on reducing run-off. Small increases in tree cover, strategically placed in agricultural landscapes, can thus increase water infiltration and percolation, improving overall water productivity while providing fuelwood, fodder, fruit, and timber (Ong and Swallow 2003; sub-section 4.3.2). Agroforestry belts have also been proposed as riparian buffers to combat non-point source water pollution from agricultural fields and help clean runoff water by reducing the velocity of runoff, thereby promoting infiltration, sediment deposition, and nutrient retention (Jose 2009). Management of riparian vegetation can improve the quality of water in the river and hence through its outflow, help protect valuable coastal ecosystems, such as the Great Barrier Reef (Pert et al. 2010).

3.4 Sustainable Management of Agroecosystems

The 21st century has seen a growing concern about the negative changes produced by agriculture on various ecosystems across the world: destruction of soil cover, topsoil depletion, reduction of biodiversity, groundwater contamination and the increasing costs of production, as well as the progressive disintegration of family farming and indigenous systems. The Millennium Ecosystem Assessment showed that agriculture has dramatically increased its ecological footprint, both in terms of negative impacts but also in terms of its supply of ecosystem services for rural communities (MA

2005). Particularly, the high demand for water and land in commercial farming systems and with it the increased risks of pollution has led to the need for a more economically, socially and environmentally viable agricultural systems in order to avoid ecosystem destruction. One of the recommendations of UNEP for dealing with the environmental food crisis is to “support farmers in developing diversified and resilient eco-agriculture systems that provide critical ecosystem services (water supply and regulation, habitat for wild plants and animals, genetic diversity, pollination, pest control, climate regulation), as well as adequate food to meet local and consumer needs” (Nellemann et al. 2009). Based on successful local experiences (e.g. Machakos in Kenya, summarized in UNDP et al. 2000), various organizations now promote alternative approaches to agriculture that are more sustainable and safeguard ecosystem services, in particular from the point of view of water management.

Sustainable agriculture is a process which meets the following criteria (FAO 1995):

- Ensures that the basic nutritional requirements of present and future generations, qualitatively and quantitatively, are met while providing a number of other agricultural products and ecosystems services.
- Provides durable employment, sufficient income, and decent living and working conditions for all those engaged in agricultural production.
- Maintains and, where possible, enhances the productive capacity of the natural resource base as a whole, and the regenerative capacity of renewable resources, without disrupting the functioning of basic ecological cycles and natural balances, destroying the socio-cultural attributes of rural communities, or causing contamination of the environment.
- Reduces the vulnerability of the agricultural sector to adverse natural and socio-economic factors and other risks, and strengthens self-reliance.

Several tools and approaches have been used to implement the concept of sustainable agriculture, such as sustainable land management, ecoagricul-

ture, conservation agriculture, conservation farming, organic agriculture, and others (Appendix 17; Francis and Porter 2011; Gomiero et al. 2011). Ecoagriculture (www.ecoagriculture.org) is the design, adaptation and management of agricultural landscapes to produce ecosystem services (watershed services, wild biodiversity, etc.) and generate positive co-benefits for production, biodiversity, and local people, while addressing climate change challenges (Scherr and McNeely 2008). Such integrated agricultural landscapes provide critical watershed functions through careful rain and soil water management. This integrated management encompasses the choice of water-conserving crop mixtures, soil, and water management (including irrigation), maintenance of soils to facilitate rainfall infiltration, vegetation barriers to slow movement of water down slopes, year-round soil cover, and maintenance of natural vegetation in riparian sites, wetlands and other strategic areas of the watershed (Section 5.4). Conservation agriculture also tries to increase ecosystem services in agriculture, mainly through reducing tillage and restoring land cover. Its primary purpose is to bring water back into the soil and keep it there. This would increase agricultural productivity and sustainability within agriculture but also delivers benefits to other ecosystems, such as reduced erosion (Appendix 17.1).

The biological diversity in agroecosystems has a key role to play in sustainable agriculture and ecosystem resilience. In addition to wild biodiversity, crop genetic diversity within the agroecosystem can make a substantial difference to resilience of the farmers’ production system (FAO and PAR 2011). The contribution of biological diversity to the functioning of agroecosystems can be substantial in various ways. Increasing the genetic diversity of crops has been particularly beneficial for pest and disease management, and helped increase levels of pollination efficiency (Hajjar et al. 2008). The assessment of diversity within the agricultural production system, access to planting materials or large enough population sizes to allow for changes in the farmers’ system, and ensuring that farmers benefit from the diverse materials they maintain are all essential in promoting functional plant diversity in agroecosystems. (Jarvis et al 2011).

A long tradition of separate science and practice in forestry and agriculture means that there are largely untapped opportunities to use trees constructively in agricultural landscapes to sustain food production while improving a range of ecosystem services. Trees have great potential to play an important role in the sustainable management of agroecosystems. In addition to impacting supporting, regulatory, and cultural ecosystem services, trees in agroecological landscapes may increase provisioning services by contributing fruit, fodder, fuelwood, and timber. The impact of changing tree cover on various ecosystem services depends on its amount, spatial configuration, species composition, and management. Hence there is a need to consider planned tree cover change at a landscape scale with the aim of meeting specific suites of objectives, including consideration of trade-offs and synergies amongst the ecosystem services affected (Pagella et al. 2011; Appendix 12.3). Enhancing tree cover on farm land has the potential to tighten nutrient, water, and carbon cycles, and promote the abundance and activity of soil organisms (Barrios et al. in press), thereby increasing and sustaining soil and water productivity. Different tree species root to different depths, have leaves at different times throughout the year, and use more or less water through transpiration, attributes that are all affected by management practices such as pruning.

3.5 Conclusion: Recognizing Agroecosystem Services

Recognizing the multiple functions of agroecosystems and the many services they provide is essential to fostering an integrated approach to natural resources management, agricultural production, and food security. However, it is equally important to recognize the variations between agroecosystems as well as variability over time in order to provide appropriate recommendations. Sustainable management plans of various agroecosystems ranging from hyper-arid and dryland to wetlands and aquatic ecosystems require strong policy support and incentives for users. The services provided by ecosystems can be optimized through appropriate land use planning that takes into account the limits of each ecosystem's carrying capacity, while multiple users – female and male agriculturalists, pastoralists, environmentalists, fishing and domestic users – need to be brought

together in common management arrangements to sustainably reconcile the needs of food production and ecosystems services for a growing population. Coherence needs also to be found between national and international initiatives and the multiple local needs and interests of affected men and women and social groups.

The ecosystem services framework provides a useful umbrella for this endeavor as this can only be achieved by healthy agroecosystems. Therefore coherence in cross-sector policies is fundamental to support collaboration among various stakeholders. Inter-sector collaboration at ministerial level is essential to ensure good ecosystem care while providing the necessary food and services to communities. The need for coherence applies at national level, between ministries of agriculture and environment, water and natural resources, but also in donor policy, and not least between national governments and international institutions (Fresco 2005).

This call for a more balanced approach in managing food security and its interrelation with ecosystem services is timely (MA 2005): worldwide, ecosystem services are in a poor state and agroecosystems have lost their capacity to recover from stress. Hence there is increasingly negative feedback concerning the interactions between food security, agriculture, water and ecosystem services. Food security is further threatened by reduced yields associated with depleted water quantity, reduced water quality, and degradation of other natural resources (such as soil fertility). These factors also negatively impact on a range of provisioning, supporting, regulatory, and cultural ecosystem services (Nellemann et al. 2009). Efforts to reactivate farmland e.g. through agrochemicals, heavily impact other ecosystem functions. In turn, dysfunctional ecosystem services further impact the agroecosystems and their production systems.

However, solutions are available. Policy makers can help to safeguard ecosystem services. Accounting for the benefits and costs of the full range of ecosystem services in policy-making and greater emphasis on natural resources and water use efficiency in food production will promote better decision making towards more sustainable farming. Greater recognition of the multiple benefits derived from integrated agroecosystems would encourage

producers to retain or adopt more sustainable farming practices, while safeguarding benefits for local, national, and global populations.

Specific potential solutions include looking for synergies between agriculture and anti-desertification efforts whereby degraded lands are brought back under productive use through rangeland conservation and better farming practices, which in turn restore surface vegetation and soil functions, in particular water retention. In arid regions, new or local cultivars and appropriate land and water management practices can increase productivity and restore degraded lands, while in semi-arid rangelands, the provision of livestock herders with incentives can help to keep and improve environmental services. Such approaches are not necessarily technically complex. But they do require a wholesale shift towards more holistic and inclusive approaches to agroecosystem management, building on the common goal of sustainability. Looking at water, ecosystem, and human needs in parallel and identifying and building upon mutually supportive approaches is the key, as is looking across sectors. By linking and combining appropriate production systems in a landscape, synergies can be explored. Drought-resistant plants, silvopastures, and perennial grasses can be cultivated in a landscape with corridors for herds, thereby providing more sustainable exploitation

options for agropastoralists. The integration of crop, tree, livestock, and in some cases aquaculture, can enhance resource recovery and the reuse of resources for feed or soil fertility

Wetlands across the world play a critical role in the provision of freshwater for human consumption and agriculture, while both fresh and saline waters provide food security by supporting fisheries, aquaculture, and other related activities. Where wetlands themselves are used for agricultural production in many parts of Africa and Asia, they help to safeguard rural poor livelihoods. Urgent steps are needed to protect rich wetland ecosystems with their multitude of functions and services, as well as the livelihoods and well-being of the dependent communities. Once these areas are identified as wetland agroecosystems with their own set of ecosystem services, effective water management can be put in place with the minimum of trade-offs against other services. This includes the reduction of pollution from upstream urban or agricultural areas, and the provision of buffer strips or strategic introduction of tree cover, but also the provision of alternative drinking sites for livestock. Monitoring of wetland functions and services is crucial to ensure the continuation of wetland ecosystems and to the continuation of their role in flood protection, biodiversity, food provision, as well as many other critical ecosystem services.

4. WATER

4.1 Introduction: Water in Ecosystems

Water plays a crucial role in the delivery of many ecosystem services, including provisioning services such as crop production, but also cultural, regulatory, and supporting services (Section 5.1). Water resources management directly affects ecosystem health, while ecosystem health underpins critical services for clean, stable water resources.

There is increasingly negative feedback on the interactions between agriculture, water, and ecosystem services, associated with depleting surface and ground water quantity, quality or both. This depletion negatively impacts a range of provisioning, supporting and regulatory (and cultural) ecosystem services. Dysfunctional ecosystem services impact agroecosystems and yields may decrease. Within this situation of increasing water scarcity and reduced ecosystem capacity to recover from shocks we have to find sustainable and equitable ways to increase food security and maintain ecosystem services. Impacts of climate change on water, food security, and ecosystem services are highly uncertain, but most scenarios and forecasts suggest higher vulnerability to damage, reduced agroecosystem capacities and undermined resilience.

Water availability differs according to agro-ecological zones; it is abundant in humid and sub-humid zones while scarce in arid zones and drylands, but it is also determined by the quantity withdrawn and human, institutional, and financial capital (Figure 5). Consequently the type of management needed for food production and maintenance of environmental services varies from using water control techniques to water harvesting and water scarcity management practices. Climate change, human use of water resources and aquatic ecosystems, and overexploitation all influence the state of the water cycle. The quantity and quality of surface and groundwater resources, and life-supporting ecosystem services are being jeopardized by the impacts of population

growth, rural to urban migration, and rising wealth and resource consumption, as well as by climate change. Currently 1.6 billion people live in areas of physical water scarcity and this could easily grow to 2 billion soon if agricultural water management does not change. Using the same practices, with increased urbanization and diets that contain more animal products, the amount of water required for agricultural evapotranspiration to feed the world's population would increase from today's figure of 7,130 km³ today, to between 12,050 and 13,500 km³, an increase of 70–90% by 2050 (CA 2007). This would strongly affect human well-being and the implementation of internationally agreed development goals, such as the Millennium Development Goals (particularly MDG 1 on hunger and poverty, and MDG 7 on environmental sustainability) set by the UN.

Under these circumstances, sustainably meeting the food and livelihood needs of a growing population will require some very difficult choices about how water is developed and managed in the next 25 years. Based on population growth, by 2025 water withdrawal for most uses (domestic, industrial, and livestock) is projected to increase by at least 50 percent (Rosengrant et al. 2002). This will severely limit water withdrawal for irrigation, constraining food production in turn. To address the challenge posed by water scarcity for food production, we must conserve water and improve the efficiency of water use and productivity per unit of water and land. This requires an ecosystem approach to integrated water management, but also eco-agricultural research and policy efforts. Countries must consider the full social, economic, and environmental costs, as well as the costs of failure to develop new water sources and conserve the existing ones.

4.2 Assessment of Current and Future Water Use

According to FAO (2007a) "Imbalances between availability and demand, the degradation of

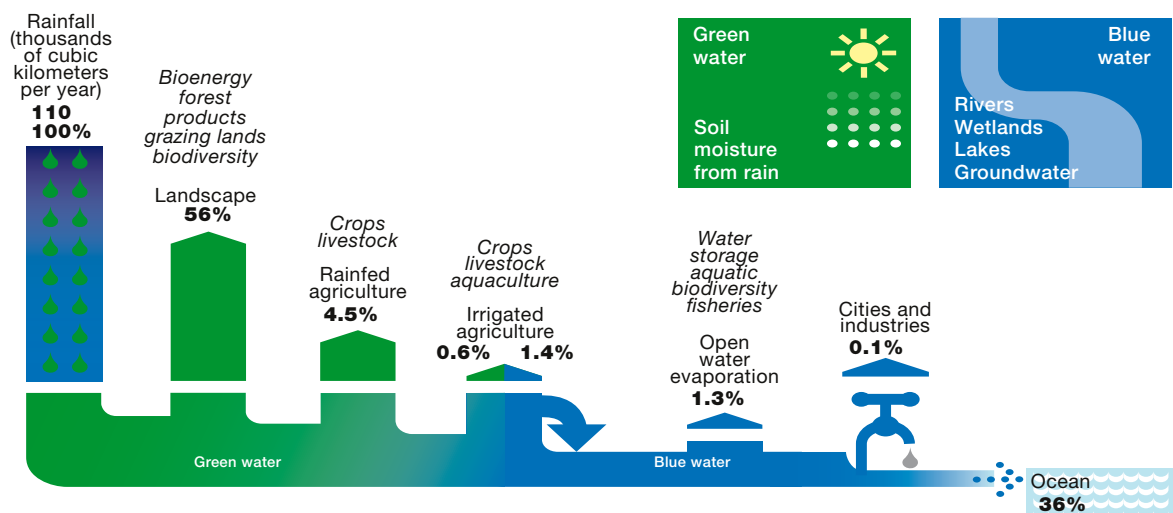


Figure 10. Global water use: surface water (blue⁷), soil water (green), and runoff, as percentages of the total amount of rainfall (CA 2007).

groundwater and surface water quality, inter-sector competition, interregional and international conflicts, all contribute to water scarcity". Physical water scarcity is when people physically do not have access to the amount and quality of water that they need. By 2025, nearly 2 billion people will be under the effects of physical water scarcity, i.e. have less than 1000 m³ water per year each (Rockström et al. 2009), as an effect of population growth alone. This may be further influenced by climate change. Economic water scarcity⁶ occurs when people do not have the financial resources to access the amount and quality of water that they need (Figure 5).

Current freshwater withdrawal from surface water sources is approximately 4,000 km³ annually for irrigation, industry and domestic purposes (Gleick 2003), with 70% (equivalent to about 2,800 km³) for food production. Estimates of annual water use in agriculture vary between authors, e.g. Oki and Kanae (2006) mention 2,660 km³ for irrigation, whereas Shiklomanov (2000) estimates 1,800 km³; Rockström (2003) estimates 5,000 km³ for rain-fed agriculture, and an additional 1,800 km³ for irrigation. Looking at global water use, irrigation is only a small part of all water used for agriculture, including grazing land

(Figure 10). Projected increase in demand depends heavily on variables like number of people, diet composition, the ability to increase water use efficiency, as well as effective allocation of production through enhanced trade and the like. Calculations for the future (2030/2050) annual water demand of agriculture range from about 2,000 km³ (De Fraiture and Wichelns 2010) to 3,000–4,000 km³ (Bindraban et al. 2010b) and 5,000 km³ (Rockström et al. 2007). Assuming a water use efficiency of 1000 liters per kg of grain and yield levels of 2, 3–4 and 5 tons per hectare respectively, an additional one billion hectares of land would be needed to capture all this water. Alternatively, the water use efficiency on the current 1.5 billion ha of arable land would have to increase by 25–70%⁸. The latter figure would imply a beneficial use of 80–90% of the rainwater falling on the land, which is highly unlikely.

An alternative way of calculating global water use related to food production is by determining the water footprint of a product: the total volume of freshwater used to produce a product, measured over the whole of the supply chain from primary production, processing, packaging, and transport, to consumption and disposal or recycling (Hoekstra 2009). This is then expressed in units of water per unit of product, specific for each value chain (more details in Appendix 18.2). However, as issues relating to e.g. the processing and disposal of a product cannot be realistically dealt with in this document, improving

6 There is also 'institutional water scarcity' that occurs where water resources and infrastructure may be available, but people cannot access water because the current set of institutions does not allow them to. It might affect for instance people at the downstream end of an irrigation system or the men and women who do not have rights to land or water.

7 Interpretations of what is labeled as 'green' and 'blue' water differ among authors. For instances aquifers (or groundwater, where the soil is saturated with water) may be called 'green' or 'blue'. In order to avoid confusion, this document refrains from the use of color labels as much as possible.

8 Some calculations give other results, such as those with PODIUM in Appendix 18.1.

water productivity in terms of unit benefits per unit of water is a more practical way of viewing efficient water use for the purposes of this publication.

4.2.1 Water vulnerability, food security, and poverty

As discussed in Chapter 2, in order to reach the Millennium Development Goal of eradicating poverty and hunger, water management in agriculture would need to be geared up to increase agricultural production and meet increasing demands while maintaining affordable prices for the poor and sustaining essential ecosystem services (Rockström et al. 2007). With continued population growth and the uncertainty that issues like global climate change bring, food and water security will continue to grow in importance (McIntyre et al. 2008). Certain geographic and climatic circumstances cause unreliable water availability, and thus have a negative effect on both water and (as a result) food security (WWA 2009). Water contributes to poverty alleviation in a variety of ways, these include; improving water supply and sanitation; enhanced health and resilience to disease; improving productivity and output; helping to provide more affordable food and working against the impacts of climate change and environmental degradation (WWA 2009). Generally, the poorest populations in the world have the poorest access to water supplies and sanitation, *and* they are the most dependent on water resources for their daily livelihoods (WWA 2009). This places them as most vulnerable to changing conditions such as climate change and population pressures (CA 2007). This is confirmed by the recent work of Sullivan and Huntingford (2009), who developed a Climate Vulnerability Index that combines data on climate change, agriculture, poverty, ecosystems and water to identify areas where poor people are most likely to be at risk from climate change at various scales.

While economic poverty decreased from 28% in 1990 to 19% in 2002 (UNEP 2007), water poverty increased over that same period (WWA 2009). Water poverty can be defined as a situation where a nation or region cannot afford the cost of sustainable clean water to all people at all times (Molle and Mollinga 2003). This suggests that unless serious efforts are made to alleviate water poverty, economic

poverty reduction programs will begin to be less effective. Increased agricultural production allows multiple ways for people to escape the condition of poverty—it allows more people to get an income from farming, and it increases food production, decreasing the overall price of food, and allowing the poor to consume a more nutritional diet and spend their income on other necessities (McIntyre et al. 2008). Access to a safe and sanitary water supply is one of the most effective ways of improving human health as one tenth of the global disease burden, including diseases such as diarrhea, malaria, and malnutrition could be prevented by improving sanitation, hygiene, and water management (WWA 2009). Every dollar invested in improved water supply yields between USD 4 and 14 in health savings (WWA 2009). Food security can sometimes be consolidated by trade policies that allow for easy import of food. Conversely, trade policies that hinder the flow of food across borders can contribute to food insecurity in places where water security is lacking.

4.2.2 Water use in agriculture

About 80% of the water used for evaporation in agriculture, comes from rain, and some 20% from irrigation (CA 2007). Estimates on the total global freshwater withdrawals amount to 3,800 km³ of which 70% goes into irrigation. However, there are significant variations among countries (CA 2007). In South Asia, total renewable freshwater resources amount to 3,655 km³ and total withdrawal for agriculture is 842 km³ per year, which is by far the highest consumptive use of water (Atapattu and Kodituwakku 2008). It is recognized that there is great potential for improvements in rainfed agriculture in these regions which, if managed properly, could arrive at agricultural yields exceeding 5–6 tons/ha (Wani et al. 2009a), and contribute greatly to food security without additional water abstraction.

Livestock production systems are often considered as being to blame for depleting, degrading and contaminating large amounts of water (Goodland and Pimentel 2000; Steinfeld et al. 2006). Although this view is relevant in the case of intensive and industrialized cattle systems (Peden et al. 2009a), smallholder livestock systems have different environmental impacts (Herrero et al. 2009). Almost a third (31%) of global water use for agriculture is



Only 10% of the water used by livestock is for drinking, the remainder is water for feed (Peden et al. 2007).

used for livestock (less than 10% of this for drinking water, more than 90% for production of feeds) (Peden et al. 2007). However, water used by livestock in arid and semi-arid rangelands is not readily available for other forms of agricultural production. This is especially true for ruminants such as cows and sheep (Bindraban et al. 2010a). With the projected increase in demand for livestock products, agricultural water use may need to double due to the increased need for feed production. However, in developing countries, the production of animal source foods can easily be doubled without use of additional water by increasing livestock water productivity (Peden et al. 2007; sub-section 4.3.3).

In aquaculture and fisheries, water pressure derives from changing demand, changing access to resources, and changing risk margins. These drivers can be addressed by increasing production efficiency, and by changing management strategies for the production process and the associated risks. However, the legal, social, institutional, and physical environments have also changed and fish growers as well as fishers, have to deal with conflicts over resources, restrictive legislation and changed consumer perceptions (sub-section 4.3.4).

4.2.3 Water-soil-plant interactions

Soils are the largest store of fresh water and therefore can make the largest contribution to food production. However, water use efficiency of soil water heavily depends on many interacting eco-physiological processes, which ultimately determine plant growth. As a result of many interacting, limiting and reducing factors, crop yields under semi-arid conditions can vary dramatically even at similar rainwater levels (French and Schultz 1984a, 1984b; Sadras and Angus 2006). Low availability of nitrogen, phosphorus, and other nutrients; pests and diseases, may all limit productivity more than water availability. When these limiting factors are removed, e.g. through application of fertilizers, effective weed control and crop protection against pest and diseases, productivity under semi-arid conditions can triple or more, hence making more effective use of rainwater (Bindraban et al. 1999). Under these conditions the slogan: "The best irrigation is fertilization" is applicable. The strong interactions between soil, water and other production factors call for simultaneous and balanced interventions to enhance water use efficiency and increase productivity (Figure 11).

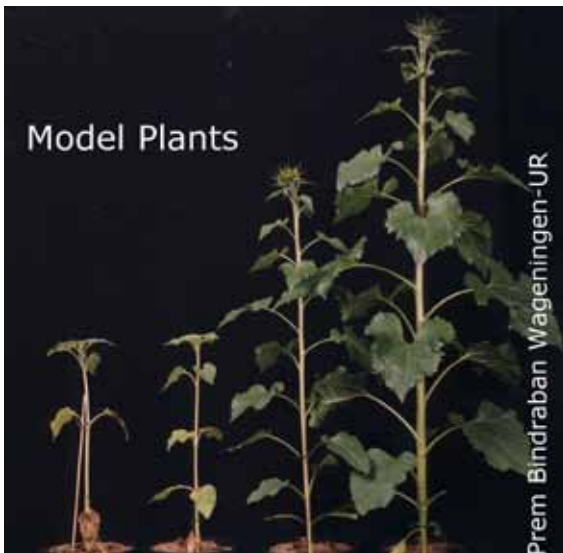


Figure 11. The effect of water and nutrients on plant growth (own experiments PS Bindraban): Plant 1 (left) is grown in a poor unfertilized soil with little water and remains small. Adding water (plant 2) hardly improves growth, as the poor soil fertility puts a stronger limit to its growth. Adding fertilizers rather than water (plant 3) does enhance growth indicating that the strongest limiting production factor (i.e. nutrients) was eliminated and water is used more efficiently. Adding both nutrients and water (plant 4, right) boosts growth to a level where neither of these factors is limiting. Here other factors, like radiation, set a ceiling to growth (Bindraban et al. 2009b, 2010b).

The above principle assumes that (rain) water is managed properly and not wasted on the spot for (plant) production because of run-off, evaporation and deep percolation. Organic fertilization (such as using

manure, compost), as opposed to chemical fertilizers, can increase the water holding capacity of the soil. Soil and water conservation and harvesting methods should be applied simultaneously to fertilization in order to reap the benefits of the available water. It should however be realized that fertilizer application might also increase production risk under variable rainfall conditions, especially if these are severe enough to induce total crop failure. Under fertilized conditions, plant growth might be too vigorous during the vegetative phase using up all available water leading to a collapse in yield with failing rainfall during the reproductive phase, in which case all investments are lost (Twomlow et al. 2008).

More than 40% of the land in sub-Saharan Africa is threatened by land degradation (Vlek et al. 2010). Loss of organic matter and the physical degradation of soil not only reduce nutrient availability, but also have significant negative impacts on other factors. Degraded soils have low infiltration and porosity that may affect the resilience of agroecosystems, local and regional water productivity, and even global carbon cycles. Accelerated on-farm soil erosion leads to substantial yield losses and contributes to downstream sedimentation. Transported sediment can lead to the degradation of natural water bodies and fill up water storage reservoirs and irrigation infrastructure (Vlek et al. 2010).



Small reservoirs are important for livestock watering in sub-Saharan Africa.

4.2.4 Tension between water for ecosystems and water for food

Competition between water users has existed for millennia, especially competition between water abstracted for direct human well-being and the water required to sustain various water-dependent ecosystems services. People with their livestock have settled near water sources for thousands of years, and human alteration of coastlines, rivers, lakes, wetlands is so widespread that it can hardly be distinguished from the original landscape. However, with increasing populations and increasing water use per capita, often there is not enough water of sufficient quality to go around. The most common result of this is that ecosystems do not receive adequate environmental flows, and ecosystem services begin to degrade. The Millennium Ecosystem Assessment showed that modifying landscapes to increase food production has resulted in adverse ecological changes (MA 2005d). Intensive hydraulic infrastructure development, much of it for food production, is one of the reasons for the 35% decline in freshwater biodiversity between 1970 and 2005 (Hails et al. 2008). Intensification through productivity gains made possible by increased agrochemical inputs pollutes waterways and poses a threat to human health (Appendix 19). Furthermore, several of the world's largest and most important rivers have been reduced to small stream size at their mouths because of over-abstraction, damaging aquatic ecosystems in rivers such as the Colorado, Murray-Darling, and Yellow (WWA 2009). A recent spatial analysis showed that at global level threats to water security are highly associated with threats to river-based biodiversity (Vörösmarty et al. 2010). Water use in agriculture affects ecosystems and the services they provide not only by reducing the amounts of water available, but also by polluting water, altering river flow patterns, and reducing habitat connectivity by drying up parts of rivers and streams (Gordon and Folke 2000).

Almost 20 years ago, it was predicted that "environmental stress due to lack of water may lead to conflict and would be greater in poor nations" (Gleick 1993). The Comprehensive Assessment of Water Management in Agriculture notes why this is now particularly important: "fifty years ago, the world had fewer than half as many people as it

has today...they required less water to produce their food. The pressure they inflicted on the environment was lower. They took from our rivers a third of the water we take now" (CA 2007). Currently many important river basins no longer have enough water for all of the human users of the resource, let alone for environmental needs (CA 2007). One third of the world's population lives with physical or economic water scarcity (CA 2007). Both are related to access: in regions of physical water scarcity, water is over-allocated, leaving little or nothing for other users, such as the environment. In economically water-scarce regions, water is available for use but access is difficult, most often because of limited investment in water infrastructure. In the case of institutional water scarcity, water and infrastructure are present but national or local institutions and norms prevent some social groups or individuals from accessing water. In all cases, though in very different ways, lack of access to water is a threat to future food production and needs to be addressed with different approaches. Without substantial change, some of the negative effects that are emerging from this overuse of water will turn into serious global problems. Other water limits have already been stretched in important food producing regions. For example, groundwater levels are declining rapidly in several major breadbasket and rice bowl regions such as the North China Plains, the Indian Punjab, and the Ogallala in Western USA (Giordano and Villholth 2007; Shah 2007). Extensive land degradation caused by poor water management practices further limits productivity gains (Bossio and Geheb 2008). Demand for aquaculture products like fish and shrimp continues to rise (Dugan et al. 2007), which means more demand for freshwater resources (Hoanh et al. 2006, 2010). Similarly, many additional animal food products from livestock and poultry will depend on grain as the limits to production on grazing land are reached (Peden et al. 2007).

Up to this point in history, we have relied on land expansion and land productivity gains fueled by irrigation for remarkable gains in food production. However, the method of expanding the use of land and water resources is reaching its limits, with land expansion for agriculture as the main driver of ecosystem change (MA 2005d). Agriculture systems fundamentally depend on the services

provided by many ecosystems, yet agriculture management during the last century has caused wide-scale changes in land cover, waterways and groundwater, contributing to ecosystem degradation (Gordon et al 2010). Wetlands the world over are under threat. Soils are seriously degraded: 40% of agricultural land worldwide is “moderately degraded” and a further 9% “strongly degraded” (Oldeman et al. 1991). These estimates were published in 1991 and there is little evidence the situation has improved in the last 20 years. Irrigation expansion across much of Asia, North America, and North Africa has fueled productivity gains in the past, but the limits have been reached as little or no additional water is available for use in these areas (Faures et al. 2007). In these physically water scarce areas, there will be increasing demand from cities and industries, but also for energy and even the environment. Increasing water withdrawals may even lead to river basin closures (Molle et al. 2010), and responses to avoid ecosystem degradation are urgently needed.

The Comprehensive Assessment argues that the greatest hope for meeting the food and water demands of the world 50 years from now lies in increasing agricultural water use productivity for many of the least productive areas (CA 2007). The good news is that the world has sufficient water to enable this to happen. Three quarters of the additional food we need for our growing population could be met by increasing the productivity of low-yield farming systems, probably to 80% of the productivity that high-yield farming systems get from comparable land (CA 2007). A substantial effort is needed to use water efficiently to increase yield per land unit and per water unit. This will reduce the pressure of food needs on land and water resources, as well as non-agricultural ecosystems and their services. Many of the world’s poorest live in currently low-yielding rainfed areas, hence improving water productivity and land productivity in these areas would result in the multiple benefits of getting more value out of currently under-utilized rain, limiting agricultural land expansion, and improving the livelihoods of these poor men and women, without threatening other ecosystem services (VWRI et al. 2008). Such approaches are feasible but require the more intelligent and equitable management of agroecosystems (Power 2010).

While water scarcity has primarily been examined for its role in the degradation of human life, it also plays an important role in ecosystem health (or lack thereof) (WWA 2009). Irrigation development has often come with a high environmental price tag. These costs range from aquatic ecosystem degradation, fragmentation and desiccation of rivers, to drying up of wetlands. When the water needs of ecosystems are not met, important ecosystem services are often disrupted, including their role in food production, but also in the provision of clean water, fish stocks, flood control, and many others. In some cases the values generated by irrigation proved to be less than the values generated by the ecosystems they replaced (Barbier and Thompson 1998; Acreman 2000). Physical water scarcity, the actual shortage of water caused by over allocation and overuse of water resources, is the primary cause of decreasing flows to ecosystems. With such reduced flows, ecosystems may not be able to deliver the full range of ecosystem services (Sections 2.3 and 3.2). This then affects provisioning services, as well as the regulation and supporting functions which underpin the provisioning capacities that can lead to economic water scarcity, which again can result in physical water scarcity when low-cost water resources are over-exploited (WWA 2009).

Other studies reveal that the conflict between irrigated agriculture and nature conservation has reached a critical point on a global scale (Lemly et al. 2000). Continued decreases in ecosystem services have probably already begun to harm agricultural productivity, and will continue to do so at an accelerating rate (Carpenter et al. 2009). When water use for increasing agricultural production, be it crops, livestock or aquaculture, trades off with the environmental flows important for these ecosystems, the overall food productivity from a given water resource may decrease (WWA 2009). Tensions between water for ecosystems and water for food do not only impact food production. Balancing water for ecosystems with water for food production is important for maintaining biodiversity and ecosystem resilience (WWA 2009). Further ecosystem services at risk include firewood, wood for building, pollination services, and clean water, all of these essential for our well-being (Carpenter et al. 2009). In order to avoid further degradation, fundamental changes are required to establish an

ecosystem-based catchment management approach (IUCN 2000). Restoring the productive capacity of highly degraded ecosystems requires re-vegetation, which in turn needs water; a need that will compete directly with the water demand for food production.

4.3 Increasing water productivity in agriculture

Water productivity is the amount of beneficial output per input unit of water, in some cases also referred to as water efficiency. Usually it is defined as a mass (kg) or monetary value of produce per unit of water evapo-transpired (Molden et al. 2010; Kijne et al. 2003). Increasing water productivity means using the least amount of water necessary to complete a particular task. This then conserves fresh water, making it available for other uses. Basin water productivity can be improved by raising water productivity for crops, irrigation, livestock, and fish per unit of water use, or by reducing non-productive evaporation and flow to sinks; tapping into more available water while also addressing trade-offs with other uses (CA 2007). As many water sources around the world are threatened by overuse, it is important to improve our ability to produce food with less water. One of the main ways to improve physical water productivity is by developing new crop varieties that do not require large quantities of water. In many areas, especially arid and semi-arid areas, it is also useful to focus on developing species that are naturally resistant to drought, disease, pests and salinity. Improved adaptive cropping systems with adequate fertilization, effective pest management and suitable farming practices can further improve the water productivity (Kijne et al. 2003; CA 2007; Atapattu and Kodituwakku 2008; Bindraban et al. 2009b, 2010b). Reducing post-harvest losses, such as those caused by pests and storage problems, can bring additional improvements of water productivity.

An entirely different approach to improving water productivity is in multiple uses of water. This can be implemented at basin level, where water is used for various purposes in parallel or in succession (reuse). The multiple uses of water can greatly increase the total value of beneficial outputs and hence increase productivity (Meinzen-Dick 1997). At field level,

crops with high water consumption such as rice can still be part of high-water-productive systems if their multiple ecosystem services are taken into consideration (Matsuno et al. 2002; Boisvert and Chang 2006). Hence current and future thinking on agricultural water management needs to focus on management strategies that seek to reduce costs, while at the same time aiming for greater integration with other food production systems, particularly livestock and fisheries, as well as safeguarding or increasing a wide range of ecosystem services. For example, Peden et al. (2005) demonstrated that pro-active integration of irrigation and livestock management can lead to increased sustainability and increased profitability in terms of investments in irrigation.

4.3.1 Increasing crop water productivity

In view of the large area under crop production, globally, a major challenge is how to grow enough food and support the livelihoods of the poor without further damaging the resource base underpinning food production. We not only have to grow enough food with limited water, we have to do it in ways that repair and sustain the environment (Gordon et al. 2010). Important livelihood and ecosystem gains can be made as people earn more income from limited resources and the ecosystem damage from agriculture is limited. In spite of the large potential benefits, obtaining increased water productivity and associated livelihood and ecosystem gains will prove difficult (Molden et al. 2010). There are only a few basic methods of using the Earth's water to grow more food: continue to expand rainfed and irrigated lands, increase production per unit of water, trade in food commodities, and changes in consumption practices. Land expansion is no longer a viable solution (sub-section 4.2.4). Therefore, improving agricultural productivity on existing lands using the same amount of water is a vital response. Where water is limited, or even for new water developments, improving water productivity will be the key.

There is great variation in water productivity across irrigated and rainfed systems. The difference can be as great as 10-fold in terms of value of produce per unit of water (Sakthivadivel et al. 1999), which shows tremendous scope for improvement. There is

also scope to reduce the water used for meat, milk and fish products by reducing the amount of water used to produce feed and changing husbandry practices (Peden et al. 2007). Supplemental irrigation, precise irrigation practices, plus better soil management practices as simple as improving soil fertility and using better seeds can play a role in improving the productivity of (rainfed) agriculture (Fischer et al. 2009; Oweis and Hachum 2009a, 2009b). For example, in Syria, 150 mm of supplemental irrigation added to 300 mm rainwater allowed for a double wheat yield (Oweis and Hachum 2006).

However, there are many reasons to be cautious in our expectation that easy gains can be made, as there are several complicating factors that require careful consideration. First, the common technical methods prescribed; such as drip irrigation, water pricing, improved pump technology, fertigation (adding nutrients to irrigation water), and better seeds will not by themselves deliver the goods (Appendix 20). Then there is a rebound effect where people who learn to use a limited water supply more productively also tend to use the “saved” water for themselves, leaving less for others (Seckler et al. 2003). There are many examples whereby upstream users of water utilize too much water and increase local productivity somewhere to the detriment of users downstream (see for example Molle et al. 2010). A basin perspective is needed to address this particular problem (sub-section 5.3.2).

A second consideration is that in highly productive areas, the scope for crop water productivity gains is limited (Molden et al. 2010). There is a biophysical limit on the amount of biomass capable of being produced per unit of transpiration (Steduto et al. 2007), differing by crop type (Seckler et al. 2003; Gowda et al. 2009). Plant breeders and crop production specialists have worked hard to increase the harvest index (the ratio between marketable produce and biomass), e.g. by shorter growing seasons and dwarf varieties for grain crops, but gains in this index seemed to have peaked. The scope for reducing water losses is also limited by canopy development: because of the higher cover with leaves, moving from 5 to 10 tons yield per hectare requires almost twice as much

evapotranspiration. Hence when yields increase, water productivity does not necessarily increase, and often more water is needed from rain, surface or groundwater to nourish crops.

Approximately 1.3 billion tons of food gets lost or wasted annually, roughly a third of the human food produced (Gustavsson et al. 2011). Hence, important productivity gains can be achieved by reducing post-harvest losses, though it is hard to quantify this potential (Parfitt et al. 2010). Especially in developing countries, 10 to 40% of yields on the field are spoilt during harvesting, storage, transport, and marketing (WRI 1998). This means that 10–40% of the inputs, including water, are wasted. These lost resources are not always easy to recover and reducing post-harvest losses may be an efficient first step towards higher productivity in agriculture (Clarke 2004; INPhO 2007). Improved food storage is also an important component of food security policies, helping individuals, communities and nations to better deal with variability.

Drought resistant varieties are important too (Gowda et al. 2009), but do not necessarily change the ratio between yield and evapotranspiration. Raising yields from one or two tons per hectare may have more to do with soil and water management than with crop varieties. Reductions in marketable yield through pest damage, disease, drought, and poor post-harvest handling also reduce water productivity, so all measures for crop protection and reduction of losses will increase water productivity.

Poorly conceived and implemented water management interventions in agriculture have resulted in high environmental and social costs, such as inequities in allocation of benefits and loss of livelihood opportunities. There are too many poorly performing water systems where productivity is low (low yield relative to high evaporation and transpiration, land productivity of around 1–3 tons of grain per hectare). This could be improved by upgrading of the distribution system, using more reliable and uniform irrigation practices (Appendix 18.3), combined with better farming practices, which would increase land and water productivity at the same time. However, often the governance and management of underperforming irrigation systems is severely lacking, or policies or factors



On-site rainwater harvesting in Tigray, Ethiopia.

outside of irrigation such as availability of inputs, subsidies on fertilizer or output prices are root cause of the problems (Mukherji et al. 2009). When this broader institutional environment is not addressed, then productivity gains tend to be unsustainable.

Economic water scarcity poses a different set of problems with a different set of solutions. In regions of high poverty and economic water scarcity, there is scope to use more water for food production, be it from existing irrigation systems, from rain, or from newly developed water resources. Even a little additional water can increase water productivity a lot. This is especially true in areas of high poverty, where combined poverty reduction and productivity gains can be made (Rockström et al. 2007), particularly within rainfed systems (Wani et al. 2009a). However, the way the water is developed and managed needs to be very different than that of the green revolution in the 1960s and 70s, starting with an elimination of the academic division between rainfed and irrigated agriculture. It would help to think of rain as the ultimate source of water for all agroecosystems (Figure 10), and consider agricultural water management options that include large-scale gravity irrigation, small-scale systems, provision of supplemental irrigation, use of groundwater, demand management, water harvesting techniques, soil moisture storage and on-farm water management as well as drainage.

Supplementary irrigation, combining rainfall and well-targeted irrigation, may achieve higher agricultural production with the same amount of water in many areas that are now 100% irrigated or 100% rainfed (Oweis and Hachum 2006; Geerts and Raes 2009). Redesign of irrigation schemes to on-demand systems where water is used to supplement rain and soil water could lead to large water savings, also providing better availability of water for ecosystems and other uses. In more traditional production systems, new drainage techniques using variable drainage depths can be introduced (Stuyt et al. 2009), as can alternative irrigation techniques that may lead to a substantial reduction of water consumption (de Vries et al. 2010). Alternative technologies such as low-tech drip systems may lead to water savings as well as reduced labor costs.

At the basin level, many irrigation systems turn out to waste less water than commonly perceived (Seckler et al. 2003). If we look at farm practices where efficiency is at 50%, we may quickly conclude that 50% of the water is wasted down the drain. However, this conclusion does not fully reflect the full facts of the matter. In fact, farmers living in or near irrigation systems in water-scarce environments make ample reuse of drainage water, and much of the 'wasted' water can be important for home gardens (Molle and Renwick 2005), livestock (Peden et al. 2005), fish

(Nguyen-Khoa et al. 2005), domestic uses leading to improved health (Boelee et al. 2007) or for recharging aquifers. There has been an incredible growth in the use of pumps to soak up water from whatever source farmers can get their hands on (Shah 2009). The result, when viewed from a larger scale, is counterintuitive: many irrigation systems are quite efficient in converting water withdrawals to productive evapotranspiration or other beneficial outputs. The problem is too much evapotranspiration, which results in declining stream flows and poor water quality (Falkenmark and Molden 2008). On top of that many areas have low yields for the high evaporation costs resulting in low water productivity. In addition, one of the drawbacks of increased land and water productivity gains is the pollution of the environment by (overuse of) agrochemicals. This may, on closer inspection, turn out to be a greater problem than water waste.

The highest potential for water productivity gains comes from low yielding rainfed areas in pockets of poverty across much of sub-Saharan Africa and South Asia (Rockström et al. 2010). Currently, some 95% of agriculture in sub-Saharan Africa and 60% in India is under rainfed cultivation (CA 2007). So far, relatively little attention has been given to water across sub-Saharan Africa. In semi-arid areas, there is enough seasonal rain available, but short, unpredictable dry spells make farming a risky business. This variability may increase with climate

change. Providing the basics (water, fertilizers, seeds and good farm practices) can easily lead to double or triple yields where grain yields are currently 1 ton per hectare. A reliable water supply, providing water at critical times, reduces risk and encourages investment in the basic inputs. Better rainwater management can also help reduce the pressure on waters being tapped from the local ecosystems and groundwater systems, thereby increasing the amount available for environmental flows and the hydrological cycle. A rainwater management strategy can also help recharge groundwater aquifers, allowing that water to be available to farmers when it is needed later in the season.

In rainfed humid tropical regions, adopting direct seeding and improved nutrient management techniques will reduce impacts on humid ecosystems (CA 2007). For example, in Lombok, Indonesia, the introduction of short duration input responsive varieties with direct seeding and the use of inorganic fertilizer increased and stabilized yields (Fagi and Kartaatmadja 2002; CA 2007).

Rainfed agroecosystems, whether they are in arid or humid regions, are vulnerable to climatic variability, which will increase under conditions of climate change. The development and utilization of early warning systems based on seasonal climate models can help address this vulnerability and could contribute to enhanced efficiency in the use



Horticulture in a converted wetland in Mozambique.

of water and nutrients. Such an approach will not only increase food production but will also have a positive effect on water quality as less nutrients and pesticides will be released. It is important that such information is made available to all male and female farmers, including marginal groups. Since both the presence of pests and the nutrients required for a complete crop are functions of the climate, knowing likely climatic conditions will allow farmers to reduce the amount of fertilizers and pesticides used. Hence a better understanding of climate variability and change can enhance agroecosystem services.

4.3.2 Increasing water productivity in agroforestry systems

In systems where annual crops provide limited ground cover during the early stages of the rainy season and may never achieve complete ground cover, soil evaporation may account for 30–60% of annual rainfall (Wallace 1996), while, in addition, a significant proportion is lost through deep drainage below the root cropping zone and runoff. For instance, it has been reported that only 6–16% of the rainfall received on a watershed in Niger was used for transpiration by millet and that most of the remainder was lost by evaporation (40%) or deep drainage (33–40%) (Rockström 1997).

There is considerable scope to develop improved agroforestry technologies to exploit these untapped reserves, although in some instances this might limit recharge of wells and aquifers. Trade-offs between how trees increase and utilize soil water are landscape and species dependent, but good combinations can be explored that help tighten nutrient, carbon and water cycling in agricultural systems (Ong et al. 2006). Complementarity may be either spatial or temporal; the former occurs when trees and crops exploit different resource pools, for example, when deep-rooted trees use water and nutrients, which shallow-rooted crops cannot access (Ong et al. 2006). Temporal complementarity occurs when trees and crops make their main demands on available resources at different times, for example, when trees are deciduous (drop their leaves) during part of the cropping season or continue to extract water during the dry season (Black and Ong 2000).

With 10% tree cover on nearly half of the world's agricultural land, agroforestry is a common reality (Zomer et al. 2009). Trees on farms have potential to improve productivity in two ways: i) trees can increase the amount of water that is used productively as tree or crop transpiration; and ii) trees can increase the productivity of the water by increasing biomass produced per unit of water used (Ong and Swallow 2003). Another intriguing possibility is to capitalize on 'hydraulic lift': the process in which water from moist soil zones of soil is transported to the upper soil layers through the root system. Strategic use of this phenomenon could capture water at a distance (Roupsard 1997; Ong and Leakey 1999; Bayala et al. 2008). The presence of trees may also enhance soil management by bringing more compost (from dead branches, leaves, or roots of trees) that can increase infiltration capacity (Hansson 2006). Thus a small change in tree cover can have a large impact on infiltration and catchment hydrology (Carroll et al. 2004), be it by enhancing infiltration or by transpiration.

4.3.3 Increasing livestock water productivity

Livestock products provide one-third of the human protein intake, but also consume almost one-third of the water used in agriculture globally (Herrero et al. 2009). Most of the world's animal production comes from rainfed mixed crop-livestock systems in developing countries and from intensive industrialized production in developed countries (Herrero et al. 2010). In response to the various drivers of livestock production, several policy, investment, and technology needs have been identified (Table A5 in Appendix 9.2). With increasing demands for animal products, along with increasing global water scarcity and competition for water (CA 2007), it is essential to increase livestock production, without causing further water depletion, and while safeguarding the environment (Descheemaeker et al. 2010b). Livestock water productivity (LWP) was first defined by Peden et al. (2007) as the ratio of livestock products and services to the water depleted and degraded in producing these. Since then, several studies have investigated the livestock-water nexus and dealt with LWP at various scales (Amede et al. 2009a, 2009b; Cook et al. 2009; Gebreselassie et al. 2009;



Cattle in South Sudan.

Haileslassie et al. 2009a, 2009b; van Breugel 2010). While sometimes contradictory in numbers, these studies offer good insights and starting points for increasing livestock water productivity⁹.

Numerous studies suggest that the water productivity of monogastric animals (poultry, pigs) is higher than that of cattle. Furthermore, Chapagain and Hoekstra (2003) have found the water use by livestock to be about 80% less than that reported by Goodland and Pimental (2000). Where cattle are prominent in developing countries, they often provide multiple services including farm power and manure for soil fertility. Manure production alone accounts for about half of cattle feed intake in developing countries. On one hand, when manure is used for soil fertility replenishment or fuel, the water cost associated with beef production will be about 50% less than commonly perceived. On the other hand, when

manure becomes a pollutant, the negative impact may be greater.

Calculations of LWP have shown that servicing and drinking, though at first sight the most obvious water uses of livestock, in reality constitute only a minor part of total water consumption in livestock-based agroecosystems (Peden et al. 2007, 2009a). The major water depletion in relation to livestock is the transpiration of water for feed production, which is generally about 50–100 times the amount needed for drinking (Singh et al. 2004; Peden et al. 2007; Gebreselassie et al. 2009). The large global variations in feed water productivity (Table 5) are not only a sign of divergent methodologies, but also illustrate that livestock water productivity of different livestock products depend on the feed type, forage production management, and growing conditions. In many non-industrial systems, rangelands contribute an important part of the annual feed intake of livestock. As these rangelands are often located on land that is unsuitable for crop production (Steinfeld et al. 2006), making use of the available biomass increases overall ecosystem productivity (Amede et al. 2009a). Analyses of LWP in the Nile Basin show a wide spatial variability, suggesting there is ample scope for improvements (Appendix 18.4).

⁹ One overlooked aspect of estimates of water productivity is that water use in units of m³ does not reflect the prices or value of water consumed (Peden et al. 2009b). Livestock grazed on arid and semi-arid pastures utilizes water that cannot be used for crops and will be depleted through evapotranspiration before it can enter ground water and surface water bodies (Bindraban et al. 2010a). Although the research remains to be done, the working hypothesis is that our understanding of water productivity of agricultural crops will change dramatically if we consider the value of water. Such an approach could lead to demand side management that would foster a rebalancing of water use among agricultural sectors.

Table 5. Global ranges of feed water productivity for different feed types derived from literature (based on Ferraris and Sinclair 1980; Sala et al. 1988; Bonachela et al. 1995; Saeed and El-Nadi 1997, 1998; Renault and Wallender 2000; Chapagain and Hoekstra 2003; Singh et al. 2004; Oweis et al. 2004; Smeal et al. 2005; Nielsen et al. 2006; Gebreselassie et al. 2009; Haileslassie et al. 2009a, 2009b; van Breugel et al. 2010).

Feed type	Feed water productivity (kg/m ³)
cereal grains	0.35 – 1.10
cereal forages	0.33 – 2.16
food-feed crops (total biomass)	1.20 – 4.02
irrigated alfalfa	0.80 – 2.30
pastures	0.34 – 2.25
(semi)-arid rangelands	0.15 – 0.60

Solutions that alleviate water scarcity through increasing livestock water productivity (LWP) can have a positive impact on farmers' livelihoods and the environment (Bossio 2009; Cook et al. 2009). Innovative interventions for improved LWP can be grouped in three categories (Peden et al. 2009; Herrero et al. 2010; Descheemaeker et al. 2010a):

- Feed related strategies for improving LWP comprise the careful selection of feed types, including crop residues and other waste products; improving feed quality; optimizing fodder or multipurpose food-feed-timber crops; increasing feed water productivity by crop selection and improvement; and implementing more sustainable grazing management practices.
- Water management for higher LWP consists of water conservation, strategic placement and monitoring of watering points, and integration of livestock production into irrigation schemes.
- Animal management strategies include improving animal health and appropriate animal husbandry, supported by raising awareness among livestock keepers, so that feed can be used more effectively and herders are able to get the same benefit from a smaller number of animals.

Designing LWP interventions that benefit the poor also requires understanding of the differentiated access to capitals and livelihood strategies of men and women and of different socio-economic groups within local communities (Clement et al.

2011). Livestock often provide the main sources of income for women, particularly in mixed crop-livestock systems. Furthermore, in order to facilitate adoption, such interventions need to be supported by an innovation process, which requires paying close attention to policies, institutions, and their associated processes (Amede et al. 2009b). For example, establishing institutions like water users associations together with policies like cost recovery for water use can contribute to improving the efficiency of feed crops irrigation. As a result, improved livestock water productivity would allow more animal products and food to be produced without increasing the volume of water depleted, as such safeguarding environmental flows and a variety of ecosystem services.

Although livestock grazing is often associated with vegetation and soil degradation (Asner et al. 2004), opportunities exist for the sustainable management of livestock grazing systems in a way that maintains ecosystem services. These include policies that enable the management of climate variability, such as early warning and response systems, improved markets, livestock-loss insurance schemes, and fodder reserves (World Bank 2009). Others deal with changing the incentive system for keeping large herds, such as payment for environmental services (sub-section 5.2.3) and increasing the level of cost recovery in use of natural resources, such as water and biomass, and veterinary services (World Bank 2009). Such incentive systems require a strong attention to issues of equity and legitimacy, as they might increase existing social inequities. Some interventions targeted at reducing land degradation and improving agricultural water productivity can, at the same time lead to improved ecosystem services (Appendices 13.3 and 18.4).

4.3.4 Increasing water productivity in aquaculture

Abstraction and discharge of water may affect ecological processes and compromise ecosystem services supporting other livelihoods. Appropriation of water for aquaculture may lead to competition with other resource users, including other aquaculture operators. Pressures to enhance water productivity in aquaculture derive from global changes and domain-specific challenges such as

production efficiency, risk management, conflict avoidance, legislation and controls, consumer demand and public perception (Verdegem et al. 2006). A number of practices and policies have been conceived to optimize water use efficiency (Appendix 18.5).

For most producers there are financial costs associated with managing (regulating, moving and conditioning) water resources as well as the negative social and legal consequences of discharging polluted water. Hence they have an interest in reducing the financial as well as environmental costs of this discharge. Consequently aquaculture farmers are generally active in trying to make more efficient use of appropriate water resources and work hard to comply with discharge standards, whether statutory or imposed by the community. Moreover, on-farm water movement and wastewater discharge may increase the likelihood of stock escaping, resulting in revenue loss and negative environmental impacts. Farmers also have an interest in reducing water intake, as this will lessen competition between various aquaculture producers, and help to avoid conflict with other water (and land) users.

Aquaculture producers, in order to have marketable products, must also manage animal health risks associated with their own water intake, that may be polluted, and the ingress of entrained aquatic

organisms that may harbor pests and diseases. Control measures adopted by farmers include screening inflows to prevent predators and other aquatic animals entering and restricting the abstraction of water as far as possible, depending instead on reducing stocking densities and promoting ecological processes to condition culture water for continued use.

Transition by producers to more intensive water management employing mechanical pumping and aeration can further reduce dependence on the appropriation of natural water resources, but may exacerbate environmental problems associated with fuel extraction or electricity generation and greenhouse gas emissions. Comprehensive Life Cycle Assessment of aquaculture systems might permit identification of the least environmentally damaging production strategies but further research and development is needed to develop practical approaches to evaluating, in concert, the environmental and social (including gender) impacts, livelihoods outcomes, financial viability and economic and ethical implications of aquaculture developments. In the short term these assessments could make life harder for poor aquaculture farmers with new costs for licenses, rents and taxes. In the longer term they may benefit as stricter controls can protect the ecological status of receiving water bodies and thereby secure water resources for other



Innovative combination of mangrove with shrimp aquaculture in Indonesia.

and future users. This would also maintain and enhance the stocks and flows of ecosystem services. Product and livelihood diversification should also be looked at to reduce dependence on aquaculture and generate more regular cash-flows and higher revenues.

4.3.5 Policy options

From the various strategies suggested above it is clear that we need ecosystems thinking to stimulate sustainable agricultural water management practices and investments (MA 2005b). A key consideration is the risk and incentive structure for producers, which often does not easily align with increases in water productivity. Water pricing seems an important policy lever, but implementation has been limited by a number of factors (Molle and Berkoff 2007). There are other options. Policies that reward conservation of water, such as cities paying for saved water, or policies that simply limit the amount of water allocated may also work (Hellegers et al. 2007). Investments in input and output market development often offer solutions, e.g. no farmers will produce tomatoes if they cannot get to markets, and farmers can only change their soil nutrient management if they have access to manure or chemical fertilizers at the right times. It is often found that the appropriate water knowledge is not available, not accessible, or that the appropriate people are not aware of it. However, creating the right incentives and providing relevant knowledge might not be sufficient as social and cultural barriers, e.g. based on gender, religion or caste, can also prevent changes in agricultural practices (FAO et al. 2010). Furthermore, local interventions need to be based on an in-depth understanding of the local politics within the same location to avoid the elite capturing all the benefits. Different kinds of thinking and practices are required by water and land professionals to address a complex physical reality and an even more complicated social and political reality.

Some of the most promising solutions for improving water productivity lie outside the water sector, such as in markets, prices, and subsidies, including in the international trade of agricultural commodities (Allan 2003). However, there are many doubts that we can rely on trade to reduce water needs

(Appendix 18.2). Trade is conducted for many economic and strategic reasons. Water is probably last on the long list of reasons for trade (Wichelns 2010). There are also serious questions about whether trade or food aid is a viable pathway to food security for places like sub-Saharan Africa. Some countries would rather invest their resources to utilize their water resources better, in order to produce their own food, and aim for greater food self-sufficiency and a reduction in trade. Countries can also focus on producing crops that do not require a lot of water, such as the small grains produced in sub-Saharan Africa. The implication is that we will probably have to rely on better agricultural practices rather than trade. On the other hand, trade will grow in importance both in terms of rural-urban connections as well as internationally, as its impact on ecosystem services at production points and at consumption locations also grows. Though the negative impacts of depleted water are likely to be disconnected from consumers, pricing changes, brought about by depleted water might eventually influence consumption patterns.

Ultimately, it is the consumers world-wide that drive water use. If we follow the chain from farmers' fields to dinner tables, we find staggering waste of food and water (Lundqvist et al. 2008). As people become wealthier, diets rapidly move to more water-intensive animal products and more calories. If we were to reduce post-harvest losses and other waste, recycle nutrients and watch our diets, there would be a water impact somewhere in the world. Ecosystem-friendly diets do not necessarily have to be all vegetarian, as (red) meat production may be an ecologically sound choice on grassland pastures where few other crops can be grown (Bindraban et al. 2010a). Hence, policy measures can support appropriate selection of land and water use towards holistic and equitable agroecosystem management that can lead to food security, increase water productivity and in addition deliver more ecosystem services.

Trans-boundary issues present challenging problems for effective water management. Tensions between countries over water allocation may lead to each actor taking as much water as they can from the basin or aquifer, resulting in severe water scarcity, and serious threats to environmental flows (Molden

et al. 2007a; WWA 2009). Fortunately, many river basin organizations have been set up to span borders and manage water on a basin scale.

It is important that policy decisions are taken to invest in water infrastructure to increase access to water. Such decisions are in the hands of governments and development banks (such as the World Bank and the Asian Development Bank). Especially in sub-Saharan Africa, many countries lack the necessary infrastructure to store and distribute water. Infrastructure projects aim to make current water withdrawals much more efficient (CA 2007). Various types of water storage for all uses within and outside agriculture have an important role to play in creating a buffer¹⁰ against water scarcity, especially under conditions of climate change (McCartney and Smakhtin 2010; Johnston and McCartney 2010). When considering the continuum of water storage options, from soil moisture and aquifers via ponds and tanks to small and large dams, but also including natural wetlands and swamps (McCartney and Smakhtin 2010), a more balanced choice can be made for each location, depending on the biophysical environment, but also social (e.g. gender), cultural and institutional parameters. This is more likely to benefit vulnerable populations with low adaptive capacity; poor women and marginal social groups with limited resources, poor social networks, and low access to services.

The development of water infrastructure has been identified as a key strategy towards poverty reduction (Kandiero 2009; World Bank 2008). Such water infrastructure developments would include development of water supply and sanitation systems, dam construction, as well as investments in irrigation systems (World Bank 2008). In the Nile and the Mekong River Basins dams and other infrastructure are being planned. Africa as a continent requires more well-engineered infrastructure that is designed, built, and operated with ecosystem services in mind. Stakeholders may need guidance on how to develop appropriate infrastructure with a view to maximizing ecosystem services and reaching an equitable share of benefits between men and women and among different social groups. The choice stakeholders face is not

only one of whether to build or not, but also how to build and how to integrate the multiple needs, interests and perceptions of local communities. Some of the older existing infrastructure needs rehabilitation and this could be done in such a way that it not only helps to reduce poverty by providing wider and more equitable access to water, but also reduces water losses in current distribution networks, improves overall efficiency of water use networks, and caters for the wider agroecosystem and its various functions and services. Infrastructure projects combined with new technological advancements can create more efficient irrigation systems that lose less water to evapotranspiration. New technology for improving water efficiency such as drip irrigation, biotechnology advances, improved pump technology, and better water practices, is already in place in many areas of high productivity, and could be implemented in areas of lower productivity also.

4.4 Conclusion: Tackling Water Scarcity in Agroecosystems

To share a scarce resource and to limit environmental damage, it is imperative to limit future water use. Important pathways to growing enough food with limited water are to increase the productivity of water in irrigated and rainfed areas, in animal husbandry and in aquaculture; improve water management in low-yielding rainfed areas; change food consumption patterns; and (possibly) through enabling trade between water rich and water scarce countries and areas. Trade and its impact on ecosystem services at the production end as well as at the point of consumption, will in any case grow in importance, both in the rural-urban context and internationally.

In pockets of poverty in sub-Saharan Africa and Asia, expanding access to water through investments in storage and distribution infrastructure and a range of specific water management solutions is crucial to food security and poverty reduction. The design of such infrastructures needs to take into account the multiple uses of water by men and women as well as the local and macro institutional and political context which will shape its access. Such solutions should be underpinned by serious changes in how we think about water and food,

¹⁰ Just as storage of food can play a key role in increasing food security.

and how we govern water and land resources. For sustainable water use, water managers must consider agriculture as an ecosystem in its social context and consider how other ecosystem services are impacted through water. Managing water as an integral part of agroecosystem management in society will make our food production systems more resilient and more sustainable.

Increasing water use efficiency for crop, livestock, and aquatic production, while preserving the functioning of water bodies in a context of increased demand for food and energy, is a real challenge. Consideration of the various ecosystem functions in irrigated and rainfed agroecosystems is crucial, as is effective water governance at different and appropriate scales to help ensure sustainable use of water resources. In some regions in the world, there is scope to develop new surface and groundwater supplies for agro – and other ecosystems which will significantly contribute to meeting growing food and energy requirements and increase resilience to climate change and other shocks. In other areas, synergies can be explored between agriculture and anti-desertification efforts whereby degraded lands are brought back under productive use through better farming practices which restore surface vegetation and soil functions, in particular water retention, thus creating a new agroecosystems with more ecosystem services. Strategic increase of tree cover can play a key role in management of water productivity by increasing water infiltration and penetration through transpiration in the delivery of fruit, fodder, timber, and fuel.

Water storage options along the continuum, from soil and groundwater to natural wetlands and dams, can make water more accessible at different spatial and temporal scales: from individual farm and household level to the level of large dams serving various communities and from year-round accessibility to the bridging of shorter or longer

dry spells, thus safeguarding the crop (McCartney and Smakhtin 2010). This is especially important in rainfed agriculture, where other water management options and appropriate farming practices can help increase agricultural and water productivity through various water management options. Redesign of irrigation schemes to on-demand systems could lead to large water savings, providing also better availability of water for other uses within or outside the agroecosystem. Support should be given to systems and approaches that ensure high water productivity as well as gender and social equity and contribute to closing the water cycle to the benefit of many ecosystem functions.

Sustainable livestock production systems should be encouraged in order to respond to changing diets and the increased demand for animal products while maintaining environmental flows and ecosystem services. The resulting improved livestock water productivity would allow more animal products and food to be produced without increasing the volume of water depleted. In other areas, solutions tackling land degradation should be encouraged through incentive policies, which could lead to both improved water productivity and environmental health.

For aquaculture, various practical approaches and policies for enhancing water use have been developed in an array of settings that might have potential elsewhere. Greater awareness of these amongst producers and policy-makers could encourage more cost-effective water management strategies that would concomitantly reduce animal, environmental and public health risks. Greater awareness would also encourage the development of policies and regulatory frameworks that would prompt adoption of more water efficient practices and hence increase water productivity without compromising either gender and social equity or the vulnerability and resilience of the poorest and marginal groups.

5. MANAGING WATER IN AGROECOSYSTEMS FOR FOOD SECURITY

5.1 Introduction: the Role of Water in Ecosystem Services

Water plays a role in all categories of ecosystem services (Section 3.1), especially in freshwater provision and the water cycle (Aylward et al. 2005; UCC-Water 2008; Figure 12):

- *Provisioning services*: water quantity and quality for consumptive use, such as drinking, domestic purposes, agriculture and industry; water for non-consumptive use, such as power generation and transport or navigation; and as habitat for aquatic organisms, for food and medicines. Values of most of these are quite easy to assess, such as water supply to urban, industrial and agricultural development, hydropower, fisheries resources for food security and livelihoods.
- *Regulatory services*: maintenance of water quality by natural filtration and water treatment; buffering of floods and erosion control, through water-land interactions as well as with flood-control infrastructure; climate regulation by being a source and sink for greenhouse gases and by influencing temperature and precipitation. Some of these services may be quantified and given explicit values, such as waste processing in relation to public health, flood retention and properties of plains, but they are often more difficult to value than provisioning services and they seldom have a price on the market.

Water ecosystem services

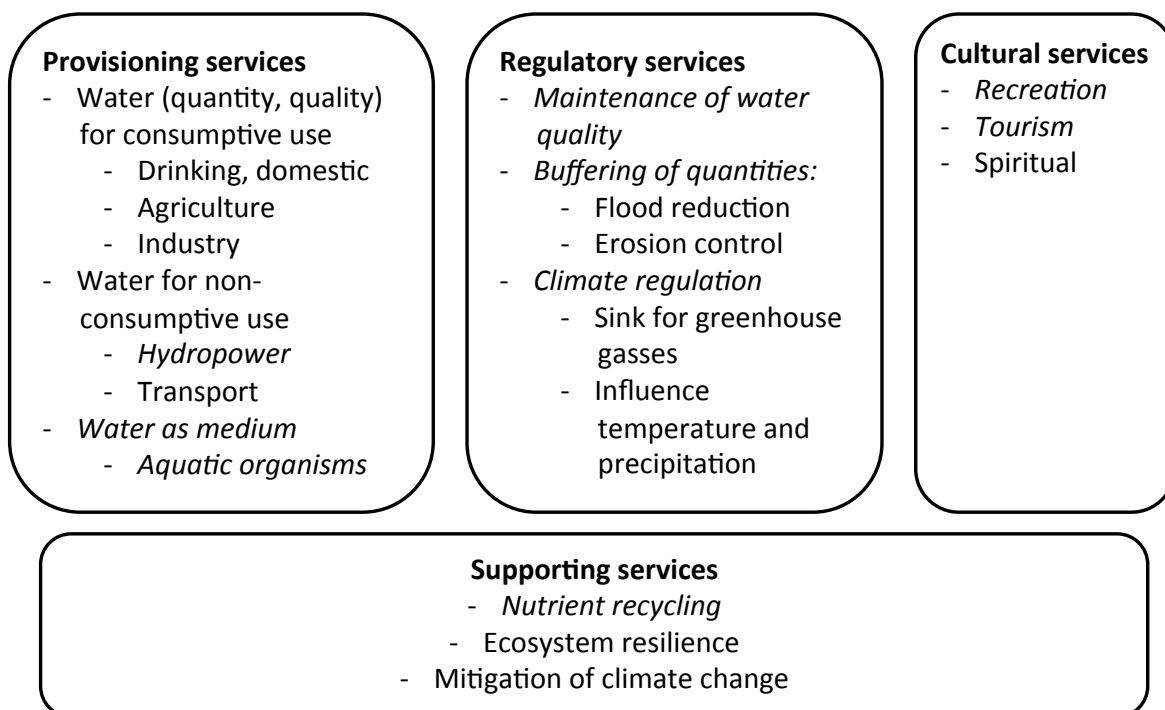


Figure 12. Water ecosystem services, based on Aylward et al. (2005), with UNEP priorities in italics (UNEP 2009a).

Table 6. Water ecosystem services in 3 main parts of basins (UCC-Water 2008).

Catchments as 'producers of water and sediment'	Floodplains as 'providers of food and fiber'	Estuaries as 'providers of food, trade and economic opportunity'
<ul style="list-style-type: none"> Glaciers: stable and clean water sources Rivers and lakes: flood regulation, food, fodder and fiber for upland people 	<ul style="list-style-type: none"> Fertile and wet soils: highly productive agroecosystems, resources for poverty alleviation Rivers, lakes and wetlands: flood regulation, food and fiber, waste processing, recreation 	<ul style="list-style-type: none"> Fertile (and flood prone) soils: highly productive agroecosystems Mangroves and lagoons: food and fiber, resources for poverty alleviation

- *Cultural services*: recreation such as river rafting or fishing as a sport; tourism such as river viewing; existential values such as in personal satisfaction from free-flowing rivers, or the role of water in religion, e.g. many societies have sacred water bodies. Out of these, some are quite easy to quantify, such as the tourism potential of lakes and other water bodies, and house prices that are often higher if they have a view over water. Spiritual values on the other hand are often quite difficult to capture.
- *Supporting services*: nutrient recycling, such as maintaining floodplain fertility; ecosystem resilience; mitigation of climate change with mangroves and floodplains providing physical buffering. These are very hard to quantify and value.

These water ecosystem services are not the same throughout river basins (Table 6) and though it is not always straightforward to quantify them, it is clear that many of these ecosystem services are central to human well-being but increasingly threatened as the previous chapters have shown. This particularly affects poor people and is likely to get worse under the influence of population growth, continued abuse of ecosystem services and global climate change (Mayers et al. 2009). Water ecosystem services, based on the water cycle, could be seen as the ultimate renewable resources and many promising solutions to the various threats exist. However, enacting these solutions requires good governance and more research is needed on how to secure the regulatory and supporting services of ecosystems in order to help with poverty reduction (Mayers et al. 2009).

Some aspects of an ecosystem can be partly substituted, which is often done for example when changing natural vegetation into preferred crops to enhance yields for human well-being. Such substitution may not necessarily (but can) change

other ecosystem services, such as habitat, or water flow. However, there is no substitution for water flows in an ecosystem perspective.

5.2 Managing Agroecosystem Services

5.2.1 Ecosystem services in agriculture

As discussed in sub-section 3.1.2, agricultural production involves a wide range of ecosystem services and processes that use water such as: nitrogen cycling, climate regulation, and soil formation, in addition to the obvious food production. The concept of ecosystem services is used to analyze trade-off scenarios when human well-being and ecological sustainability need to be addressed simultaneously. The ecosystem perspective aims to bridge interdisciplinary gaps between fields as far apart as religion and biology, political science and geology, or engineering and biodiversity, thereby addressing the system comprehensively. The major challenge lies in quantifying values and measuring feedback cycles (Nicholson et al. 2009) and more research is required into ecosystem services, especially those associated with water (Carpenter et al. 2009).

The Comprehensive Assessment of Water Management in Agriculture (CA) states that agriculture is fundamentally dependent on ecosystem services and emphasizes that the past century has seen unprecedented alterations of land cover, watercourses, and aquifers due to agricultural expansion (CA 2007). Rural poor women and men are often more closely and directly dependent on several ecosystem services and are affected the most severely when services degrade, for example clean drinking water or the availability of firewood (WRI et al. 2008). Future agricultural management decisions will thus occur in a context where there is more

competition for water and greater demands on food production together with other demands on ecosystems. These decisions will affect the rural poor and sustainable management must be implemented so that shifts in the character and functioning of ecosystems are able to sustain what people need from them (CA 2007).

Agriculture and ecosystem services are thus interrelated in at least three ways: (1) agroecosystems generate beneficial ecosystem services such as soil retention, food production, and aesthetics; (2) agroecosystems receive beneficial ecosystem services from other ecosystems such as pollination from non-agricultural ecosystems; and (3) ecosystem services from non-agricultural systems may be impacted by agricultural practices. The role of ecosystem services in agroecosystems is often poorly understood by those in agricultural production. Yet food production, itself a provisioning ecosystem service, is critical to the survival of humanity and dominates much of the world's terrestrial and marine environments. At the same time, growing demands for food, coupled with degrading land and water management practices that erode the natural resource base, place substantial constraints on ecosystem services provided by and inherent in these agroecosystems (Abel et al. 2003; Sandhu et al. 2010).

Until recently, ecosystem services in agriculture – other than production of food or other agricultural products – have been assigned relatively low economic value compared to those in other natural ecosystems due to a lack of understanding and limited data availability (Costanza et al. 1997). However, 5 billion hectares of land are currently cultivated or used for pasture, equal to approximately one third of Earth's total land area (Foley et al. 2005) and this area generates and interacts with an enormous amount of agroecosystem services. There is a need to address the under-estimation of ecosystem services in farmland and develop concepts, policies and methods of evaluating these ecosystem services, as well as the ways in which ecosystem services in these systems can be maintained and enhanced in a way which is socially acceptable. Agroecosystems may very well offer the best chance of increasing global ecosystem services, if land and water are managed in a way that enhances natural and social capital (Porter et al. 2009). Specifically, enhancing

the supporting and regulatory ecosystem services is vital to meeting the food demands of a population forecast to reach 9 billion by 2050 (UNFPA 2009). The success of modern agriculture so far has largely been based on provisioning ecosystem services, particularly food and fiber. However, the expansion of these marketable ecosystem services has resulted in the degradation of other highly valuable and essential regulatory ecosystem services such as climate regulation, water regulation, biodiversity, and protection against soil erosion (Porter et al. 2009).

Swinton et al. (2006) suggest that incentivizing a systems approach to agricultural management (rather than a problem-response approach) can support the sustainable production of ecosystem services such as climate regulation, wildlife conservation, and biological pest control and pollinator management. Bennett et al. (2005) suggest that the ways in which ecosystems produce services are insufficiently understood and that uncertainty needs to be accounted for in the decision making process. They suggest that future management questions will have to address the complexity of ecosystems in their social context in order that ecological services can be maintained and to assess the degree to which technology can substitute for ecological services.

5.2.2. Decision making over ecosystem services

Decisions regarding management of agroecosystem services will typically involve social, economic and environmental trade-offs, some of them among different services (MA 2005a; Figure 8). For example, managing a landscape to maximize food production will probably not maximize water purification for people downstream, and native habitats conserved near agricultural fields may provide both crop pollinators and crop pests (Steffan-Dewenter et al. 2001). The question about whether intensive or extensive agriculture best optimizes the various trade-offs associated with the provision of ecosystem services is an important issue requiring targeted research.

Conversely, ecosystem services have several roles in decision-making processes. Pritchard et al. (2000) suggest that they are used in three main ways: First and most fundamentally, ecosystem services are used to show that natural and agroecosystems are linked

to human well-being, even when a service's value is not expressed in a market. Second, ecosystem services can be used for economic valuation as a way to describe the relative importance of various types of ecosystems. Third, by assessing their value, ecosystem services can be used to evaluate a particular decision in a specific place, for example, by using the value of these services in a cost benefit analyses.

Connections between ecological sustainability and human well-being can be expressed by using the concept of "ecological character": the various components and processes in an ecosystem that underpin the delivery of ecosystem services (MA 2005a). Without managing for the sustainability of ecological character, the long-term ability of an ecosystem to support human well-being may be compromised. These kinds of management trade-offs often require decision makers to estimate the marginal values of ecosystem services and to capture the costs and benefits of a specific quantity and quality of services (Daily 1997) for men and women and different social groups¹¹. Marginal value is used in this process because monetary valuation cannot express the overall importance of environmental goods and services, only the value of the resource if there were to be a little more or a little less of it (Heal 2000). Therefore, the value of an ecosystem service reflects its availability. Water is a good example here: it is important, renewable but not replaceable. However, water is often provided freely or at a minimal cost to consumers. Water prices, therefore, do not reflect the value of water and give no information on what consumers would be willing to pay if there were a little more or a little less of the resource (Heal 2000).

Ecosystem services can be used to compare different ecosystem types, in terms of their contributions to the availability of a certain service. Most commonly, "total valuation" is the tool used to bring environmental services into decision-making processes where

trade-offs between conservation and development need to be assessed comparatively (Emerton 2005). Total valuation attempts to account for all of the characteristics of an ecosystem, which includes "its resource stocks or assets, flows of environmental services, and the attributes of the ecosystem as a whole" (MA 2005a). As mentioned above, this is an incomplete process that is limited in its capacity to value ecosystems fully; however, as Daily (1997) points out, "markets play a dominant role in patterns of human behavior, and the expression of value—even if imperfect—in a common currency helps to inform the decision-making process." For the quantification of values at the country level a useful concept has been proposed by Dasgupta (2010) who argues that neither gross domestic product (GDP) nor the human development index (HDI) can determine whether development is sustainable. An assessment of wealth per capita is much more useful as it includes the total of all capital assets: infrastructure such as buildings and roads, health, skills, knowledge and institutions, and also natural capital, which may easily be left out of other assessments (Dasgupta 2010).

These methods are increasingly important to today's agricultural water use decisions. Bennett et al. (2005) points out that, with growing demands on food production and water use, demands on ecosystem services, in many cases, could surpass the capacity of certain ecosystems to supply these services. In these contexts, decision makers will need to make "trade-offs between the production of various ecosystem services and the social and economic benefits and risks of using technology to provide them" (Bennett et al. 2005). With a clear understanding of ecosystem services and their values, agroecosystems and non-agricultural terrestrial ecosystems can be compared (Power 2010). Many goods and provisioning services come from non-agriculture land, such as food, fodder, fiber, and timber, and in decisions over water allocation the whole range of ecosystem services, their benefits (values) and costs (social, financial, water) have to be taken into account (TEEB 2010). Then well-balanced decisions can be made about which ecosystem services are to be enhanced, at the expense of which other services, or how ecosystems can be optimized to provide the

11 Differentiating the groups here is important because different groups, for example men and women, young and old, or poor and rich, make very different use of the services available to them and may value these services very differently. The different use various social groups make of water and ecosystems, and the impacts of that in relation to development and conservation projects is discussed in more detail in other publications (e.g. Thompson and Swatuk 2000; Goma Lemba et al. 2001; Sudarshan 2001; Hassan et al. 2005; www.genderandwater.org).

widest range of ecosystem services (Power 2010; Figures 8 and 16).

5.2.3 Payments for ecosystem services

Payments for Ecosystems Services (PES), also known as Payments for Environmental Services (or benefits) is the practice of compensating individuals or communities for undertaking actions that increase the provision of ecosystem services such as water purification, flood mitigation and carbon sequestration (Kelsey Jack et al. 2008). PES comes under the heading of economic or market based incentives aimed at motivating the desired decision-taking through charges, tradable permits, subsidies and market friction reductions. In the context of food production, PES typically involves incentives that favor the provision of conventional outputs such as food and fiber (FAO 2007b). While the term “PES” has been in common use since the 1990s, PES type schemes have been around since at least the 1930s, when in the wake of the American Dust Bowl, the federal government paid farmers to avoid farming on poor quality erodible land. Demand for a wide range of ecosystem services from agriculture will increase due to a greater awareness of both their value and the costs inherent in their depletion (FAO 2007b).

Today there are literally hundreds of ongoing PES schemes of all shapes and sizes, all over the world. Some are directed towards achieving poverty reduction on a local level, while others maximize the output of goods on an industrial scale. However, all of the schemes essentially involve three steps (WWF 2010a): 1) An assessment of the range of ecosystem services that flow from a particular area, and who they benefit; 2) An estimate of the economic value of these benefits to the different groups of people; and 3) A policy, subsidy, or market to capture this value and compensate individuals or communities for their action.

Developing mechanisms to implement PES is challenging, not least due to the fact that while the concept is simple, the reality of making such schemes operational can be very complex, and budgetary resources are often a constraint – especially in poorer countries. Nevertheless, PES

can trigger creativity in finding innovative solutions. When effectively designed, PES schemes can give both providers and users of ecosystem services more accurate indications of the consequences of their actions, so that the mix of services provided matches more closely the true preferences of the society (FAO 2007b). Appendix 21 provides four examples of payments for ecosystem services, including two summaries of what are generally regarded as successful PES watershed protection schemes in India and China. A related and comparable concept is that of green water credits, where incentives are given for sound water management or sediment control by appropriate tillage methods or other eco-efficient farming techniques (Dent and Kauffman 2007; Jansen et al. 2007). The idea is to create investment funds so that farmers can take intervention measures for better management of soil and water upstream, which will then be paid for by downstream users that receive more and better quality water.

Many changes in resource use that could benefit the environment are not likely to be adopted by farmers in the absence of motivating policy measures, because they would result in lower benefits for the producers (FAO 2007b). For example, setting land aside from crop production and placing (or leaving) it under natural grass or forest cover could enhance carbon sequestration, water quality and biodiversity, but might result in lower returns to the farmer (Tschakert 2007). Reducing livestock numbers or managing manure to reduce nitrogen runoff to surface water, infiltration to groundwater or emissions to the atmosphere could benefit the environment, but would probably increase costs, increase labor or reduce returns to the farmer (Steinfeld et al. 2006; FAO 2007b).

But even when more environmentally sustainable land management practices could result in beneficial economic returns, adoption is not guaranteed. For example, cropping and livestock practices which improve soil, plant nutrient and water management often lead to higher farm productivity and income as well as increased provision of environmental services such as soil carbon sequestration, biodiversity conservation and watershed protection (FAO 2007b). Yet, their adoption can be constrained by limited access to information, appropriate

technologies and finances (FAO 2007b), as well as by subsidies for agricultural production that can lead to practices which degrade ecosystems. Other reasons include inclusion or exclusion in social networks (Warriner and Moul 1992), land tenure (Tenge et al. 2004), as well as socio-cultural determinants. For instance, farmers and livestock keepers might have other motives as well as direct financial gain. Maintaining high herd numbers may lead to environmental degradation, but also may be an important saving mechanism or risk coping strategy of the livestock keeper, who, in addition, may get a higher status from having a larger herd (Turner and Williams 2002; Butt 2010).

5.3 Managing Water Efficiently for Ecosystems and Food Production

Various options are available for improving the efficiency of water use for food and ecosystems, several of which have been discussed in Chapter 4. A fundamental problem with this is that while agricultural water requirements can be calculated quite accurately, we do not really know how much water is needed to support other land use types and freshwater systems, and the ecosystem services they provide. Even in agroecosystems, water requirements may change if water use is to be optimized for the full range of ecosystem services.

5.3.1 Efficient water management

From a national resource policy and planning perspective it is important to recognize the broad objectives that lie behind the promotion of efficient water management. Countries invariably have numerous economic, social, environmental and political demands and counter-demands for multiple goods and services that require water as an input. Dealing with the inevitable trade-offs and finding synergies between water for food and other ecosystem services is notoriously difficult. The challenge for many countries is to find ways to close the gap between the projected future water demands and the current supply in a way that meets their development objectives, is cost effective, and

protects various users, including women, men, youth, and ecosystems. In these circumstances there is a need for matching the supply with the demand by 1) increasing supply; 2) reducing demand; 3) increasing productivity of water use; and 4) efficient and equitable allocation, whereby the optimal distribution of water, as well as the optimal productivity (of a wide range of ecosystem services), are considered together with the equity of distribution.

The water cycle provides the bloodstream of the biosphere (Figure 6) and enables the ecosystem to provision goods such as food, fuel and timber; regulate the environment; and provide for cultural services and basic ecological processes (Gordon et al. 2010). Consequently, the efficient and equitable management of water resources is of vital importance for our existence, as well as the existence of many of the living organisms that share our planet. The challenges related to the increasing water scarcity and the added complexities of climate change as discussed in previous chapters highlight the need for river basins and countries to carefully consider their water resources and how they manage them. Particularly in situations of scarcity, the goal will be to achieve the greatest possible water use efficiency in a socially acceptable manner as suggested under point 4 in the paragraph above.

Considered in its most basic form, the term “water use efficiency” is all about measuring the amount of water needed to produce a given unit of any good or service. Therefore, minimizing the amount of water needed to produce a good or service will result in greater efficiency, as the desired outputs are maximized. The aim is not always to reduce water use, but rather to optimize its utilization. From a food production point of view, much of the attention in the literature on water use efficiency is given to how to maximize the amount of material produced per unit of water (increasing ‘water productivity’, see Section 4.3). However, long term ecosystem services perspectives and country-specific objectives may need a different emphasis, bringing about alternative decision making. In these circumstances there is a need for allocative efficiency, negotiated between various users and uses. As eloquently described by the Professor Tony Allan of the London School of Economics and Political Science, “If

allocative efficiency is not achieved, it is possible to be doing the wrong thing extremely efficiently. It would be much more useful to be doing the right thing, that is with efficiently allocated water, a little badly.” (Lundqvist and Gleick 1997).

5.3.2 Integrated Water Resources Management (IWRM)

One of the ways in which allocative efficiency can be achieved is through Integrated Water Resources Management (IWRM). IWRM as defined by the Global Water Partnership is, “A process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems” (GWP 2000). This approach is of value due to its holistic ability to help to take into account multiple economic, social and environmental needs, as well as its ability to function as an all-encompassing framework to help consider and apply regulatory instruments, and to assimilate other practical measures that address ecosystem management. Balancing water for food and other ecosystem services, a process that involves trying to calculate

and agree upon who should have the right to access water resources and when, has historically led to the further entrenchment of silo-like, sectoral policy making and planning at national government level. This takes little or no consideration of gendered water uses beyond the interests and jurisdiction of individual sectors. Recognition of the lack of sustainability in current water management situations has resulted in an explosion of interest in the IWRM approach in recent years (Snellen and Schrevel 2004)¹². The IWRM approach strives to ensure coordination of all the sector uses, so that the impacts of one particular user on all the other affected users are taken into account.

One of the key tenants of IWRM is a holistic approach to basin management. Because borders often divide river basins in ways that make water management particularly difficult, river basin organizations are appearing and growing more powerful (Molden et al. 2007a). These river basin organizations generally seek to manage basin issues (such as sustaining environmental flows, managing water distribution between urban and rural users, and coordinating with Farmer Organizations) through the tenants of IWRM (Black and GWP 2003; Briscoe and Malik 2006). As illustrated by Figure 13 below, the IWRM approach

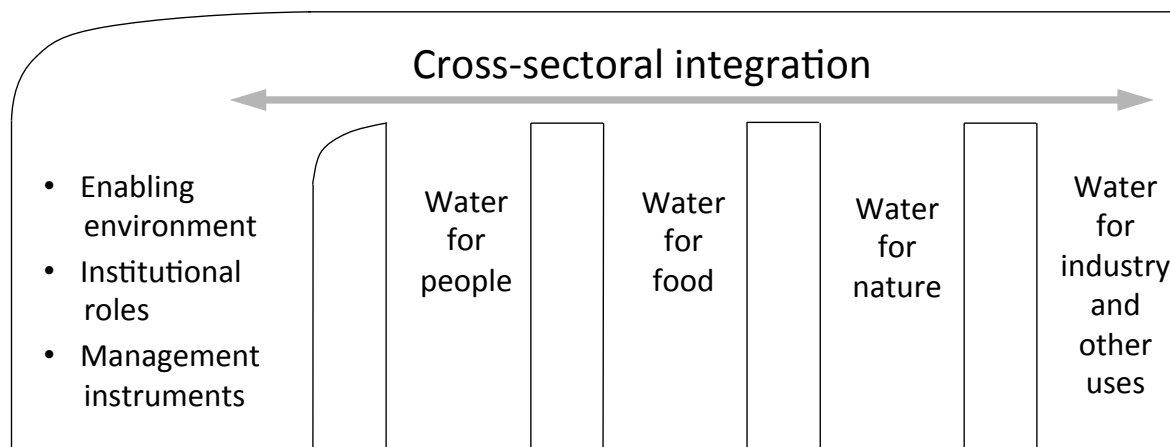


Figure 13. The IWRM Comb (after GWP 2000).

¹² Not all attention to IWRM has been positive: some 10 years ago, practitioners and scientists started to criticize the concept of IWRM for not being practical, for requiring a complete reform of the water sector while neglecting politics and cultural differences. This discussion started at conferences (Biswas 2004) was reviewed by various authors (e.g. Rahaman and Varis 2005; Matz 2008), and was followed by a stream of publications trying to move from a polarization of views to a more rational critical analyses that could offer alternatives (e.g. Medema et al. 2008; Chéné 2009; Saravanan et al. 2009).

strives to ensure coordination of all sector users, so that the impacts of one particular user are taken into account for all other affected users. Consequently, planners for water supply and sanitation (Water for People), for irrigation and fisheries (Water for Food) and for nature conservation (Water for Nature, see also sub-section 5.3.5) and so on must take other needs into consideration, particularly in terms of water allocation and the resulting impacts.

To implement the IWRM vision, there is a need to ensure coherence and appropriate linkages (Figure 14) between the main national and local development objectives with respect to:

- *Economic development objectives* relating to monetary resources, such as economic growth, management of monetary assets, and economic sector development.
- *Social development objectives* relating to human resources, such as poverty alleviation, health, education, and job creation.
- *Environmental development objectives* relating to natural resources, such as water policies, pollution control policies, nature conservation policies, agricultural land policies, forest policies, and fisheries policies.

The IWRM management cycle starts with the planning processes and continues to the implementation of frameworks, action plans and monitoring of progress (Appendix 22.1). IWRM is especially powerful at the river basin level, though its operational reality is highly complicated in trans-boundary rivers, where various countries have their own agendas and may be reluctant to transfer too much influence and control to trans-national river basin bodies. In the earliest stages of IWRM policy and plan making, every country must give thought to the types of instruments that can be applied in order to produce the desired results. One of the best introductions for policy makers and decision takers to regulatory instruments applicable to water resources management (as well as IWRM in general), is the GWP ToolBox available at <http://www.gwptoolbox.org/>. Some of these regulatory instruments are discussed briefly below.

Associated with the concept of IWRM, is the paradigm of good water governance: political, social, economic, legal, and administrative systems that develop and manage water resources and water services delivery at different levels of society at the same time as recognizing the role played by ecosystem services (WWA 2009). Good water governance seeks to remedy the diverse problems posed by vastly different water systems through the

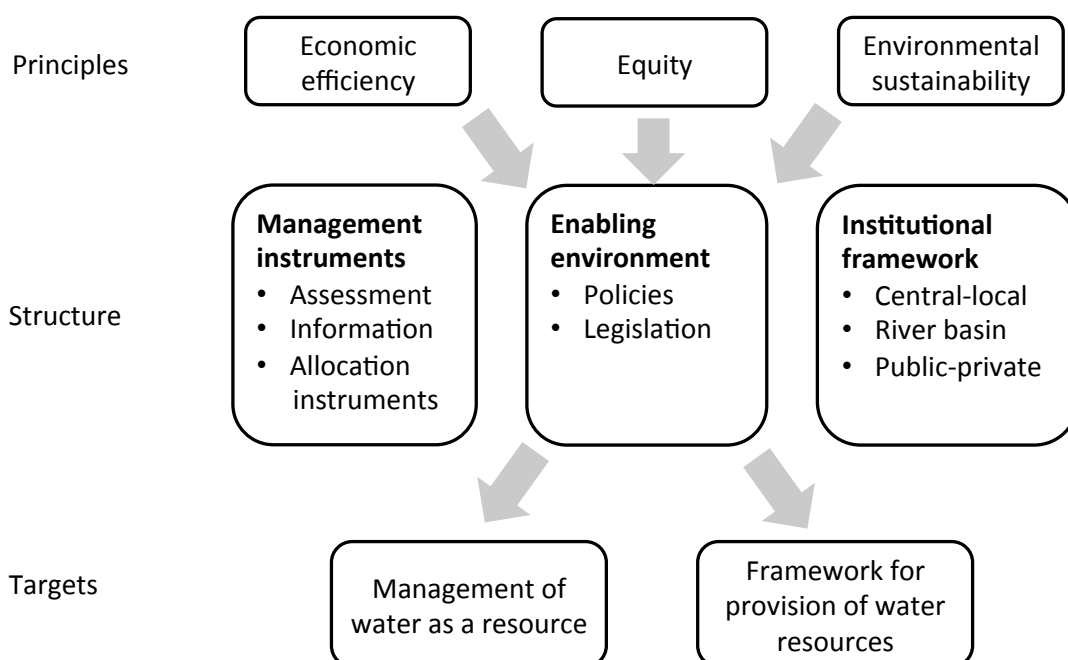


Figure 14. Linkages between principles, structure and targets of IWRM (based on UCC-Water 2008).

use of universally good and transparent decision-making processes. In these, adaptive management is key, taking into account the adaptive capacity of the water resources themselves (rain, surface, and underground water) as well as the adaptive capacity of their governing institutions. Water management that involves collaborative planning and an inclusive consultative process would encourage consensus and a buy-in among all the stakeholders that are dependent on the water resources and their various uses. This would include CBOs and other men and women community representatives.

According to the 2010 Water Resources Group, the challenge for many countries, as mentioned above, is to find ways to close the gap between the projected future water demands and the current supply and future available supplies in a way that meets their development objectives in a cost effective way, at the same time as protecting people and ecosystems. These country-specific strategies and plans will involve a combination of the three core ways of matching water supply with demand (WRG 2009):

- *Expanding supply:* This is particularly relevant in countries with limited infrastructure but abundant water supply. This has long been the preferred option in a number of countries, but is now becoming prohibitively expensive, though there is renewed donor interest (AfDB, World Bank) in investing in water infrastructure in sub-Saharan Africa. In addition, there is huge potential in using rainwater to increase crop yields and enhance resilience in many countries (Rockström et al. 2010).
- *Increasing the productivity of existing water use:* This entails producing the same output with less water as well as increasing productivity while keeping water usage the same (see also Section 4.3).
- *Reducing demand by shifting the economy towards less water-intensive activities:* For example, a country may decide to focus more on the production of a less water-intensive staple crop, or may even decide to rely more heavily on agricultural imports (sub-section 4.3.5). This may be hard to manage as all types of production have associated, often not quantified, investments.
- *Allocative efficiency:* based on the notion of optimal distribution and optimal productivity, incorporates both the second and the third options, which are both demand oriented.

While there is a great variety of policies and measures that can be employed under the heading of “water demand management”, it is common to distinguish between three distinct classes of water-use (demand) regulatory instruments (more details in Appendix 22.2):

- *Economic and market-based instruments:* These are signals (incentives and disincentives) to motivate desired decision-making, such as pricing or subsidies.
- *Regulatory instruments:* This is where government bodies establish a legal framework of laws, rules, and standards (such as water quality and supply standards), which is used to guide users and service providers in their duties and obligations, and possibly punish them for non-compliance. Experience of enforcing laws and regulations in the water sector can be difficult in practice.
- *Awareness and capacity building instruments:* These serve to encourage self-enforcement and social regulation in areas such as water conservation, best practices, and responsible behavior in an effort to promote cultural change, typically through voluntary compliance. Examples of these instruments include guidelines, rules of conduct and public information campaigns aimed at for instance water conservation.

It is widely accepted that all these instruments need to be employed within a mixed regulatory system. Each of the above has advantages and disadvantages and each requires different expertise and timescales for implementation. The appropriate mix is likely to vary markedly depending upon the socio-economic, political and environmental conditions prevailing in a country (GWP 2003). The ultimate water demand management benefits can be expressed in different ways: as gains yielded by increased economic efficiency of water use; as avoided losses resulting from current or future droughts; and as avoided or postponed capital costs

of enhanced water production. These benefits are complementary but may not necessarily reinforce each other. Where augmented water supply is possible and socially beneficial, water demand management is worth pursuing until the marginal costs of water saving do not exceed the marginal costs of building a new or extending existing water storage/production facilities. Where current water supply meets the demand under normal conditions, the water demand management policies can create 'buffer' capacity against periods of below-normal water availability and thus help to avoid some drought-inflicted costs. And finally where some water demands cannot be satisfied, water demand management can help to achieve more value to be produced by using the available water.

Key elements of a successful water demand management strategy include an explicit agenda and strong responsible institutions. Capacity building is important in the design, implementation and monitoring of activities for water demand management, so that the institutions can play a leading role in further developing sustainable and equitable water policies (Brooks and Wolfe 2007). Hence the costs of water demand management measures include implementation costs (capital and maintenance, compliance costs); transaction costs (administrative and enforcement costs); and wider costs inflicted on environment and society and not internalized in the above cost categories, including the opportunity costs of spending the capital. These costs are place and project specific. A sound economic analysis has to provide an overview of the gendered and social distribution of these costs (EPA 2008).

5.3.3 IWRM and ecosystem services

Water scarcity is commonly a result of mismanagement rather than an absolute lack of water and better farm-level water management can change that (Rockström et al. 2010). If the world is to succeed in curbing malnourishment and hunger, a doubling of food production over the coming 20–30 years is required, particularly in sub-Saharan Africa and parts of South and East Asia (Godfray et al. 2010a). This in turn requires not only major water investments in agroecosystems, but also facilitation of agricultural inputs such as nutrients,

planting material and farming implements to realize these water investments and support an economic sector that suffers from droughts and dry spells, most notably in tropical agriculture.

Hence, in order for IWRM to be efficient, rain, soil, and surface water resources (Figure 10) should be managed together. The focus of IWRM so far has mostly been on planning, allocating and managing surface water resources for irrigation, industry and water supply, while recognizing the need to safeguard environmental water flows for aquatic ecosystem functions in rivers, lakes, wetlands and estuaries. Yet key ecosystem services, such as agricultural production, and a range of provisioning services from non-agricultural land depend on water in the soil profile and aquifers in terrestrial ecosystems. As a consequence of this, the water resource management needs to shift its focus to increase flows and supply of water, watershed-wide (Johnson et al. 2001). In rainfed agriculture, emphasis must be on securing water to bridge dry spells and to increase agricultural and water productivity through new water management options (sub-section 4.3.1). Low yields and low water productivity due to large, non-productive water flows offer windows of opportunity which can be realized by implementing new approaches that encompass rain, soil, and runoff water resources from catchment to basin scale (Rockström et al. 2010).

An integrated approach to land, water, and ecosystem management can be most effective at the basin level to support food production and ecosystem resilience (CA 2007). This could be based on IWRM (Falkenmark 2003b), but could also incorporate elements of the ecosystem services framework (ESF) and perhaps also benefit from the multiple use water services approach (MUS) (van Koppen et al. 2006, 2009). Ecological uncertainty in the decision making process is important to account for; therefore, diverse scientifically informed arguments should be weighed against each other when predicting ecological outcomes. The three approaches each have their merits in this complicated decision making process. Though all are integrative and promote a more holistic view and analysis of water resources and uses, they tend to be applied at different scales and with different entry points: MUS at local level and with a focus on water supply infrastructure,

IWRM starting with higher level policies, institutions or organizations, and ESF on catchment scale ecosystems (Nguyen-Khoa and Smith 2010). In this document, we propose to rephrase at least one tooth (water for food) in the IWRM comb and manage

'water for multifunctional agroecosystems' (Figure 15). This avoids much of the current dichotomy between 'water for food' and 'water for nature' (or environment) and would help deliver more balanced ecosystem services (Figure 16).

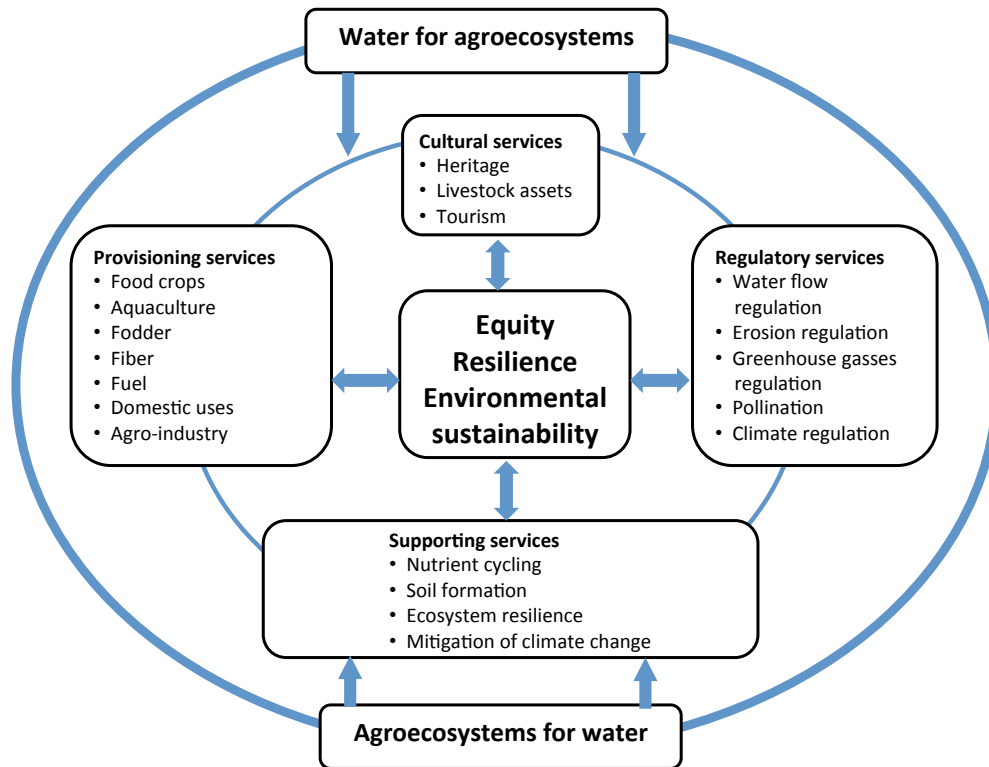


Figure 15. Water for multifunctional agroecosystem would bring more equity, environmental sustainability and economic efficiency.

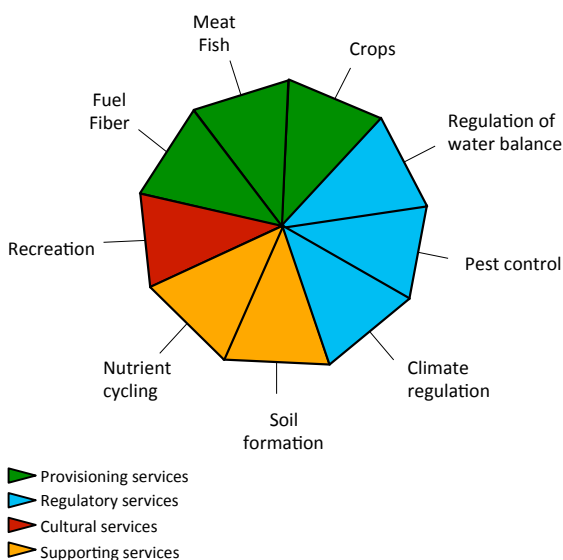


Figure 16. Managing water for multifunctional agroecosystems would help a more balanced provision of provisioning, regulatory, cultural and supporting ecosystem services, as compared to Figure 8 (adapted from CA 2007 and Gordon et al. 2010).

More balanced ecosystem services cannot be achieved overnight and changing an agricultural production system into a multifunctional agroecological landscape will take time, even if biophysically practicable or socially acceptable. However, the value of ecosystem services delivered by changes in agriculture practice can increase substantially through measures to increase water and land productivity and by interventions that support specific ecosystem functions. These can consist of, for example, the introduction or reintroduction of habitat corridors and the integration of further tree crops, livestock and aquaculture in conventional cropping systems, as well as measures to retain freshwater and organic matter in agricultural soils. In Minnesota, USA, environmental as well as economic benefits increased under scenarios that changed agricultural practices towards multifunctional landscape management (Boody et al.



Fish ponds as part of the landscape, between rice fields and farms in Vietnam.

2005). Ecosystem services as well as farm income increased with the degree to which more sustainable practices were adopted (Appendix 12.4), while the additional costs for nature conservation were offset by the reduction in commodity subsidies (Boody et al. 2005). This example shows how the additional ecosystem services come from within the production system, as agroecological landscapes provide a wider diversity of supporting services, and from the enhanced quality of the surrounding ecosystems resulting for instance from reduced pollution.

A major challenge in improving water for ecosystem services (Figure 15) is that the role of water in regulatory and supporting services is poorly understood, both in agroecosystems and other non-agricultural ecosystems. So even if there is a policy of holistic management, this may not be sufficient to ensure all ecosystem services are accounted for. This is another reason why it is so important to encourage adaptive management as part of everyday practice in governance systems to help take into account the implications of climate change on water resources and agroecosystems when planning sustainable water management practices. This can be supported by further identification, evaluation and adoption of applicable tools that help increase the production

of food per unit of water, without harmful trade-offs. Such tools include the economic valuation and gendered cost benefit analysis of ecosystem services, assessment of environmental flow, risk and vulnerability assessment, strategic and environmental impact assessment and probability-based modeling.

5.3.4 Practical approaches to water management in agroecosystems

Regardless of the overall approach, be it IWRRM or other, there is growing recognition that more practical approaches to the fundamental issue of ecosystem management must be employed. More specific policy options and management approaches can help strike a balance between increased food production and the preservation of ecosystems (Gordon et al. 2010), e.g. improved management practices on agricultural lands can increase the efficiency with which water is used to produce food (Section 4.3). Shifting from mono-cropping to multifunctional agroecosystems can create synergies among ecosystem services, meaning that all the services are valued and cared for rather than just the crop yield output and its associated water productivity (Nguyen-Khoa and

Smith 2008). This better ecosystem management can benefit agriculture and improve system water productivity in several ways:

- Increased yields in resource-conserving agriculture can go hand in hand with reduced environmental impacts through increased water use efficiency and productivity, improved water quality and increased carbon sequestration (e.g. in well-managed grazing lands).
- Biodiversity is important for securing multi-functionality by acting as an insurance mechanism by increasing the resilience of ecosystems and of the livelihoods of men and women who rely on them (FAO and PAR 2011).
- Species may seem redundant during some stages of ecosystem development but can be crucial for ecosystem restoration after disturbance.

Integrated management of agroecosystems directly links environmental sustainability aspects to other national, sub-regional and local economic and social development aspects. Several practical approaches which can be used to address ecosystem sustainability and enhance resilience that are currently receiving a significant amount of attention are payments for ecosystem services (PES: sub-section 5.2.3) and the management of environmental flows (next sub-section 5.3.5). Other practical approaches aimed at increasing water productivity in agriculture have been discussed in other parts of Section 4.3 and some examples of management of agroecosystems for climate change are summarized in Appendix 23.

5.3.5 Water for nature: environmental flows

The concept of environmental flows is closely linked to the concept of ecosystem services. The Global Environmental Flows Network defines an environmental flow as “the quantity, quality and timing of water flows required to sustain ecosystem services, in particular those related to downstream wetlands and aquatic ecosystems and the human livelihoods and well-being that depend on these ecosystems” (adapted from eFlowNet 2010). Hence it is more or less the same as ‘water for

nature’ in IWRM or ‘water for ecosystem services’, including provisioning and supporting services (for fish and other aquatic food) and regulation of water quantity and quality. Studying environmental flows is directly related to the ecosystem services that derive from rivers, wetlands, and coastal regions. Even in arid areas with no permanent water bodies, the infrequent flow from rainwater runoff is still necessary for proper ecosystem functioning. While only a few countries have begun to study environmental flows in their major water infrastructure projects, the concept is gaining international recognition. Many scientists are integrating the concept into IWRM, thereby increasing the likelihood of its uptake by other international and state actors.

Environmental flows are seasonal and site-specific. The idea is that consumptive water use (for provisioning services) should be set at levels that do not undermine other ecosystem services. Hence it is critically important that in water resources planning a certain volume of water is reserved for the maintenance of freshwater ecosystem functions and the services they provide to women and men, also referred to as Environmental (or Ecological) Water Requirements (EWR: Appendix 24.1). High flows of different frequencies are important for channel maintenance and wetlands flooding, while low flows of different magnitudes are important for algae control, fish spawning, and maintaining the diversity of aquatic habitats. In arid areas, plants and animals have adapted to depend on infrequent flow for health and reproduction. In other areas, if flow regimes of water courses are altered due to dams or other water abstractions upstream, sufficient flow at the right times should be maintained in the water course for the maintenance of aquatic ecosystem services downstream. Communities in catchments of dams need to be trained and assisted to come up with agriculture practices that reduce siltation and thus increase the lifetime of dams, thereby increasing the efficiency of water use (Appendices 24.2, 24.3, 24.4, and 24.5).

Maintaining the full spectrum of naturally occurring flows in a river is normally impossible due to water resources development and catchment land use changes. Planned environmental flows can therefore be seen as a compromise between river basin development (for irrigation as well as for flood



Flood plains like this one in Nepal are integral part of an agroecological landscape and require special water allocations (environmental flows).

control, hydropower, and navigation) on one hand and maintenance of natural river ecology on the other. Another useful way of thinking about environmental flows is that of 'environmental demand' – similar to agricultural, industrial or domestic water demand (Smakhtin and Eriyagama 2008). These flows aim to maintain an ecosystem in, or upgrade it to, some prescribed or negotiated condition also referred to as 'desired future state', 'environmental management class (EMC)', 'ecological management category' or 'level of environmental protection' (e.g. DWAF 1997; Acreman and Dunbar 2004). The higher the EMC, the more water will need to be allocated for ecosystem maintenance or conservation, and more flow variability will need to be preserved.

Actual estimation of environmental flows is complicated by the lack of both understanding of, and quantitative data on, relationships between river flows and the multiple components of river ecology. Few countries have determined the required environmental flows at the river basin level and included provision for such flows in national water allocation frameworks. In most cases, limited information is available at project level, such as for large dam projects.

The major criteria for determining environmental flows should include the maintenance of flow

variability, which affects the structural and functional diversity of rivers and their floodplains, and which in turn influences the diversity of aquatic species (Bunn and Arthington 2002). Many environmental flow assessment methods, which directly or indirectly encompass the above principles, have been developed in recent years (Tharme 2003; Acreman and Dunbar 2004; IWMI 2007). These techniques differ significantly in required input information and output accuracy. Some of them – like holistic methods of high confidence – follow a detailed protocol, involve significant fieldwork, multidisciplinary panels of experts, and take a long time to complete for a single river basin (King and Louw 1998; King et al. 2003). Other (desktop) methods are based primarily on ecologically relevant hydrological characteristics, indices, or analysis of hydrological time series (Tennant 1976; Hughes and Hannart 2003; Smakhtin and Anputhas 2006). The ELOHA (Ecological Limits of Hydrological Alteration) concept is a framework for broadly assessing environmental flow needs in a large region when in-depth studies cannot be performed for all rivers in a region (Arthington et al. 2006). Different techniques are used for different purposes – from general water resources planning to detailed schedules of managed dam releases, in a context of adaptive management (Poff et al. 2010).

EWR required for maintaining a fair condition of freshwater ecosystems range globally from 20 to 50 percent of the mean annual river flow in a basin. It is shown that even at estimated modest levels of EWR, parts of the world are or will soon be environmentally water stressed (Smakhtin et al. 2004) and some authors even argue that environmental flows could be the biggest threat to agriculture (Strzepek and Boehlert 2010). Figures 17 and 18 show environmental water requirements in global river basins (as percentage of total available water), and the environmental water stress index (WSI), respectively. The WSI reflects the scarcity of water for human use by taking into account EWR.

5.4 Water Management in Agroecological Landscapes

Managing agricultural land to deliver multiple services considerably improves values derived. This is best done at the landscape level, linking ecosystems and managing natural resources such as water and land specifically to enhance ecosystem services, thereby integrating all sources of water in the basin, from rain, in the soil, in aquifers and as surface water. As stated in sub-section 5.3.3, water is then no longer supplied to crops, trees, livestock, or fish, but to multifunctional agroecosystems linked and managed together at the river basin



Figure 17. A global distribution of estimated total EWR expressed as a percentage of long-term mean annual river runoff (Smakhtin et al. 2004).

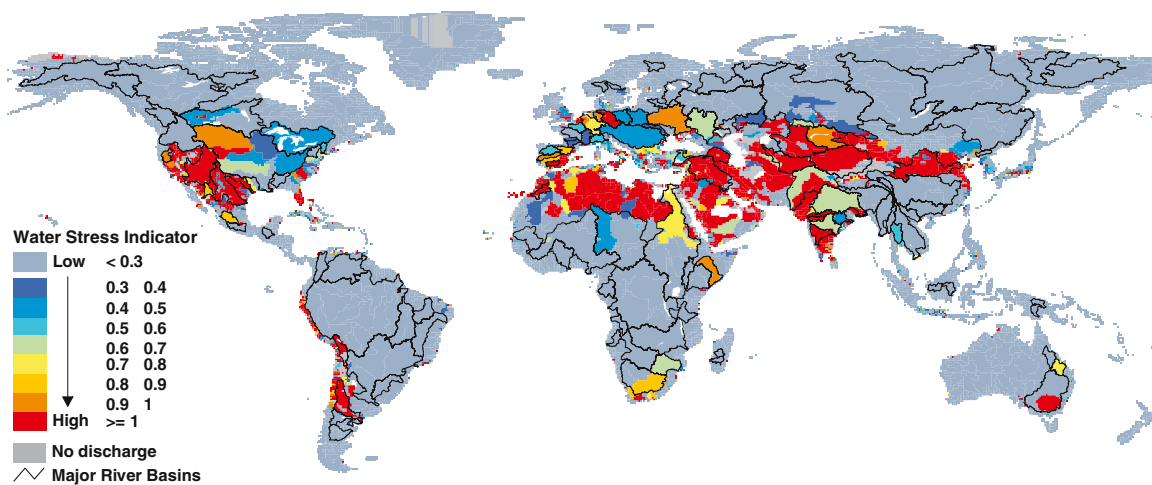


Figure 18. Map of a water stress indicator which takes into account EWR. Areas shown in red are those where EWR presented in Figure 18 may not be satisfied under current water use. Most of the areas with variable flow regimes (and consequently the modest EWR of 20-30% of MAR) fall into the areas of environmental water scarcity (Smakhtin et al. 2004).

or landscape level. In this way, synergies can be exploited and productivity can be improved, while obtaining added value from improved carbon storage, erosion control, water retention, waste treatment, and cultural and recreational values including tourism. Notably, most of these added services do not conflict with agricultural production but in many cases improve both its productivity and sustainability.

The recommendations in this section are based on the findings on the various types of ecosystems and integrated ways to enhance water management for food security (Chapters 2, 3, 4 and 5). In addition, principles of sustainable water management for agriculture in ecoagriculture have been incorporated (Molden et al. 2007c). As a result, the specific recommendations concerning water are only part of the larger message on how to manage natural resources sustainably and make the transition from production systems to multipurpose agroecosystems. These guiding principles have been combined from various sources and would increase ecosystem services and sustainability while using the same resources, hence be more productive (Swift et al. 2004; Molden et al. 2007c; van der Zijpp et al. 2007; Bossio and Geheb 2008; Hajjar et al. 2008; Swallow and Meinzen-Dick 2009; World

Bank 2009; Zomer et al. 2009; Garrity et al. 2010; McCartney and Smakhtin 2010):

- *Promote diversity within the production systems:* Optimizing the diversity of the above and below ground biotic components within the production system (crop biodiversity, animal diversity, soil biodiversity, and pollinators) can increase the adaptive capacity of the cropping system to buffer against fluctuations in water availability, temperatures, pests and diseases, thereby enhancing the resilience of rural livelihoods. Synergies with livestock and aquaculture can be explored to increase resource recovery and productivity, for instance in crop-livestock systems, rice-fish culture, tree-crop systems, aquaculture in reservoirs, forest-pastures, or wastewater-fed aquaculture. Integration of trees can help fix nitrogen, tighten nutrient, water, and carbon cycles, and produce additional goods, such as year-round availability of fodder and biomass for use as organic fertilizer and fuel.
- *Promote diversity in landscapes:* Landscapes with high levels of biodiversity are more resilient and better able to mitigate environmental impacts. Large monocropped areas can be



Agroecological landscape in Nepal with fields, houses and trees.

developed into landscapes with higher levels of biodiversity by identifying and linking natural habitat patches, including aquatic ecosystems. Habitat integrity and connectivity can be maintained by incorporating hedgerows, multi-purpose trees, and corridors of natural vegetation interconnecting parcels of agricultural land and natural ecosystems (such as wetlands and forests – these may need to be specifically developed where they are too far away). In large irrigated areas, canals and roads can be lined with perennial vegetation such as trees, thereby also serving as important passages and habitats for animals. Canals and other waterways can connect aquatic ecosystems and thereby maintain the connectivity of migratory routes, providing the variety in habitats required for subsequent life cycle stages such as spawning. Landscape-scale planning of strategic tree cover interventions can reduce flow accumulation by providing sites for water infiltration and penetration (for example contour hedgerows can also reduce run-off and soil erosion on slopes and buffer strips may protect water courses). By incorporating both fodder production and grazing land, livestock can be managed at the landscape level too, thereby enabling animals to reach otherwise inaccessible feed sources and avoiding overgrazing and trampling of vulnerable areas. This creates landscapes that are more resilient and better able to mitigate environmental impacts, as hedgerows and buffer strips also reduce runoff and erosion, and help protect watercourses and field crops.

- *Choose the right infrastructure and operation:* Infrastructure planning and operation can widen the focus from delivering water to field crops to providing water for multiple uses by different members of society, including water for bathing, laundry, animal drinking, home gardens, fish ponds and many other domestic and productive. It would also have to take into account current access to water and where necessary, expand this with appropriate structures for harvesting of rain or runoff water, complemented with site-specific water storage and distribution infrastructure. This would need to take into account property rights and their gendered nature,

including the rights to the use and management of shared water resources.

- *Mobilize social organization and collective action:* Engaging local communities in water resources management and ownership is critical to ensure these practices meet the needs of the people and are carried into the future for meeting food and environmental needs. This would also include management of other natural resources, such as land and the use of common forest and grazing lands. Alternative grazing management practices can only have a substantial impact when compliance is high. However, efforts need to be made to ensure that management and ownership involve equitable access across diverse and sometimes marginalized groups within local communities. Devolution of responsibilities has to be matched with devolution of rights or power. Raising awareness among them about the implications of alternative types of water use and the trade-offs will greatly enhance their capacity to conserve biodiversity and manage water efficiently.
- *Develop institutions for integrated natural resources management:* Up until now, relatively more effort has been placed on building institutions to manage irrigation delivery than in overall water and natural resource management. But institutions must be developed and supported to maintain healthy multifunctional agroecosystems and ensure equity of access, use and control over resources. At a larger scale, equitable institutional arrangements need to incorporate the means to deal with both on-site and off-site effects. The introduction of new structures or new rules might increase local or macro social inequalities. Care has to be taken that inequalities do not lead to conflicts over resources or to a lack of trust and cooperation which can jeopardize an efficient and sustainable management of natural resources.
- *Supportive policies:* National level policies can support the development and management of early warning and response systems for climate change, but also improved markets, buffers of

food and fodder, as well as insurance schemes to cover loss of yields or livestock. Incentive systems such as payments for ecosystem services (PES) can support the transition to more sustainable farming systems, including for instance the stimulation of smaller herds. Multifunctional agroecological landscapes need supporting services in all sectors, ranging from water distribution and soil fertility monitoring, to veterinary services and public health facilities.

The agroecosystem approach can thus improve food security and nutrition by diversifying food sources at the landscape level while also improving sustainability. For example, rice fields in Vietnam are used to grow rice (increase food security); reduce erosion and buffer water quantities (both regulatory services); retain nutrients (supporting services); and at the same time diversifying production by allowing for fish and other aquatic animals in the rice fields and in ponds interspersed with the fields for domestic and animal use. Similarly, multipurpose trees help increase infiltration and reduce runoff (regulatory services) and can be used in agricultural landscapes to connect forest habitats; bringing insects for pollination and soil organisms closer to fields; cycle nutrients and carbon (supporting services); and also diversify production by providing fuelwood and timber in addition to fodder and fruit (increasing food security).

In aquatic ecosystems, recognition of the full range of provisioning ecosystem services, not only fish, is vital if the true value of such 'aqua-ecosystems' is accounted for in the livelihoods of people and local and national economies – and safeguarded. Beyond capture fisheries, aquatic ecosystems also provide biodiversity, cultural services, and aesthetic values. Catering for aquatic ecosystem service at the basin level, for instance by continued provision of fish stocks and environmental flows, may actually benefit more people and make significant contributions to their well-being and resilience (Brummett et al. 2010).

Some approaches, such as those designed specifically for arid areas (Appendix 14), are capable of saving water and increasing the use of low-quality water. On the contrary, in humid tropical regions that receive rain throughout the year water

is not often considered a scarce resource. Hence farmers may engage in agricultural practices that require water in abundance, such as flooding of fields, which is common in rice cultivation, or shift from production of lower producing grain to water consumptive ones such as maize. Even during dry spells farmers are not accustomed to reducing water use and may not adopt coping strategies such as maintaining alternate wet and dry conditions or rainwater harvesting, and cropping of aerobic seed varieties (e.g. Wani et al. 2009b).

When managing agroecosystems as part of ecoagriculture or other landscape approaches, the catchment areas merit special attention. Often these are degraded and need to be rehabilitated (Appendix 25). This implies re-growth of grass and trees, which requires water. Hence in these areas, the water for agroecosystems will not result in many provisioning services, except possibly some fodder as part of cut and carry systems. During this rehabilitation phase there may thus be higher water requirements for regulatory and supporting services (including carbon capture), with less water for downstream river flows. In the long term this may be compensated by reductions in erosion (and siltation of downstream infrastructure), increased infiltration and higher downstream river flows, though the hydrology of these systems is not always predictable. This does show that water management for agroecosystems is complex and interlinked with wider catchment and ecosystem management.

Ministries of environment may be in the best position to promote this ecosystem services approach to food security at the landscape level. This would involve promoting recognition of ecosystem services in food security policy and planning, and promoting better cooperation between other sectors to improve sustainability and productivity of food supply systems. Ministries can support the implementation of the above guiding principles for instance by promoting habitat connectivity in agricultural landscapes and ecological solutions to the threat birds and other animals pose to seedlings and crops; linking the management of agroecosystems and other ecosystems, such as freshwater and coastal ecosystems, to reduce waste and negative externalities; and supporting agroecosystem services and multifunctionality in food production



Photo: Vladimir Smakhin

Well-managed agroecological landscapes can have high esthetical values (cultural services), such as this irrigated rice landscape in China.

systems. To play this expanded role, the ministries of environment would need a clear mandate and the resource and capacity building that is necessary to fulfill it.

5.5 Conclusion: Managing Agroecosystem Services for Food Security

Food and financial crises have increased the pressure on natural resources while opening the thinking on alternative ways of considering agroecosystems as potential long term providers of goods and services if managed in a sustainable and equitable way. This report through the study of interrelation between ecosystems, water and food security is aimed at increasing the understanding and knowledge of these interactions for better planning and gendered decision making processes.

To ensure food security it is important for decision makers to support the management of agroecosystem services by taking appropriate policy measures that encourage the use of technologies and approaches such as sustainable land management, integrated water resources management and more sustainable agricultural practices by female and male farmers. Solutions include not only managing the impact of agriculture on ecosystems but better management

of agroecosystems and non-agricultural ecosystems in order to support improved water security for agriculture. These approaches among others provide equitable access rights, better soils and water conservation, qualitative and quantitative water resources, improved livestock and fish management, and diversified biodiversity (CA 2007; UNEP 2007, 2009a, 2010; Nellemann et al. 2009; WWA 2009; Herrero et al. 2010).

Water is already scarce and improving food security will put more pressure on water resources and ecosystems. With increasing trans-boundary as well as urban-rural tensions, finding an equitable way to distribute water seems difficult. It is possible to produce the food needed, but if present practices continue it is not probable that this will solve the many poverty and environmental challenges confronting us. When water for ecosystems and water for food are considered separately, additional tension is created and the problem gets even more challenging. Hence, in order to share a scarce resource and guarantee long-term sustainability, it is imperative to find wiser ways to meet future water demands. For sustainable water use, water managers must consider agriculture as an ecosystem with all its services, and in turn consider how these services may be impacted by water. Agroecosystems are huge providers of food, animals, products, services



Photo: Karen Conniff

In many parts of Sri Lanka, rice cultivation is done in terraced small valleys surrounded by banana plantations, home gardens and forest: typical humid tropical agroecological landscapes.

and incomes which could ensure food security, if they are well managed, in sustainable ways, to maintain ecosystem functions and benefit from the full range of ecosystem services.

This calls for a shift in the management of water from water for food to water for multifunctional agroecosystems, considering the whole ecosystem base of provisioning, regulatory, cultural and supporting services. More research is needed on tools to analyze the potential at various spatial scales and over time in order to define an appropriate and practical management approach. Some major areas where attention needs to be given are: the role of agroecosystems in water storage and supply, particularly regarding renewable recharge of groundwater and improved soil moisture storage, and the role of water transpiration through agricultural crops in sustaining local and regional water cycles. There are considerable opportunities for seeking mutually supportive approaches between agricultural and ecosystem interests whereby agroecosystems can be sustained or improved by making them multifunctional. This could reduce their water use (more ecosystem services per drop) while also improving the health of the ecosystems. A key requirement to achieve this desired outcome is a shift towards better ecosystem

based management whereby multiple objectives can be reached through building on these synergies (IWMI 2010). This increasing complexity requires adaptive, participatory and cross-scale innovative research and consultation to form the basis for sound prioritization for policies and management. Specific research needs include a better understanding of the role of women and youth, resilient livelihoods and adaptive management institutions in addition to integrating cost-benefit analyses of water requirements for ecosystem services. The time scale needs to take into account the potential impacts of climate change, especially for vulnerable populations with low adaptive capacity, to ensure food security targets.

Evidence shows that implementing pro-poor policy responses to environmental problems enhances human health, socio-economic growth and aquatic environmental sustainability (MA 2005). However, it is not always clear what policies are best, especially when evaluating decisions about ecosystems for water and food production, as these different systems operate on different time scales but also underlie each other. Healthy agroecosystems have the potential to provide a high diversity of nutritional food based on their biodiversity while through their functioning qualitative and quantitative

water is provided to the various living organisms to the benefit of human beings. Wise management of agroecosystems is key to addressing food security issues (FAO Netherlands 2005).

Many of the recent synthesis assessments on environment and water suggest that concerted global actions are needed to address the root causes, while local efforts can reduce human vulnerability to shocks and chronic food insecurity. There is scope for actions at all levels and scale: local, national and river basin level. Recognizing the multiple ecosystem services of agroecosystems, coupled with elements of Integrated Water Resource Management (IWRM) at the basin scale, including consideration of all water resources above and below the ground, can be a powerful and sustainable response to freshwater scarcity. Because agriculture accounts for more than 70 percent of global water use, agroecosystems are a logical target for water savings and demand management efforts. Stakeholders who pay attention to increasing the productivity of rain-fed agriculture and aquaculture, which can contribute to improved food security, are proving to be successful. There is evidence that IWRM at the basin scale, improved effluent treatment and wetland restoration, accompanied by improved education and public awareness, are effective responses, even to water quality threats (UNEP 2007).

However, even with improved practices, questions still remain as to how we will manage water in ecosystems for agriculture, nature, and cities in the future. What are the various agroecosystem functions and services that water can provide? How do we decide how much water should be used for crop irrigation and energy production and how much should be used for nature conservation? Is it acceptable that agriculture has created artificial environments and replaced natural ecosystems? Can we manage our agroecosystems differently so that more ecosystem services are provided with the same natural resources, especially land and water? Will this lead to long-term sustainability and increased well-being for more people? To ensure that we have enough water for food and for a healthy planet, we must go beyond implementing the known improved techniques, incentives and institutions, and invest in understanding the various ecosystem

functions and services, as well as their interaction, in agroecosystems, that cover so much of the earth's surface. An ecosystem services perspective to agriculture can also help in the consideration of agronomic questions such as crop choices and soil fertilization, but institutional and market issues need to be addressed in these choices too.

Typically in most agroecosystems till now the provisioning ecosystem services of biomass for harvesting food, fodder, fiber or other valued goods is targeted, sometimes at an expense of other supporting or regulatory services (Foley et al. 2005; Gordon et al. 2010; Raudseppe-Hearnes et al. 2010). Water availability is one of the restrictions to growth of biomass so much agricultural management is focused around the supply of water to further enhance the provisioning capacity of biomass, usually in combination with other inputs such as manure, fertilizer, improved seeds, and pest control.

At the same time, water plays a significant role in the support and regulation of various other services in agroecosystems, for example maintaining non-agricultural vegetation, such as shade trees, grasslands and aquatic habitats. All these habitats are key sources for additional food, fodder, fiber for many people, not the least the poor and most vulnerable living in food insecurity and poverty (WRI et al. 2008). These uses of water in the landscape can be hampered if agricultural activities are viewed in isolation and receive disproportionately more water, which will deplete their ecosystems capacities (FAO Netherlands 2005). The capacity of multipurpose agroecosystems will be enhanced, when the water quantity and quality are adequate for the whole range ecosystem services (Figures 15 and 16), which will lead to greater environmental sustainability, more equity and result in higher economic efficiency in the long term. In some cases, the difference between natural ecosystems and agroecosystems becomes blurred, e.g. with the emergence of culture-based fisheries and stock enhancement programs in wetlands, and fisheries from water storage reservoirs for irrigation and hydropower generation that often become important sources of food and income in remote and highland areas. This creates its own challenges of governance, equitable benefit distribution and environmental impacts.

This document has shown the importance of ecosystem services in agriculture and how better managed water and ecosystems can contribute to food security. While this is not an entirely new message, this publication has combined recent findings from water management, crop production, livestock management, aquaculture and agroforestry in a systematic way to give theoretical background and practical recommendations on how this can be done. The next step is to put these guidelines

into practice and monitor the process closely, to see how it works in reality and where adaptations are required in the approach. Baseline valuation assessments of ecosystem services in agricultural production systems can then be compared with those in real life agroecological landscapes, providing an evidence base on what works and what does not in the application of an ecosystem services approach to water and food security.

GLOSSARY

- Acacia – any of various often spiny trees or shrubs of the genus *Acacia* in the pea (*Fabaceae*) family, having alternate, bi-pinnately compound leaves or leaves represented by flattened leafstalks and heads or spikes of small flowers
- AfDB – African Development Bank
- agrochemical – chemical used in agriculture, including fertilizers to increase soil fertility and pesticides (herbicides, insecticides etc.) to control pests
- agroecosystem – agriculture viewed as a set of human practices embedded and part of its own ecosystem that has certain ecosystem needs, functions and services and that interacts with other ecosystems. Agroecosystem management is then the management of natural resources and other inputs for the production of food and other provisioning, cultural, regulatory and supporting ecosystem services.
- AIES – The Arava Institute for Environmental Studies, see <http://www.arava.org/>
- AKST – Agricultural Knowledge, Science, and Technology
- alfalfa – lucerne or lucerne grass (*Medicago sativa*), a flowering plant in the pea family *Fabaceae*, grown for fodder, mainly for cattle
- alkalinization – process whereby soils become more alkaline
- allocative efficiency – optimal distribution of water for optimal productivity of a wide range of ecosystem services
- amalou – type of nut butter
- aquaculture – farming aquatic organisms, where there is intervention to enhance yields, ownership of stocked organisms is retained, or rights to exploit benefits controlled
- aquifer – also called groundwater, where the soil is saturated with water
- arboreal pasture – area where trees and plants are planted and used for livestock grazing
- Argania – species of tree native to the *Sapotaceae* family
- arid – areas where the ratio of mean annual rainfall to mean annual potential evapotranspiration varies between 0.05 and 0.20
- basin closure – a situation in which all water in a river basin has been allocated and hardly any flow reaches the sea anymore
- berm – level, earthen wall constructed for protection or flood control
- biodiversity – the variability among living organisms, including terrestrial, marine, and other aquatic ecosystems. Biodiversity includes diversity within species, between species, and between ecosystems (TEEB 2010)
- biome – a large geographic region, characterized by life forms that develop in response to relatively uniform climatic conditions. Examples are tropical rain forest, savannah, desert, tundra (TEEB 2010)
- biomimicry – the examination of nature, its models, systems, processes, and elements to emulate or take inspiration from in order to solve human problems (e.g. studying a leaf to invent a better solar cell), see <http://www.biomimicryinstitute.org/>
- biophysical – natural resources, including, water, soil and biosphere, with all natural elements in it.
- black water (sewage) – wastewater containing fecal matter and urine
- blue water – water in rivers, lakes and aquifers, though water in the soil, including groundwater, is sometimes referred to as ‘green’ water
- CA – Comprehensive Assessment of Water Management in Agriculture (2007), see <http://www.iwmi.cgiar.org/Assessment/>
- CBD – Convention on Biological Diversity, see <http://www.cbd.int>
- CBO – Community-Based Organization
- CDMRs – Community Driven Management Responses
- CGIAR – Consultative Group on International Agricultural Research, see <http://www.cgiar.org/>
- climate change – “a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods” (Pachauri and Reisinger 2007)
- cms – cubic meters per second
- corps – US Army Corps of Engineers
- CPWF – CGIAR Challenge Program on Water and Food, see <http://www.waterandfood.org/>
- CSIRO – Commonwealth Scientific and Industrial Research Organisation in Australia, see <http://www.csiro.au/>
- cut and carry system – feed for livestock is harvested off – farm and brought to the farm for consumption there, as opposed to grazing systems
- deciduous trees – trees that drop their leaves part of the year, be it during dry spells (in tropical areas) or during the cold season (in temperate regions)

- desertification – the degradation of resources (land, water, vegetation, biodiversity) in arid, semi-arid, and dry sub-humid areas. It is caused primarily by human activities and climatic variations and leads to a downward spiral of productivity loss and increasing poverty
- DHI – UNEP-DHI Centre for Water and Environment, see <http://www.unepdhi.org/>
- driver – any natural or human-induced factor that directly or indirectly causes a change in an ecosystem (MA 2005)
- DSS – decision support system
- DWAF – Department of Water Affairs and Forestry, South Africa
- ecoagriculture – a strategy and related practices for managing rural landscapes to simultaneously sustain and enhance rural livelihoods, produce food and fiber sustainably, and conserve or restore biodiversity and ecosystem services, see <http://www.ecoagriculture.org/>
- ecological character – “components and processes that comprise [an ecosystem] and that underpin the delivery of ecosystem services” (MA 2005)
- ecological footprint – unit of supporting ecosystem required per unit of production.
- ecosystem – a dynamic complex of plants, animals, microorganisms and their nonliving environment, of which people are an integral part (UNEP 2009a)
- ecosystem health – a comprehensive and integrated approach that reflects the health of the living and non-living world around us.
- ecosystem services – the direct and indirect contributions of natural and managed ecosystems to human well-being. The concept ‘ecosystem goods and services’ is synonymous with ecosystem services (TEEB 2010). These include provisioning services such as food, water, timber, and fiber; regulatory services that affect climate, floods, disease, wastes, and water quality; cultural services that provide recreational, aesthetic, and spiritual benefits; and supporting services such as soil formation, photosynthesis, and nutrient cycling (MA 2005)
- EFA – Environmental Flow Assessment
- efficiency – achieving maximum output from a given level of resources used to carry out an activity (OECD 2005)
- ELOHA – Ecological Limits of Hydrological Alteration, a framework for broadly assessing environmental flow needs in a large region when in-depth studies cannot be performed for all rivers in a region (Arthington 2006)
- EMC – environmental management class (DWAF 1997)
- ENEE – Honduras’ National Utility Company
- environmental flow – “the quantity, quality and timing of water flows required to sustain ecosystem services, in particular, those related to downstream wetlands and aquatic habitats, and the human livelihoods and well-being that depend on them (adapted from eFlowNet 2010).
- ESF – ecosystem services framework
- eutrophication – a process whereby water bodies, such as lakes, estuaries, or slow-moving streams receive excess nutrients that stimulate excessive plant growth (algae, periphyton attached algae, and nuisance plants weeds)
- EWR – Environmental (or ecological) Water Requirements
- existential values – values of ecosystem services in itself, e.g. nature, but also personal satisfaction from free-flowing rivers, or spiritual values accredited to water bodies
- FAO – Food and Agriculture Organization of the United Nations
- fertigation – (automatic) control of water and nutrients, with constant monitoring of ions. This technology can produce clean water from air or brackish water
- fisheries (inland capture fisheries) – subsistence, artisanal, small-scale and commercial fisheries employing a range of fixed and moving fishing gears for fish, molluscs, crustaceans and other aquatic animal species in freshwaters
- food security – exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food (FAO2010)
- GDP – gross domestic product
- GE – grain equivalent
- GEO4 – Global Environmental Outlook, report by UNEP (2007)
- germplasm – collection of genetic resources for organisms
- GHG emissions – Green House Gas emissions that can enhance global warming
- GLWD – Global Lakes and Wetlands Database (Lehner and Döll 2004)
- green water – water stored in soil or biomass, sometimes also used to refer to rainwater
- grey water – wastewater produced from baths and showers, clothes washers, and lavatories
- ha – hectare = 10,000 m²
- halophyte – plants that have (very) high tolerance of salt in water or soil
- HDI – human development index
- herbivory – providing plant material as food for grazing animals (herbivors)
- human well-being – concept prominently used in the Millennium Ecosystem Assessment – it describes elements largely agreed to constitute ‘a good life’, including basic material goods, freedom and choice, health and bodily well-being, good social relations, security, peace of mind, and spiritual experience (TEEB 2010).
- hyper-arid – areas where the ratio of mean annual rainfall to mean annual potential evapotranspiration is less than 0.05
- hypolimnetic waters – the deepest and undisturbed water layers of a lake (coldest in summer and warmest in winter)

- IAASTD – The International Assessment of Agricultural Knowledge, Science, and Technology for Development (McIntyre et al. 2008)
- IHA – Indicators of Hydrological Alteration
- ILRI – International Livestock Research Institute (part of CGIAR), see <http://www.ilri.org/>
- ILWS – Institute for Land, Water and Society of Charles Sturt University, see <http://www.csu.edu.au/research/ilws/>
- IPCC – Intergovernmental Panel on Climate Change
- IRBM – Integrated River Basin Management
- ISRIC – World Soil Information, see <http://www.isric.org/>
- IUCN – International Union for Conservation of Nature, see <http://www.iucn.org/>
- IWMI – International Water Management Institute (part of CGIAR), see <http://www.iwmi.org>
- IWRM – Integrated Water Resources Management: A holistic approach to coordinated water development and management that seeks to achieve a balance among the objectives of social equity, economic efficiency and environmental sustainability by considering rainwater, surface, and soil water resources in a broad biophysical and social context (adapted from GWP 2000).
- lalob – nitrogen-fixing tree species of the *Prosopis* family
- landscape – a wider unit of land, interlinking various agroecosystems and other elements, natural or man-made, that is managed in a holistic way
- liman – a man-made, low-lying reservoir dammed by dikes designed to trap runoff
- LWP – livestock water productivity (sub-section 4.3.3)
- MA – Millennium Ecosystem Assessment, see <http://www.maweb.org/en/Index.aspx>
- macrophyte – A macroscopic plant, commonly used to describe aquatic plant, that is large enough to be visible to the naked eye
- monogastrics – animals with only one stomach, such as pigs, poultry and humans (contrary to ruminants like cattle, sheep and goats, that have 4 stomachs)
- MUS – Multiple Use water Services, also: Multiple Use Systems (van Koppen et al. 2006)
- OECD – Organisation for Economic Co-operation and Development
- paddy-aquaculture – agroecosystem where immersed or ‘wet’ rice cultivation is combined with aquaculture, usually in the same fields
- PELUM – Participatory Ecological Land Use Management, see <http://www.pelumrd.org>
- PES – Payment for Ecosystem (or environmental) Services or benefits
- resilience (of ecosystems) – their ability to function and provide critical ecosystem services under changing conditions (TEEB 2010).
- salinization (salination) – increase in salt concentration in an environmental medium, notably soil (OECD 2001)
- SEI – Stockholm Environment Institute, see <http://sei-international.org/>
- semetar – type of porridge
- silviculture – the art and science of controlling the establishment, growth, composition, and quality of forest vegetation for the full range of forest resource objectives / forest agriculture
- stover – the leaves and stalks of grain or bean plants that remain after the main product is harvested. Stover can remain in the field as stubble for direct grazing or can be collected for use as fodder for livestock, fuel, or other uses elsewhere.
- swale – low-lying track of flat land that is usually consisting of swamp or marsh. These can be natural or man-made for flood control and water storage
- TEEB – The Economics of the Environment and Biodiversity, an international initiative, hosted by UNEP, that draws attention to the global economic benefits of biodiversity (<http://www.teebweb.org/>).
- TNC – The Nature Conservancy, see <http://www.nature.org/>
- total valuation (of ecosystems) – economic tool that attempts to account for all of the characteristics of an ecosystem, including “its resource stocks or assets, flows of environmental services, and the attributes of the ecosystem as a whole” (MA 2005)
- Trade-off – a choice that involves losing one quality or service (of an ecosystem) in return for gaining another quality or service. Many decisions affecting ecosystems involve trade-offs, sometimes mainly in the long term (TEEB 2010).
- UNCCD – United Nations Convention to Combat Desertification
- UNEP – United Nations Environment Program, see <http://www.unep.org/>
- wadi – valley or dry riverbed
- WANI – Water And Nature Initiative at IUCN
- water foot prints – amount of water required to produce one unit of output
- water governance – “political, social, economic, legal, and administrative systems that develop and manage water resources and water services delivery at different levels of society recognizing the role played by environmental services” (WVA 2009)
- water poverty – a situation where a nation or region cannot afford the cost of sustainable clean water to all people at all times (Molle and Mollinga 2003).
- water productivity – beneficial output per unit of water
- water scarcity – amount of water resources is less than 1 000 m³ per capita per year

- water-thrifty plants – plants that use water very economically and can withstand longer periods of drought
- wetlands – areas of marsh, fen, peat land or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water to the depth of which at low tide does not exceed six meters. Wetlands may incorporate riparian and coastal zones adjacent to wetlands, and islands or bodies of marine water deeper than six meters at low tide within the wetlands, as well as areas where soil is permanently or seasonally saturated with moisture, see <http://www.ramsar.org>
- WHO – World Health Organization of the United Nations, see <http://www.who.int>
- WorldFish center (part of CGIAR), see <http://www.worldfishcenter.org>
- WUR – Wageningen University & Research centre, see <http://www.wur.nl/UK/>
- WWA – World Water Assessment, see <http://www.unesco.org/water/wwap/>
- WWDR – World Water Development Report, with results from the WWA
- WWF – World Wildlife Fund, see <http://www.wwf.org/>
- xiji – enhanced wild cropping systems where a family or groups holds tenure and replants, cares for and guards the harvested plant material and the resource trees
- zoonotic diseases – diseases transmissible from animals to humans

REFERENCES

This list holds references of the main report as well as from all appendices. As much as possible, internet links have been provided for easy access. The editor and publisher cannot be held not responsible for errors in these.

- Abel, N.; Cork, S.; Gorddard, R.; Langridge, J.; Langston, A.; Plant, R.; Proctor, W.; Ryan, P.; Shelton, D.; Walker, B.; Yialeloglou, M. 2003. *Natural values: exploring options for enhancing ecosystem services in the Goulburn Broken Catchment*. CSIRO Sustainable Ecosystems, Canberra.
http://www.ecosystemservicesproject.org/html/publications/docs/nveo/Natural_Values.pdf
- Acreman, M. 2000. *Background study for the World Commission of Dams*. Reported in WCD (World Commission on Dams). 2000. *Dams and development: a new framework for decision-making*. Earthscan Publications, London and Sterling, VA.
- Acreman, M.; Dunbar, M.J. 2004. Defining environmental river flow requirements – a review. *Hydrology and Earth System Sciences* 8 (5): 861–876. <http://www.hydrol-earth-syst-sci.net/8/861/2004/hess-8-861-2004.pdf>
- Ahmed, N.; Bunting, S.W.; Rahman, S.; Brugere, C. 2011. Small-scale fishing in the old Brahmaputra River, Bangladesh: socio-economic and ecological challenges. Faculty of Fisheries, Bangladesh Agricultural University, Mymensingh, Bangladesh.
- Allen, D.; Springate-Baginski, O. 2008. Good Practice Toolkit for Integrated Wetland Assessment integrating species assessment, livelihoods assessment and ecosystem service valuation for improved wetland planning and management. Presentation from the Water Pavilion at the IUCN World Conservation Congress, Barcelona 2008.
- Allan, J. 1998. Virtual water: a strategic resource global solutions to regional deficits. *Groundwater* 36 (4): 545–546. <http://dx.doi.org/10.1111/j.1745-6584.1998.tb02825.x>
- Allan, J.A. 2003. Virtual water – the water, food, and trade nexus: useful concept or misleading metaphor? *Water International* 28 (1): 106–113.
- Alegria, H.; Bidleman, T.F.; Figueroa, M.S. 2006. Organochlorine pesticides in the ambient air of Chiapas, Mexico. *Environmental Pollution* 140 (3): 483–491. <http://dx.doi.org/10.1016/j.envpol.2005.08.007>
- Amede, T.; Descheemaeker, K.; Peden, D.; van Rooyen, A. 2009a. Harnessing benefits from improved livestock water productivity in crop-livestock systems of sub-Saharan Africa: synthesis. *The Rangeland Journal* 31: 169–178. <http://dx.doi.org/10.1071/RJ09023>
- Amede, T.; Geheb, K.; Douthwaite, B. 2009b. Enabling the uptake of livestock-water productivity interventions in the crop-livestock systems of sub-Saharan Africa. *The Rangeland Journal* 31: 223–230.
<http://dx.doi.org/10.1071/RJ09008>
- Arthington, A.H.; Bunn, S.E.; Poff, N.L.; Naiman, R.J. 2006. The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications* 16 (4): 1311–1318.
[http://dx.doi.org/10.1890/1051-0761\(2006\)016\[1311:TCOPEF\]2.0.CO;2](http://dx.doi.org/10.1890/1051-0761(2006)016[1311:TCOPEF]2.0.CO;2)
- Asner, G.P.; Elmore, A.J.; Olander, L.P.; Martin, R.E.; Harris, A.T. 2004. Grazing systems, ecosystem responses and global change. *Annual Review of Environment and Resources* 29: 261–299.
<http://dx.doi.org/10.1146/annurev.energy.29.062403.102142>
- Atapattu, S.S.; Kodituwakku, D.C. 2009. Agriculture in South Asia and its implications on downstream health and sustainability: A review. *Agricultural Water Management* 96 (3): 361–373.
<http://dx.doi.org/10.1016/j.agwat.2008.09.028>
- Aylward, B.; Bandyopadhyay, J.; Belausteguigotia, J.C. 2005. Freshwater ecosystem services. In *Ecosystems and Human Well-Being: Policy Responses, Volume 3*. Millennium Ecosystem Assessment, Island Press, Washington, Covelo and London, and www.maweb.org
- Barbier, E.B.; Thompson, J.R. 1998. The value of water: floodplain versus large-scale irrigation benefits in northern Nigeria. *Ambio* 27 (6): 434–440.
- Barrios, E.; Sileshi, G.W.; Shepherd, K.; Sinclair, F. in press. Agroforestry and soil health: trees, soil biota and ecosystem services. In Wall, D.H. (ed.) *The Oxford handbook of soil ecology and ecosystem services*. Oxford: Oxford University Press.

- Bates, B.C.; Kundzewicz, Z.W.; Wu, S.; Palutikof, J.P. eds. 2008. *Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change*, IPCC Secretariat, Geneva, 210 pp.
<http://www.ipcc.ch/pdf/technical-papers/climate-change-water-en.pdf>
- Batker, D.; de la Torre, I.; Costanza, R.; Swedeen, P.; Day, J.; Boumans, R.; Bagstad, K. 2010. Gaining ground. wetlands, hurricanes and the economy: the value of restoring the Mississippi River Delta. Tacoma: Eartheconomics. <http://www.eartheconomics.org>
- Bayala, J.; Heng, L.K.; van Noordwijk, M.; Ouedraogo, S.J. 2008. Hydraulic lift study in two native tree species of agroforestry parklands of West African dry savanna. *Acta Oecologia* 34: 370–378.
<http://dx.doi.org/10.1016/j.actao.2008.06.010>
- Behnke, R.H.; I. Scoones; Kerven, C. eds. 1993. *Range ecology at disequilibrium: New models of natural variability and pastoral adaptation in African savannas*. ODI, London.
- Bennet, E.; Robinson, J.G. 2000. Hunting of wildlife in tropical forests, implications for biodiversity and forest peoples, Environment Department Paper 76. Washington, DC: World Bank.
<http://go.worldbank.org/2RNUFGIOU0>
- Bennett, E.M.; Peterson, G.D.; Levitt, E.A. 2005. Looking to the future of ecosystem services. *Ecosystems* 8 (2): 125–132. <http://dx.doi.org/10.1007/s10021-004-0078-y>
- Bennett, E.M.; Peterson, G.D.; Gordon, L.J. 2009. Understanding relationships among multiple ecosystem services. *Ecology Letters* 12: 1394–1404. <http://dx.doi.org/10.1111/j.1461-0248.2009.01387.x>
- Benyus, J. 1997. *Biomimicry. Innovation inspired by nature*. Harper Collins
- Berg, H.; Michelsen, P.; Troell, M.; Folke, C.; Kautsky, N. 1996. Managing aquaculture for sustainability in tropical Lake Kariba, Zimbabwe. *Ecological Economics* 18 (2): 141–159.
[http://dx.doi.org/10.1016/0921-8009\(96\)00018-3](http://dx.doi.org/10.1016/0921-8009(96)00018-3)
- Berndes, G. 2002. Bioenergy and water—the implications of large-scale bioenergy production for water use and supply. *Global Environmental Change* 12 (4): 253–271.
[http://dx.doi.org/10.1016/S0959-3780\(02\)00040-7](http://dx.doi.org/10.1016/S0959-3780(02)00040-7)
- Beveridge, M.C.M. 2004. *Cage aquaculture*. (3rd ed). Oxford: Blackwell Publishing Ltd.
- Beveridge, M.C.M.; Muir, J.F. 1993. *Environmental impacts and sustainability of cage culture in Southeast Asian lakes and reservoirs*. Proceedings of the First AADCP Workshop, Types of lakes and reservoirs and the ecological constraints on the enhancement of production, Melaka, Malaysia, 18–22 October 1993.
- Beveridge, M.C.M.; Phillips, M. 1993. *Environmental impacts of tropical inland aquaculture*. In: Pullin, R.S.V.; Rosenthal, H.; Maclean, J.L. eds. *Environment and aquaculture in developing countries*. ICLARM, Conference Proceedings 31.
- Beveridge, M.C.M.; Phillips, M.J.; Macintosh, D.J. 1997. Aquaculture and the environment: the supply and demand for environmental goods and services by Asian aquaculture and the implications for sustainability. *Aquaculture Research* 28 (10): 797–807. <http://dx.doi.org/10.1046/j.1365-2109.1997.00944.x>
- Bharucha, Z.; Pretty, J. 2011. The roles and values of wild foods in agricultural systems. *Philosophical Transactions of the Royal Society B* 365: 2913–2926. <http://dx.doi.org/10.1098/rstb.2010.0123>
- Bhatia, R.; Falkenmark, M. 1992. *Water resource policies and the urban poor: innovative approaches and policy imperatives. A background paper for the working group on water and sustainable urban development*. International Conference on Water and the Environment, 26–31 January, Dublin, Ireland.
- Bindraban, P.S.; Bulte, E.; Conijn, S. 2009a. Can biofuels be sustainable by 2020? *Agricultural Systems* 101 (3): 197–199. <http://dx.doi.org/10.1016/j.agsy.2009.06.005>
- Bindraban, P.; Bulte E.; Giller, K.; Meinke, H.; Mol, A.; van Oort, P.; Oosterveer, P.; van Keulen, H.; Wollni, M. 2009b. *Beyond competition – Pathways for Africa's agricultural development*. Plant Research International, Wageningen UR, Report 242. <http://edepot.wur.nl/8400>
- Bindraban, P.; Conijn, S.; Jongschaap, R.; Jing Qi; Hanjira, M.; Kijne, J.; Steduto, P.; Udo, H.; Oweis, T.; de Boer, I. 2010a. Enhancing use of rainwater for meat production on grasslands – an ecological opportunity towards food security. Paper presented to the *International Fertiliser Society, Cambridge, 10 December 2010. Proceedings 686*. Leek: International Fertiliser Society.
- Bindraban, P.S.; Jongschaap, R.E.E.; van Keulen, H. 2010b. Resource use in food production with special emphasis on water. In: Sonesson, U.; Berlin, J.; Ziegler, F. eds. *Environmental assessment and management in the food industry*. Woodhead Publishing Limited, Cambridge, UK, 560 pp.
- Bindraban, P.S.; Verhagen, A.; Uithol, P.W.J.; Hensira, P. 1999. *A land quality indicator for sustainable land management: the yield gap*. Report 106. Research Institute for Agrobiology and Soil Fertility (AB-DLO).
- Biswas, A.K. 2004. Integrated Water Resources Management: a reassessment. A Water Forum Contribution. *Water International* 29 (2): 248–256. <http://dx.doi.org/10.1080/02508060408691775>
- Black, C.R.; Ong, C.K. 2000. Utilization of light and water in tropical agriculture. *Agricultural and Forest Meteorology* 104 (1): 25–47. [http://dx.doi.org/10.1016/S0168-1923\(00\)00145-3](http://dx.doi.org/10.1016/S0168-1923(00)00145-3)

- Black, M.; GWP – Global Water Partnership. 2003. *Poverty reduction and IWRM*, Stockholm: Global Water Partnership Technical Committee.
- Boelee, E.; Laamrani, H.; van der Hoek, W. 2007. Multiple use of irrigation water for improved health in dry regions of Africa and south-Asia. *Irrigation and Drainage* 56: 43–51. <http://dx.doi.org/10.1002/ird.287>
- Boelee, E.; Madsen, H. 2006. Irrigation and schistosomiasis in Africa: ecological aspects. IWRM Research Report 99. Colombo, Sri Lanka: International Water Management Institute. <http://dx.doi.org/10.3910/2009.099>
- Boisvert, R.N.; Chang, H.H. 2006. *Multifunctional agricultural policy, reduced domestic support, and liberalized trade: An empirical assessment for Taiwanese rice*. Comprehensive Assessment of Water Management in Agriculture Research Report 14. Colombo, Sri Lanka: International Water Management Institute. 44p. <http://dx.doi.org/10.3910/2009.379>
- Bonachela, S.; Orgaz, F.; Fereres, E. 1995. Winter cereals grown for grain and for the dual purpose of forage plus grain II. Water use and water-use efficiency. *Field Crops Research* 44 (1): 13–24. [http://dx.doi.org/10.1016/0378-4290\(95\)00046-3](http://dx.doi.org/10.1016/0378-4290(95)00046-3)
- Boody, G.; Vondracek, B.; Andow, D.A.; Krinke, M.; Westra, J.; Zimmerman, J.; Welle, P. 2005. Multifunctional agriculture in the United States. *BioScience* 55 (1): 27–38. <http://www.danielcharles.com/multi-functional%20ag%20study.pdf>
- Bos, M.G.; Nugteren, J. 1974. *On irrigation efficiencies*. ILRI Publication 19, International Institute for Land Reclamation and Improvement (ILRI), Wageningen, The Netherlands: 138 pp
- Bossio, D. 2009. Livestock and water: understanding the context based on the 'Comprehensive Assessment of Water Management in Agriculture'. *The Rangeland Journal* 31: 179–186. <http://dx.doi.org/10.1071/RJ09001>
- Bossio, D.; Geheb K. eds. 2008. *Conserving land, protecting water*. Comprehensive Assessment of Water Management in Agriculture Series 6. Wallingford, UK: CAB International; Colombo, Sri Lanka: International Water Management Institute (IWRM); Colombo, Sri Lanka: CGIAR Challenge Program on Water and Food. http://www.iwmi.cgiar.org/Publications/CABI_Publications/CA_CABI_Series/Conserving_Land_Protecting_Water/protected/9781845933876.pdf
- Bossio, D.; Noble A.; Molden D.; Nangia V. 2008. Land degradation and water productivity in agricultural landscapes. In: Bossio, D.; Geheb, K. eds. *Conserving land, protecting water*. Wallingford, UK: CAB International; Colombo, Sri Lanka: International Water Management Institute (IWRM); Colombo, Sri Lanka: CGIAR Challenge Program on Water and Food. pp 20-32. http://www.iwmi.cgiar.org/Publications/CABI_Publications/CA_CABI_Series/Conserving_Land_Protecting_Water/protected/9781845933876.pdf
- Bostock, J.; McAndrew, B.; Richards, R.; Jauncey, K.; Telfer, T.; Lorenzen, K.; Little, D.; Ross, L.; Handisyde, N.; Gatward, I.; Corner, R. 2010. Aquaculture: global status and trends. *Philosophical Transactions of the Royal Society B* 365: 2897–2912. <http://dx.doi.org/10.1098/rstb.2010.0170>
- Brauman, K.A.; Daily, G.C.; Duarte, T.K.; Mooney, H.A. 2007. The nature and value of ecosystem services: an overview highlighting hydrologic services. *Annual Review of Environmental Resources* 32: 67–98. <http://dx.doi.org/10.1146/annurev.energy.32.031306.102758>
- Briscoe, J.; Malik, R.P.S. 2006. *India's Water Economy: Bracing for a turbulent future*, Oxford University Press, USA.
- Brits, J.; van Rooyen, M.W.; van Rooyen, N. 2002. Ecological impact of large herbivores on the woody vegetation at selected watering points on the eastern basaltic soils in the Kruger National Park. *African Journal of Ecology* 40 (1): 53–60. <http://dx.doi.org/10.1046/j.0141-6707.2001.00344.x>
- Brooks, D.; Wolfe, S. 2007. Institutional assessment for effective WDM implementation & capacity development. WDM Research Series: Working Paper No. 4. Cairo: Regional Water Demand Management in the Middle East & North Africa (WaDImena). http://www.idrc.ca/uploads/user-S/1218971321112186454001RS4_Effective_WDM_institutions_ENG.pdf
- Brugere C.; McAndrew K.; Bulcock P. 2001. Does cage aquaculture address gender goals in development? Results of a case study in Bangladesh. *Aquaculture Economics & Management* 5 (3/4): 179–189. <http://dx.doi.org/10.1080/13657300109380286>
- Brummett, R.E.; Lemoalle, J.; Beveridge, M.C.M. 2010. Can water productivity metrics guide allocation of freshwater to inland fisheries? *Knowledge and Management of Aquatic Ecosystems* 399: 1–7. <http://dx.doi.org/10.1051/kmae/2010026>
- Bunn, S.E.; Arthington, A.H. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management* 30 (4): 492–507. <http://dx.doi.org/10.1007/s00267-002-2737-0>
- Bunting, S.W. 2001. Appropriation of environmental goods and services by aquaculture: a re-assessment employing the ecological footprint methodology and implications for horizontal integration. *Aquaculture Research* 32: 605–609. <http://dx.doi.org/10.1046/j.1365-2109.2001.00563.x>
- Bunting, S.W. 2007. Confronting the realities of wastewater aquaculture in peri-urban Kolkata with bioeconomic modelling. *Water Research* 41 (2): 499–505. <http://dx.doi.org/10.1016/j.watres.2006.10.006>

- Bunting SW (in press) *Principles of sustainable aquaculture: promoting social, economic and environmental resilience*. Earthscan, UK.
- Bunting, S.W.; Shpigel, M. 2009. Evaluating the economic potential of horizontally integrated land-based marine aquaculture. *Aquaculture* 294 (1–2): 43–51. <http://dx.doi.org/10.1016/j.aquaculture.2009.04.017>
- Burke, E.J.; Brown, S.J.; Christidis, N. 2006. Modeling the recent evolution of global drought and projections for the twenty-first century with the Hadley Centre climate model. *Journal of Hydrometeorology* 7 (5): 1113–1125. <http://dx.doi.org/10.1175/JHM544.1>
- Butt, B. 2010. Seasonal space-time dynamics of cattle behavior and mobility among Maasai pastoralists in semi-arid Kenya. *Journal of Arid Environments* 74 (3): 403–413. <http://dx.doi.org/10.1016/j.jaridenv.2009.09.025>
- CA (Comprehensive Assessment). 2007. *Water for food, water for life: a comprehensive assessment of water management in agriculture*. London: Earthscan, Colombo: International Water Management Institute. <http://www.iwmi.cgiar.org/assessment/Publications/books.htm>
- Cai, K.; Chen, F.; Cui, K.; Gao, M.; Fu, J.; Gan, L.; He, H.; Jiang, B.; Luo, S.; Liu, Y.; Li, H.; Shang, R.; Tong, X.; Wang, Q.; Wang, W.; Ye, Y.; Zhang, J.; Zhao, H.; Zhuang, X. 2010. HighARCS situation analysis report – China site. South China Agricultural University, China.
- Cairns, J. 1995. Ecosystem services: an essential component of sustainable use. *Environmental Health Perspectives* 103 (6): 534. <http://ehp.niehs.nih.gov/docs/1995/103-6/editorial.html>
- Cannon, T.; Twigg, J.; Rowall, J. 2003. Social vulnerability, sustainable livelihoods and disasters, report for DFID's Conflict and Humanitarian Assistance Department (CHAD) and Sustainable Livelihoods Office. <http://www.proventionconsortium.org/themes/default/pdfs/CRA/DFIDSocialvulnerability.pdf>
- Cárcamo, J.C.; Opperman, J.; Esselman, P.; Avalos, R.; Silk, N. (no date) *Developing environmental flow recommendations based on traditional knowledge*. PowerPoint Presentation. The Nature Conservancy. http://www.riversymposium.com/2007_Presentations/C2G_C%3A1rcamo.pdf
- Carpenter, S.R.; Bennett, E.M.; Peterson, G.D. 2006. Scenarios for ecosystem services: an overview. *Ecology and Society* 11 (1): 29. <http://www.ecologyandsociety.org/vol11/iss1/art29/>
- Carpenter, S.R.; Mooney, H.A.; Agard, J.; Capistrano, D.; DeFries, R.S.; Díaz, S.; Dietz, T.; Duraiappah, A.K.; Oteng-Yeboah, A.; Pereira, H.M.; Perrings, C.; Reid, W.V.; Sarukhan, J.; Scholes, R.J.; Whyte A. 2009. Science for managing ecosystem services: beyond the Millennium Ecosystem Assessment. *Proceedings of the National Academy of Sciences* 106 (5): 1305–1312. <http://dx.doi.org/10.1073/pnas.0808772106>
- Carroll, Z.L.; Bird, S.B.; Emmett, B.A.; Reynolds, B.; Sinclair, F.L. 2004. Can tree shelterbelts on agricultural land reduce flood risk? *Soil Use and Management* 20 (3): 357–359. <http://dx.doi.org/10.1111/j.1475-2743.2004.tb00381.x>
- Cecchi, G.; Wint, W.; Shaw, A.; Marletta, A.; Mattioli, R.; Robinson, T. 2010. Geographic distribution and environmental characterization of livestock production systems in Eastern Africa. *Agriculture, Ecosystems & Environment* 135 (1–2): 98–110. <http://dx.doi.org/10.1016/j.agee.2009.08.011>
- Chapagain, A.; Hoekstra, A. 2003. Virtual water trade: a quantification of virtual water flows between nations in relation to international trade of livestock and livestock products. In Hoekstra, A.Y. ed. *Virtual water trade. Proceedings of the international expert meeting on virtual water trade*. Value of Water Research Report Series 12. Delft, Netherlands: United Nations Educational, Scientific and Cultural Organization, Institute for Water Education. <http://www.waterfootprint.org/Reports/Report12.pdf>
- Chapagain, A.K.; Hoekstra, A.Y. 2008. The global component of freshwater demand and supply: an assessment of virtual water flows between nations as a result of trade in agricultural and industrial products. *Water International* 33 (1): 19–32. <http://dx.doi.org/10.1080/02508060801927812>
- Chéné J-M. 2009. Integrated Water Resources Management: theory versus practice. *Natural Resources Forum* 33 (1): 2–5. <http://dx.doi.org/10.1111/j.1477-8947.2009.01203.x>
- Chorus, I.; Bartram, J. 1999. *Toxic cyanobacteria in water. A guide to their public health consequences, monitoring, and management*. London: F & FN Spon and World Health Organisation.
- Cirera, X.; Masset, E. 2010. Income distribution trends and future food demand. *Philosophical Transactions of the Royal Society B* 365: 2821–2834. <http://dx.doi.org/10.1098/rstb.2010.0164>
- Clarke, B. 2004. *High-hopes for post-harvest. a new look at village-scale crop processing*. FAO Diversification booklet 4. Agricultural Support Systems Division. Rome: Food and Agriculture Organization of the United Nations. <http://www.fao.org/docrep/006/y5111e/y5111e00.htm>
- Clement, F.; Haileslassie, A.; Ishaq, S.; Blummel, M.; Murty, M.; Samad, M.; Dey, S.; Das, H.; Khan, M.A. 2011. Enhancing water productivity for poverty alleviation: role of capitals and institutions in the Ganga Basin. *Experimental Agriculture* 47 (S1): 133–151. <http://dx.doi.org/10.1017/S0014479710000827>
- Clemings, R. 1996. *Mirage: the false promise of desert agriculture*. New York: Random House

- Conservation Fund. 2008. Garcia River forest earns top carbon credit verification. <http://www.conservationfund.org/node/750> (accessed 06Oct2010).
- Cook, S.E.; Andersson, M.S.; Fisher, M.J. 2009. Assessing the importance of livestock water use in basins. *The Rangeland Journal* 31: 195–205. <http://dx.doi.org/10.1071/RJ09007>
- Cooper, P.J.M.; Leakey, R.R.B.; Rao, M.R.; Reynolds, L. 1996. Agroforestry and the mitigation of land degradation in the humid and sub-humid tropics. *Experimental Agriculture* 32: 235–290. <http://dx.doi.org/10.1017/S0014479700026223>
- Costanza, R.; d'Arge, R.; deGroot, R.; Farber, S.; Grasso, M.; Hannon, B.; Limburg, K.; Naeem, S.; O'Neill, R. V.; Paruelo, J.; Raskin, R. G.; Sutton, P.; van den Belt, M. 1997. The value of the world's ecosystem services and natural capital. *Nature* 387: 253–260. <http://dx.doi.org/10.1038/387253a0>
- Daily, G. 1997. *Nature's services*. Island Press, Washington, D.C., USA.
- Dale, V.H.; Polasky, S. 2007. Measure of the effects of agricultural practices on ecosystem services. *Ecological Economics* 64 (2): 286–296. <http://dx.doi.org/10.1016/j.ecolecon.2007.05.009>
- Danin, A. 1983 *Desert vegetation of Israel and Sinai*, Cana Publishing, Jerusalem
- Dasgupta, P. 2010. Nature's role in sustaining economic development. *Philosophical Transactions of the Royal Society B* 365: 5–11. <http://dx.doi.org/10.1098/rstb.2009.0231>
- de Fraiture, C.; Cai, X.; Amarasinghe, U; Rosegrant, M.; Molden, D. 2004. *Does international cereal trade save water? The impact of virtual water trade on global water use*. Comprehensive Assessment of Water Management in Agriculture Research Report 004. Colombo, Sri Lanka: International Water Management Institute (IWMI), Comprehensive Assessment Secretariat. 32p. <http://dx.doi.org/10.3910/2009.389>
- de Fraiture, C.; Giordano, M.; Yongsong Liao. 2008. Biofuels and implications for agricultural water use: blue impacts of green energy. *Water Policy* 10 (S1): 67–81. <http://dx.doi.org/10.2166/wp.2008.054>
- de Fraiture, C.; Wichelns, D.; Rockström, J.; Kemp-Benedict, E. et al. 2007. Looking ahead to 2050: scenarios of alternative investment approaches. In: CA. *Water for food, water for life: A comprehensive assessment of water management in agriculture*. London, UK: Earthscan; Colombo, Sri Lanka: International Water Management Institute (IWMI). pp 91–145. <http://www.iwmi.cgiar.org/assessment/Publications/books.htm>
- de Fraiture, C.; Wichelns, D. 2010. Satisfying future demands for agriculture. *Agricultural Water Management* 97 (4): 502–511. <http://dx.doi.org/10.1016/j.agwat.2009.08.008>
- de Vries, M.E.; Rodenburg, J.; Bado, B.V.; Sow, A.; Leffenaar, P.; Giller, K.E. 2010. Rice production with less irrigation water is possible in a Sahelian environment. *Field Crops Research* 116 (1–2): 154–164. <http://dx.doi.org/10.1016/j.fcr.2009.12.006>
- de Wit, M.; Stankiewicz, J. 2006. Changes in surface water supply across Africa with predicted climate change. *Science* 311 (5769): 1917–1921. <http://dx.doi.org/10.1126/science.1119929>
- Dent D.; Kauffman J. H. 2007. Green water credits for rainwater management by farmers. *Global Water News* 4: 4–6. http://www.gwsp.org/fileadmin/downloads/GWSP_NL4_Internetversion.pdf
- Department of Conservation. 2007. The economic values of Whangamarino Wetland. DOCDM-141075. <http://www.doc.govt.nz/publications/conservation/threats-and-impacts/benefits-of-conservation/the-economic-values-of-whangamarino-wetland/>
- Descheemaeker, K.; Amede, T.; Haileslassie, A. 2010a. Improving water productivity in mixed crop-livestock farming systems of sub-Saharan Africa. *Agricultural water management* 97 (5): 579–586. <http://dx.doi.org/10.1016/j.agwat.2009.11.012>
- Descheemaeker, K.; Mapedza, E.; Amede, T.; Ayalneh, W. 2010b. Effects of integrated watershed management on livestock water productivity in water scarce areas in Ethiopia. *Physics and Chemistry of the Earth* 35 (13–14): 723–729. <http://dx.doi.org/10.1016/j.pce.2010.06.006>
- Descheemaeker, K.; Raes, D.; Nyssen, J.; Poesen, J.; Haile M.; Deckers, J. 2009. Changes in water flows and water productivity upon vegetation regeneration on degraded hillslopes in northern Ethiopia: a water balance modelling exercise. *The Rangeland Journal* 31: 237–249. <http://dx.doi.org/10.1071/RJ09010>
- Diabaté, A.; Baldet, T.; Chandre, F.; Akogbeto, M.; Darriet F.; Brengues C.; Guillet, P.; Hemingway, J.; Small, G.J.; Hougard, J.M. 2002. The role of agricultural use of insecticides in resistance to pyrethroids in *Anopheles gambiae* sl in Burkina Faso. *American Journal of Tropical Medicine and Hygiene* 67 (6): 617–622. <http://www.ajtmh.org/cgi/content/abstract/67/6/617>
- Diuk-Wasser, M.A.; Touré, M.B.; Dolo, G.; Bagayoko, M.; Sogoba, N.; Sissoko, I.; Traoré, S.F.; Taylor, C.E. 2007. Effect of rice cultivation patterns on malaria vector abundance in rice-growing villages in Mali. *American Journal of Tropical Medicine and Hygiene* 76 (5): 869–874. <http://www.ajtmh.org/cgi/content/abstract/76/5/869>
- Dixon, J.; Gulliver, A. 2001. *Farming systems and poverty. improving farmers' livelihoods in a changing world*. FAO, Rome; World Bank, Washington DC. <http://www.fao.org/DOCREP/003/Y1860E/y1860e00.htm#TopOfPage>

- DOF (Department of Fisheries). 2009. *Fishery statistical yearbook of Bangladesh 2007–2008*. Fisheries Resources Survey System, Department of Fisheries, Bangladesh.
- Dong-Oh Cho. 2007. The evolution and resolution of conflicts on Saemangeum Reclamation Project. *Ocean & Coastal Management* 50 (11–12): 930–944. <http://dx.doi.org/10.1016/j.ocecoaman.2007.02.005>
- Drechsel, P.; Giordano, M.; Gyiele, L. 2004. *Valuing nutrients in soil and water: concepts and techniques with examples from IWMI studies in the developing world*. IWMI Research Report 82. Colombo, Sri Lanka: International Water Management Institute. <http://www.dx.doi.org/10.3910/2009.083>
- Drechsel, P.; Scott, C.A.; Raschid-Sally, L.; Redwood, M.; Bahri, A. 2010. *Wastewater irrigation and health: Assessing and mitigating risk in low-income countries*. London: Earthscan, with the International Water Management Institute and the International Development Research Centre. http://www.iwmi.cgiar.org/Publications/books/pdf/Wastewater_Irrigation_and_Health_book.pdf
- Dugan P, Sugunan V.V.; Welcomme R.L.; Bene C.; Brummett R.E.; Beveridge M.C.M. et al. 2007. Inland fisheries and aquaculture. In: CA. *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. Earthscan, London, and International Water Management Institute, Colombo. pp 459–483. <http://www.iwmi.cgiar.org/assessment/Publications/books.htm>
- Dung, L.C.; Hoanh, C.T.; Le Page, C.; Bousquet, F.; Gajeseni, N. 2009. Facilitating dialogue between aquaculture and agriculture; lessons from role playing games with farmers in the Mekong Delta, Vietnam. *Water Policy* 11 (S1): 80–93. <http://dx.doi.org/10.2166/wp.2009.105>
- DWAF (Department of Water Affairs and Forestry). 1997. White paper on a National Water Policy for South Africa. Department of Water Affairs and Forestry, Pretoria, South Africa. <http://www.africanwater.org/wp3.htm>
- eFlowNet. 2010. *Global Environmental Flows Network*. <http://www.eflownet.org>
- Ehrlich, P.; Mooney, H. 1983. Extinction, substitution, and ecosystem services. *BioScience* 33 (4): 248–254. <http://www.jstor.org/stable/1309037>
- Ellis, E.C.; Ramankutty, N. 2008. Putting people in the map: anthropogenic biomes of the world. *Frontiers in Ecology and the Environment* 6 (8): 439–447. <http://dx.doi.org/10.1890/070062>
- Ellis, J.E.; Swift, D.M. 1988. Stability of African pastoral ecosystems: alternate paradigms and implications for development. *Journal of Range Management* 41: 450–459.
- Emerton, L. (ed) 2005. Values and rewards: counting and capturing ecosystem water services for sustainable development. IUCN Water, Nature and Economics Technical Paper No. 1. Colombo, IUCN – The World Conservation Union, Ecosystems and Livelihoods Group Asia. http://cmsdata.iucn.org/downloads/2005_047.pdf
- Enters, T. 1998. Methods for the economic assessment of the on- and off-site impact of soil erosion. IBSRAM Issues in Sustainable Land Management No. 2. Bangkok: International Board for Soil Research and Management. http://www.landecon.cam.ac.uk/up211/B06/reading/session3/enters_1998.pdf
- EPA (Environmental Protection Agency) 2008. Guidelines for preparing economic analyses, external draft edition, National Centre for Environmental Economics, Office of Policy Economics and Innovation, US Environmental Protection Agency. <http://yosemite.epa.gov/EE/epa/eed.nsf/pages/Guidelines.html>
- Erlanger, T.E.; Keiser, J.; Caldas De Castro, M.; Bos, R.; Singer, B.H.; Tanner, M.; Utzinger, J. 2005. Effect of water resource development and management on lymphatic filariasis, and estimates of populations at risk. *American Journal of Tropical Medicine and Hygiene* 73: 523–533. <http://www.ajtmh.org/cgi/content/full/73/3/523>
- Even-Ari, M.; Shanan, L.; Tadmor, N. 1982. *Negev: the challenge of a desert*, Harvard University Press
- Fagi, A.M.; Kartaatmadja. 2002. Gogorancah Rice in Indonesia: a traditional method in the modern era. In Pandey, S.; Mortimer, M.; Wade, L.; Tuong, T.P.; Lopez, K.; Hardy, B. eds. *Direct seeding research strategies and opportunities*. Los Banos, Philippines: International Rice Research Institute
- Falconer, I. R. 2001. Toxic cyanobacterial bloom problems in Australian waters: risks and impacts on human health. *Phycologia* 40 (3): 228–233. <http://dx.doi.org/10.2216/i0031-8884-40-3-228.1>
- Falkenmark, M. 2003a. Freshwater as shared between society and ecosystems: from divided approaches to integrated challenges. *Philosophical Transactions of the Royal Society B* 358: 2037–2049. <http://dx.doi.org/10.1098/rstb.2003.1386>
- Falkenmark, M. 2003b. Water management and ecosystems: *Living with change*. GWP TEC background papers 9. Stockholm, Sweden: Global Water Partnership (GWP) 50p. http://www.cawater-info.net/bk/iwrm/pdf/tec_paper9_e.pdf
- Falkenmark, M. 2008. Water and sustainability: a reappraisal. *Environment Magazine* March/April. <http://www.environmentmagazine.org/Archives/Back%20Issues/March-April%202008/Falkenmark-full.html>
- Falkenmark, M.; Finlayson, C.M.; Gordon, L.J. et al. 2007. Agriculture, water, and ecosystems: avoiding the costs of going too far. In: CA. *Water for food, water for life: a comprehensive assessment of water management in agriculture*. Earthscan, London, and International Water Management Institute, Colombo. pp 233–277. <http://www.iwmi.cgiar.org/assessment/Publications/books.htm>

- Falkenmark, M.; Molden, D. 2008. Wake up to realities of river basin closure. *International Journal of Water Resources Development* 24 (2): 201–215. <http://dx.doi.org/10.1080/07900620701723570>
- Falkenmark, M.; Rockström, J. 2004. *Balancing water for humans and nature*. London: Earthscan.
- FAO. 1995. Sustainability issues in agricultural and rural development policies. Trainer's Manual, Vol. 1. Rome: Food and Agriculture Organization of the United Nations.
- FAO. 2006. *Global Forest Resources Assessment 2005, progress towards sustainable forest management*. FAO Forestry Paper 147. Rome: Food and Agriculture Organization of the United Nations. <http://www.fao.org/forestry/fra2005>
- FAO. 2007a. Coping with water scarcity: challenges of the twenty-first century. World Water day 2007. Rome: Food and Agriculture Organization of the United Nations. <http://www.fao.org/nr/water/docs/escarcity.pdf>
- FAO. 2007b. *The State of Food and Agriculture: Paying Farmers for Environmental Services*. Rome: Food and Agriculture Organization of the United Nations. <http://www.fao.org/docrep/010/a1200e/a1200e00.htm>
- FAO. 2007c. Gridded livestock of the world 2007, by Wint, G.R.W.; Robinson, T.P. Rome: Food and Agriculture Organization of the United Nations, 131 pages. <ftp://ftp.fao.org/docrep/fao/010/a1259e/a1259e01.pdf>
- FAO. 2008a. Water for agriculture and energy in Africa: resources and challenges in the context of climate change. *African Union Ministerial meeting*. Sirte, Libyan Arab Jamahiriya, 15–17 December 2008. http://www.sirtewaterandenergy.org/docs/2009/Sirte_2008_BAK_2.pdf
- FAO. 2008b. *The state of food and agriculture 2008. Biofuels: prospects, risks and opportunities*. Rome: Food and Agriculture Organization of the United Nations. <ftp://ftp.fao.org/docrep/fao/011/i0100e/i0100e.pdf>
- FAO. 2009a. *The State of World Fisheries and Aquaculture 2008*. Rome: Food and Agriculture Organization of the United Nations, Rome, Italy. <http://www.fao.org/docrep/011/i0250e/i0250e00.htm>
- FAO. 2009b. *Global Agriculture towards 2050*. High Level Expert Forum – How to Feed the World in 2050. HLEF2050 Issues briefs. <http://www.fao.org/wsfs/forum2050/wsfs-forum/en/>
- FAO. 2009c. *Investment*. High Level Expert Forum – How to Feed the World in 2050. HLEF2050 Issues briefs. <http://www.fao.org/wsfs/forum2050/wsfs-forum/en/>
- FAO. 2009d. *Coping with a changing climate: considerations for adaptation and mitigation in agriculture*. Rome: Food and Agriculture Organization of the United Nations. <http://www.fao.org/docrep/012/i1315e/i1315e00.htm>
- FAO. 2010. *The state of food insecurity in the world. Addressing food insecurity in protracted crises*. Rome: Food and Agriculture Organization of the United Nations. <http://www.fao.org/publications/sofi/en/>
- FAO, IFAD, ILO. 2010. *Gender dimensions of agricultural and rural employment: Differentiated pathways out of poverty. Status, trends and gaps*. Rome: Food and Agricultural Organization of the United Nations, International Fund for Agricultural Development, International Labour Office. <http://www.fao.org/docrep/013/i1638e/i1638e00.htm>
- FAO Netherlands. 2005. Make it happen. Report on the conference on water for food and ecosystems. The Hague, January 31 – February 4, 2005. http://www.fao.org/ag/wfe2005/conference08_en.htm
- FAO, PAR (Platform for Agrobiodiversity Research). 2011. Biodiversity for food and agriculture. Contributing to food security and sustainability in a changing world. Outcomes of an expert workshop held by FAO and the Platform on Agrobiodiversity Research from 14–16 April 2010 in Rome, Italy. Rome : Food and Agricultural Organization of the United Nations, Platform for Agrobiodiversity Research. http://agrobiodiversityplatform.org/files/2011/04/PAR-FAO-book_lr.pdf
- Faures, J.M.; Svendsen, M.; Turral, H. et al. 2007. Reinventing irrigation. In CA. *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. Earthscan, London, and International Water Management Institute, Colombo. pp.353–394. <http://www.iwmi.cgiar.org/assessment/Publications/books.htm>
- Ferraris, R.; Sinclair, D.F. 1980. Factors affecting the growth of *Pennisetum purpureum* in the wet tropics. II. Uninterrupted growth. *Australian Journal of Agricultural Research* 31(5): 915–925. <http://dx.doi.org/10.1071/AR9800915>
- Finlayson, C.M.; D'Cruz, R. 2005. Inland water system. In: Hassan, R.; Scholes, R.; Ash, N. eds. *Ecosystem and human well-being: current state and trends: findings of the Conditions and Trends Working Group*. Island Press, Washington, DC. <http://www.maweb.org/documents/document.289.aspx.pdf>
- Finlayson, C.M.; Davidson, N.C.; Spiers AG.; Stevenson, N.J. 1999. Global wetland inventory – current status and future priorities. *Marine and Freshwater Research* 50(8): 717–727. <http://dx.doi.org/10.1071/MF99098>
- Fischer, G.; Van Velthuizen, H.; Hizsnyik, E.; Wiberg, D. 2009. *Potentially obtainable yields in the semi-arid tropics*. Global Theme on Agroecosystems Report 54, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics. http://www.iwmi.cgiar.org/assessment/files_new/publications/ICRISATReport_54.pdf

- Fischlin, A.; Midgley, G.F.; Price, J.T.; Leemans, R.; Gopal, B.; Turley, C.; Rounsevell, M.D.A.; Dube, O.P.; Tarazona, J.; Velichko, A.A. 2007. Ecosystems, their properties, goods, and services. In Parry, M.L.; Canziani, O.F.; Palutikof, J.P.; van der Linden, P.J.; Hanson, C.E. (eds) *Climate change 2007: impacts, adaptation and vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, p211–272. Cambridge: Cambridge University Press.
http://www.ipcc.ch/publications_and_data/ar4/wg2/en/contents.html
- Foley, J. A.; DeFries, R.; Asner, G. P.; Barford, C.; Bonan, G.; Carpenter, S. R.; Chapin, F. S.; Coe, M. T.; Daily, G. C.; Gibbs, H. K.; Helkowski, J. H.; Holloway, T.; Howard, E. A.; Kucharik, C. J.; Monfreda, C.; Patz, J. A.; Prentice, I. C.; Ramankutty, N.; Snyder, P. K. 2005. Global consequences of land use. *Science* 309 (5734): 570–574. <http://dx.doi.org/10.1126/science.1111772>
- Folke, C. 2006. Resilience: the emergence of a perspective for social–ecological systems analysis. *Global Environmental Change* 16 (3): 253–267. <http://dx.doi.org/10.1016/j.gloenvcha.2006.04.002>
- Folke, C.; Kautsky, N.; Berg, H.; Jansson, A.; Troell, M. 1998. The ecological footprint concept for sustainable seafood production: a review. *Ecological Applications* 8: S63–S71.
[http://dx.doi.org/10.1890/1051-0761\(1998\)8\[S63:TEFCFS\]2.0.CO;2](http://dx.doi.org/10.1890/1051-0761(1998)8[S63:TEFCFS]2.0.CO;2)
- Foresight. The Future of Food and Farming (2011) *Final Project Report*. The Government Office for Science, London.
<http://www.bis.gov.uk/foresight/our-work/projects/current-projects/global-food-and-farming-futures/reports-and-publications>
- Francis, C.A.; Porter, P. 2011. Ecology in sustainable agriculture practices and systems. *Critical Reviews in Plant Sciences* 30: 64–73. <http://dx.doi.org/10.1080/07352689.2011.554353>
- French, R.J.; Schultz, J.E. 1984a. Water use efficiency of wheat in a Mediterranean type environment. I. The relation between yield, water use and climate. *Australian Journal of Agricultural Research* 35 (6): 743–764.
<http://dx.doi.org/10.1071/AR9840743>
- French, R.J.; Schultz, J.E. 1984b. Water use efficiency of wheat in a Mediterranean type environment. II. Some limitations to efficiency. *Australian Journal of Agricultural Research* 35 (6): 765–775.
<http://dx.doi.org/10.1071/AR9840765>
- Fresco, L.O. 2005. Water, food and ecosystems in Africa. *Spotlight*. Rome: Food and Agriculture Organization of the United Nations. <http://www.fao.org/ag/magazine/0502sp1.htm>
- Fundación Defensores de la Naturaleza. 2010. Reserva de Biosfera Sierra de las Minas...
http://www.defensores.org.gt/index.php?option=com_content&view=article&id=2&Itemid=2#minas (accessed 06Oct2010).
- Gandini, G.; Villa, E. 2003. Analysis of the cultural value of local livestock breeds: a methodology. *Journal of Animal Breeding and Genetics* 120 (1): 1–11. <http://dx.doi.org/10.1046/j.1439-0388.2003.00365.x>
- Gardner, T.A.; Barlow, J.; Chazdon, R.; Ewers, R.M.; Harvey, C.A.; Peres, C.A.; Sodhi, N.S. 2009. Prospects for tropical forest biodiversity in a human-modified world. *Ecology Letters* 12 (6): 561–582.
<http://dx.doi.org/10.1111/j.1461-0248.2009.01294.x>
- Garrity DP (2004) Agroforestry and the achievement of the Millennium Development Goals. *Agroforestry Systems* 61 (1): 5–17. <http://dx.doi.org/10.1023/B:AGFO.0000028986.37502.7c>
- Garrity, D.P.; Akinnifesi, F.K.; Ajayi, O.C.; Weldesemayat, S.G.; Mowo, J.G.; Kalinganire, A.; Larwanou, M.; Bayala, J. 2010. Evergreen agriculture: a robust approach to food security in Africa. *Food Security* 2(3): 197–214. <http://dx.doi.org/10.1007/s12571-010-0070-7>
- Gebreselassie, S.; Peden, D.; Haileslassie, A.; Mpairwe, D. 2009. Factors affecting livestock water productivity: animal scale analysis using previous cattle feeding trials in Ethiopia. *The Rangeland Journal* 31: 251–258.
<http://dx.doi.org/10.1071/RJ09011>
- Geerts, S.; Raes, D. 2009. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agricultural Water Management* 96 (9): 1275–1284. <http://dx.doi.org/10.1016/j.agwat.2009.04.009>
- Geist, H.J.; Lambin, E.F. 2004. Dynamic causal patterns of desertification. *BioScience* 54 (9): 817–829.
[http://dx.doi.org/10.1641/0006-3568\(2004\)054\[0817:DCPOD\]2.0.CO;2](http://dx.doi.org/10.1641/0006-3568(2004)054[0817:DCPOD]2.0.CO;2)
- German, L.; Mansoor, H.; Alemu, G.; Mazengia, W.; Amede, T.; Stroud, A. 2007. Participatory integrated watershed management: Evolution of concepts and methods in an ecoregional program of the eastern African highlands. *Agricultural systems* 94 (2): 189–204. <http://dx.doi.org/10.1016/j.agry.2006.08.008>
- Gichuki, F.N.; Kodituwakku, D.C.; Nguyen-Khoa, S.; Hoanh, C.T. 2009. Cross-scale trade-offs and synergies in aquaculture, water quality and environment: research issues and policy implications. *Water Policy* 11 (S1): 1–12. <http://dx.doi.org/10.2166/wp.2009.100>
- Giordano, M.; Villholth, K. eds. 2007. *The agricultural groundwater revolution: opportunities and threats to development*. Comprehensive Assessment of Water Management in Agriculture Series 3. Wallingford, UK: CAB International. 419p. http://www.iwmi.cgiar.org/Publications/CABI_Publications/CA_CABI_Series/Ground_Water/protected/index_1845931726.htm

- Gleick, P.H. ed. 1993. *Water in crisis: a guide to the world's fresh water resources*. Oxford University Press, New York.
- Gleick, P.H. 2003. Water Use. *Annual Review of Environment and Resources* 28: 275–314. <http://dx.doi.org/10.1146/annurev.energy.28.040202.122849>
- Global Water Partnership (GWP). 2001. Framework for Action (FFA). Stockholm, Sweden.
- Godfray, H.C.J.; Beddington, J.R.; Crute, I.R.; Haddad, L.; Lawrence, D.; Muir, J.F.; Pretty, J.; Robinson, S.; Thomas, S.M.; Toulmin, C. 2010a. Food security: the challenge of feeding 9 billion people. *Science* 327 (5967): 812–818. <http://dx.doi.org/10.1126/science.1185383>
- Godfray, H.C.J.; Crute, I.R.; Haddad, L.; Lawrence, D.; Muir, J.F.; Nisbett, N.; Pretty, J.; Robinson, S.; Toulmin, C.; Whiteley, R. 2010b. The future of the global food system. *Philosophical Transactions of the Royal Society B* 365 (1554): 2769–2777. <http://dx.doi.org/10.1098/rstb.2010.0180>
- Goma Lemba, S.; Nwukor, E.; Dagnachew, S. 2001. Assessing women and environment. 5 years after Beijing: what efforts in favour of African women? Addis Ababa: Economic Commission for Africa. http://www.uneca.org/acgs/Publications/en_0109_environment.pdf
- Gomiero, T.; Pimentel, D.; Paoletti, M.G. 2011. Environmental impact of different agricultural management practices: conventional vs. organic agriculture. *Critical Reviews in Plant Sciences* 30: 95–124. <http://dx.doi.org/10.1080/07352689.2011.554355>
- Goodland, R.; Pimentel, D. 2000. Environmental sustainability and integrity in the agriculture sector. In: Pimentel, D.; Westra, L.; Noss, R.F. eds. *Ecological integrity: integrating environment. Conservation and health*. Washington, DC: Island Press. pp 121–38.
- Gordon, L.; Folke, C. 2000. Ecohydrological landscape management for human well-being. *Water International* 25 (2): 178–184. <http://dx.doi.org/10.1080/02508060008686816>
- Gordon, L.J.; Finlayson, C.M.; Falkenmark, M. 2010. Managing water in agriculture for food production and other ecosystem services. *Agricultural Water Management* 94(4): 512–519. <http://dx.doi.org/10.1016/j.agwat.2009.03.017>
- Gowda, C.L.L.; Serraj, R.; Srinivasan, G.; Chauhan, Y.S.; Reddy, B.V.S.; Rai K.N.; et al. 2009. Opportunities for improving crop water productivity through genetic enhancement of dryland crops. In: Wani, S.P.; Rockström, J.; Oweis, T.; eds. *Rainfed agriculture: unlocking the potential*. Comprehensive Assessment of Water Management in Agriculture Series 7. Wallingford, UK: CABI; Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT); Colombo, Sri Lanka: International Water Management Institute (IWMI). pp 133–163. http://www.iwmi.cgiar.org/Publications/CABI_Publications/CA_CABI_Series/Rainfed_Agriculture/Protected/Rainfed_Agriculture_Unlocking_the_Potential.pdf
- Grainger, A. 1990. *The Threatening Desert*. Earthscan Publications Ltd., London
- Gregory, P.J.; Ingram, J.S.I.; Andersson, R.; Betts, R.A.; Brovkin, V.; Chase, T.N.; Grace, P.R.; Gray, A.J.; Hamilton, N.; Hardy, T.B.; Howden, S.M.; Jenkins, A.; Meybeck, M.; Olsson, M.; Ortiz-Monasterio, I.; Palm, C.; Payn, T.W.; Rummukainen, M.; Schulze, R.E.; Thiem, M.; Valentin, C.; Wilkinson, M.J. 2002. Environmental consequences of alternative practices for intensifying crop production. *Agriculture, Ecosystems & Environment* 88 (3): 279–290. [http://dx.doi.org/10.1016/S0167-8809\(01\)00263-8](http://dx.doi.org/10.1016/S0167-8809(01)00263-8)
- Gurung, T.B. 2002. Fisheries and aquaculture activities in Nepal. *Aquaculture Asia* 7 (4): 39–44.
- Gustavsson, J.; Cederberg, C.; Sonesson, U.; van Otterdijk, R.; Meybeck, A. 2011. Global food losses and food waste. Rome: Food and Agriculture Organization of the United Nations. http://www.fao.org/fileadmin/user_upload/ags/publications/GFL_web.pdf
- GWP. 2000. Integrated Water Resources Management, GWP Technical Committee Background Paper 4, Stockholm: Global Water Partnership.
- GWP. 2003. IWRM ToolBox, Version 2, GWP, Stockholm: Global Water Partnership. <http://www.gwptoolbox.org/>
- GWP. 2004. Integrated Water Resources Management (IWRM) and Water Efficiency Plans by 2005. Why, What and How? GWP Technical Committee Background Paper 10, Stockholm: Global Water Partnership.
- Haileslassie, A.; Peden, D.; Gebreselassie, S.; Amede, T.; Descheemaeker, K. 2009a. Livestock water productivity in mixed crop–livestock farming systems of the Blue Nile basin: assessing variability and prospects for improvement. *Agricultural Systems* 102 (1–3): 33–40. <http://dx.doi.org/10.1016/j.agsy.2009.06.006>
- Haileslassie, A.; Peden, D.; Gebreselassie, S.; Amede, T.; Wagnew, A.; Tadesse, G. 2009b. Livestock water productivity in the Blue Nile basin: assessment of farm scale heterogeneity. *The Rangeland Journal* 31: 213–222. <http://dx.doi.org/10.1071/RJ09006>
- Hails, C.; Humphrey, S.; Loh, J.; Goldfinger, S.; eds. 2008. *Living planet report 2008*. Gland, Switzerland: World Wide Fund For Nature (WWF). 45p http://assets.wwf.org.uk/downloads/lpr_2008.pdf

- Hajjar, R.; Jarvis, D.I.; Gemmill-Herren, B. 2008. The utility of crop genetic diversity in maintaining ecosystem services. *Agriculture Ecosystems & Environment* 123: 261–270.
<http://dx.doi.org/10.1016/j.agee.2007.08.003>
- Hamilton, A. J.; Stagnitti, F.; Xiong, X.; Kreidl, S. L.; Benke, K. K.; Maher, P. 2007. Wastewater Irrigation: The State of Play. *Vadose Zone Journal* 6: 823–840.
- Hansen, M.C.; Stehman, S.V.; Potapov, P.V. 2010. Quantification of global gross forest cover loss. *Proceedings of the National Academy of Sciences of the United States of America* 107 (19): 8650–8655.
<http://dx.doi.org/10.1073/pnas.0912668107>
- Hansson, L. 2006. Comparisons of infiltration capacities in different parklands and farming systems of semi-arid Burkina Faso. Graduate Thesis in Soil Science, Swedish University of Agricultural Sciences, Department of Forest Ecology.
- Harvey, C.A.; Medina, A.; Sanchez, D.M.; Vilchez, S.; Hernandez, B.; Saenz, J.C.; Maes, J.M.; Casanoves, F.; Sinclair, F.L. 2006. Patterns of animal diversity in different forms of tree cover in agricultural landscapes. *Ecological Applications* 16 (5): 1986–1999.
[http://dx.doi.org/10.1890/1051-0761\(2006\)016\[1986:POADID\]2.0.CO;2](http://dx.doi.org/10.1890/1051-0761(2006)016[1986:POADID]2.0.CO;2)
- Hassan, R.; Scholes, R.; Ash N. eds. 2005. *Ecosystems and Human Well-being: Current State and Trends. Findings of the Condition and Trends Working Group*. Millennium Ecosystem Assessment V1. World Resources Institute, Island Press, Washington DC.
- Heal, G. 2000. Valuing ecosystem services. *Ecosystems* 3 (1): 24–30.
<http://dx.doi.org/10.1007/s100210000006>
- Hellegers, P.J.G.J.; Perry, C.J.; Berkoff, J. 2007. Water pricing in Haryana, India. http://www.iwmi.cgiar.org/Publications/CABI_Publications/CA_CABI_Series/Water_Pricing/protected/Molle%20&%20Berkoff_Chap%2008.pdf. In: Molle, F.; Berkoff, J. eds. *Irrigation water pricing: the gap between theory and practice*. Comprehensive Assessment of Water Management in Agriculture Series 4. Wallingford, UK: CABI. pp.192–207.
- Herrero, M.; Thornton, P.K.; Gerber, P.; Reid, R.S. 2009. Livestock, livelihoods and the environment: understanding the trade-offs. *Current Opinion in Environmental Sustainability* 1: 111–120.
- Herrero, M.; Thornton, P.K.; Notenbaert, A.M.; Wood, S.; Msangi, S.; Freeman H.A.; Bossio, D.; Dixon, J.; Peters, M.; van de Steeg, J.; Lynam, J.; Parthasarathy Rao, P.; Macmillan, S.; Gerard, B.; McDermott, J.; Seré, C.; Rosegrant, M. 2010. Smart investments in sustainable food production: revisiting mixed crop-livestock systems. *Science* 327 (5967): 822 – 825. <http://dx.doi.org/10.1126/science.1183725>
- Herrmann, S.M.; Anyamba, A.; Tucker, C.J. 2005. Recent trends in vegetation dynamics in the African Sahel and their relationship to climate. *Global Environmental Change* 15: 394–404.
<http://dx.doi.org/10.1016/j.gloenvcha.2005.08.004>
- Hirji, R.; Davis R. 2009. *Environmental flow in water resources policies, plans and projects: case studies*. The World Bank Environment Department Paper No: 117. Washington: The World Bank
- Hoanh, C.T.; Tuong, T.P.; Hardy, B. 2006. *Environment and Livelihoods in Tropical Coastal Zones: managing Agriculture-Fishery-Aquaculture Conflicts*. Comprehensive Assessment of Water Management in Agriculture Series 2. Wallingford, UK: CABI; Los Banos, Philippines: International Rice Research Institute (IRRI); Colombo, Sri Lanka: International Water Management Institute (IWMI). 309p. http://www.iwmi.cgiar.org/Publications/CABI_Publications/CA_CABI_Series/Coastal_Zones/protected/Hoanh_1845931076.pdf
- Hoanh, C.T.; Szuster, B.W.; Kam, S.P.; Ismail, A.M.; Noble, A.D. eds. 2010. *Tropical deltas and coastal zones: food production, communities and environment at the land-water interface*. Comprehensive Assessment of Water Management in Agriculture Series 9. Wallingford, UK: CABI; Colombo, Sri Lanka: International Water Management Institute (IWMI); Penang, Malaysia: WorldFish Center; Los Banos, Philippines: International Rice Research Institute (IRRI); Bangkok, Thailand: FAO Regional Office for Asia and the Pacific; Colombo, Sri Lanka: CGIAR Challenge Program on Water and Food (CPWF). 477p. http://www.iwmi.cgiar.org/Publications/CABI_Publications/CA_CABI_Series/Coastal_Zones/protected/9781845936181.pdf
- Hoekstra, A.Y. ed. 2009. *Water Footprint Manual: State of the Art 2009*. Enschede: Water footprint Network. www.waterfootprint.org/downloads/WaterFootprintManual2009.pdf
- Hoekstra, A.Y.; Chapagain, A.K. 2008. *Globalization of water: sharing the planet's freshwater resources*. Malden, MA, USA: Blackwell. 208p.
- Hoekstra, A.Y.; Chapagain, A.K.; Aldaya, M.M.; Mekonnen, M.M. 2011. *The Water Footprint Assessment Manual. Setting the global standard*. London, Washington DC: Earthscan. <http://www.waterfootprint.org>
- Hollis, G.E.; Adams, W.M.; Kano, M.A. eds. 1993. *The Hadejia-Nguru Wetlands: environment, economy and sustainable development of a Sahelian floodplain wetland*. IUCN, Gland, Switzerland. 244 pp.
- Howard, A. 1943. *An Agricultural Testament*, Oxford University Press

- Howarth, R.W.; Bringezu, S. eds. 2008. *Biofuels: Environmental Consequences and Interactions with Changing Land Use. Proceedings of the Scientific Committee on Problems of the Environment (SCOPE)*. International Biofuels Project Rapid Assessment, 22–25 September 2008, Gummersbach Germany. Cornell University, Ithaca NY, USA. <http://cip.cornell.edu/biofuels>
- Hughes, D.A.; Hannart, P. 2003. A desktop model used to provide an initial estimate of the ecological instream flow requirements of rivers in South Africa. *Journal of Hydrology* 270 (3–4): 167–181. [http://dx.doi.org/10.1016/S0022-1694\(02\)00290-1](http://dx.doi.org/10.1016/S0022-1694(02)00290-1)
- Hurni H. 1990. Degradation and conservation of soil resources in the Ethiopian Highlands. in Messerli, B.; Hurni, H. eds. *African mountains and highlands. Problems and perspectives*. African Mountains Association (AMA), Marceline, Missouri. p. 51–63
- IdRC. 2006. The integrated environmental management of the Zarqa river. Final report by Interdisciplinary Research Consultants.
- IIED and SOS Sahel UK. 2010. *Modern and Mobile. The future of livestock production in Africa's drylands*. IIED and SOS Sahel International UK
- ILO – International Labor Organization. 2000. Safety and Health in Agriculture. International Labor Conference, 88th Session, May 30–June 15. Geneva.
- Immerzeel, W.; Stoorvogel, J.; Antle, J. 2008. Can payments for ecosystem services secure the water tower of Tibet? *Agricultural Systems* 96 (1–3): 52–63. <http://dx.doi.org/10.1016/j.agsy.2007.05.005>
- INPhO. 2007. Information Network on Post-harvest Operations. <http://www.fao.org/inpho/>
- Israelsen, O.W. 1932. *Irrigation principles and practices*. Wiley and Sons, New York, New York. 411 pp.
- IUCN. 2000. *Vision for water and nature: A World Strategy for Conservation and Sustainable Management of Water Resources in the 21st Century*. IUCN, Gland, Switzerland.
- IUCN – World Conservation Union. 2007a. *Using the Environmental Flows approach in Vietnam*. <http://www.csdwand.net/data/sheet.asp?cn=Vietnam&fn=LA1838> (accessed 06Oct2010).
- IUCN – World Conservation Union. 2007b. Al Azraq Basin National Dialogue lifts hopes for a better future. http://www.iucn.org/about/work/programmes/pa/wcpa_project/?228
- IUCN – World Conservation Union. 2008a. Azraq Oasis Restoration. PowerPoint Presentation. http://cmsdata.iucn.org/downloads/presentation_azraq_web_1.pptx
- IUCN – World Conservation Union. 2008b. The Azraq Oasis Restoration Project Document 2008 – 2010. Unpublished report. http://cmsdata.iucn.org/downloads/azraq_project_documenta__2010_2.pdf
- IUCN – World Conservation Union. 2008c. Huong River Basin. http://iucn.org/about/work/programmes/water/wp_where_we_work/wp_our_work_projects/wp_our_work_hrb/
- IUCN – World Conservation Union. 2009. The Restoration and Economic Development of Zarqa River Basin. PowerPoint Presentation at http://cmsdata.iucn.org/downloads/pps_zarqa.ppt
- IUCN – World Conservation Union. 2010. Pangani River Basin Flow Assessment. http://www.iucn.org/about/work/programmes/water/wp_where_we_work/wp_our_work_projects/wp_our_work_pan/pangani_fa_reports/
- IUCN – World Conservation Union. 2010. Water for people and nature. Water And Nature Initiative, IUCN Water program. http://cmsdata.iucn.org/downloads/update_wani_brochure_sept2010.pdf
- IUCN Vietnam. 2005. Environmental flows: rapid environmental flow assessment for the Huong River Basin, Central Vietnam. Hanoi: IUCN Vietnam.
- IWMI. 2007. Environmental flow assessment for aquatic ecosystems: a database of methodologies. <http://dw.iwmi.org/ehdb/efm/efm.asp>
- IWMI. 2010. Water, Land and Ecosystems Consortium Research Program 5. Submitted to the CGIAR consortium board by IWMI on behalf of Africa Rice, Bioversity, CIAT. CIP. CPWF. IITA, ICARDA, ICRAF, ICRISAT, IFPRI, ILRI, IRRI, IWMI, WorldFish.
- Jansen, H.C.; Hengsdijk, H.; Legesse, D.; Ayenew, T.; Spliethoff, P.C.; Hellegers, P.J.G.J. 2007. *Land and water resources assessment in the Ethiopian Central Rift Valley: ecosystems for water, food and economic development*. Alterra report 1587, Wageningen.
- Janzen, H.H. 2004. Carbon cycling in earth systems – a soil science perspective. *Agriculture, Ecosystems & Environment* 104 (3): 399–417. <http://dx.doi.org/10.1016/j.agee.2004.01.040>
- Jarvis, D.I.; Hodgkin, T.; Sthapit, B.R.; Fadda, C.; Lopez-Noriega, I. 2011. An heuristic framework for identifying multiple ways of supporting the conservation and use of traditional crop varieties within the agricultural production system. *Critical Reviews in Plant Sciences* 30: 125–176. <http://dx.doi.org/10.1080/07352689.2011.554358>
- Jensen, M.E. 2007. Beyond irrigation efficiency. *Irrigation Science* 25 (3): 233–245. <http://dx.doi.org/10.1007/s00271-007-0060-5>

- Jiménez, B.; Drechsel, P.; Koné, D.; Bahri, A.; Raschid-Sally, L.; Qadir, M. 2010. Wastewater, sludge and excreta use in developing countries: an overview. In: Drechsel, P.; Scott, C.A.; Raschid-Sally, L.; Redwood, M.; Bahri A. eds. *Wastewater irrigation and health: Assessing and mitigation risks in low-income countries*. Earthscan-IDRC-IWMI, UK.
- Johnson, N.; Revenga, C.; Echeverria, J. 2001. Ecology – Managing water for people and nature. *Science* 292: 1071–1072. <http://dx.doi.org/10.1126/science.1058821>
- Johnston, R.; McCartney, M. 2010. *Inventory of water storage types in the Blue Nile and Volta river basins*. IWMI Working Paper 140. International Water Management Institute, Colombo. <http://dx.doi.org/10.5337/2010.214>
- Jose, S. 2009. Agroforestry for ecosystem services and environmental benefits: an overview. *Agroforestry Systems* 76 (1): 1–10. <http://dx.doi.org/10.1007/s10457-009-9229-7>
- Jung, M.; Reichstein, M.; Ciais, P.; Seneviratne, S.I.; Sheffield, J.; Goulden, M.L.; Bonan, G.; Cescatti, A.; Chen, J.; de Jeu, R.; Dolman, A.J.; Eugster, W.; Gerten, D.; Gianelle, D.; Gobron, N.; Heinke, J.; Kimball, J.; Law, B.E.; Montagnani, L.; Mu, Q.; Mueller, B.; Oleson, K.; Papale, D.; Richardson, A.D.; Rouspard, O.; Running, S.; Tomelleri, E.; Viovy, N.; Weber, U.; Williams, C.; Wood, E.; Zaehle, S.; Zhang, K. 2010. Recent decline in the global land evapotranspiration trend due to limited moisture supply. *Nature* 467: 951–954. <http://dx.doi.org/10.1038/nature09396>
- Kandiero, T. 2009. *Infrastructure Investment in Africa*. Development Research Brief 10. Tunisia: African Development Bank.
- Kanowski, J.; Catterall, C.P.; Harrison, D.A. 2008. Monitoring the outcomes of reforestation for biodiversity conservation. In: Stork, N.; Turton, S. (eds.) *Living in a dynamic tropical forest landscape*, p526–536. Oxford: Wiley-Blackwell.
- Kay, B.H. ed. 1999. *Water resources: Health, environment and development*. New York, NY, USA: E & FN Spon Ltd. 250 pages.
- Kearney, J. 2010. Food consumption trends and drivers. *Philosophical Transactions of the Royal Society B* 365: 2793–2807. <http://dx.doi.org/10.1098/rstb.2010.0149>
- Keiser, J.; Caldas de Castro, M.; Maltese, M.F.; Bos, R.; Tanner, M.; Singer, B.H.; Utzinger, J. 2005a. Effect of irrigation and large dams on the burden of malaria on a global and regional scale. *American Journal of Tropical Medicine and Hygiene* 72(4): 392–406. <http://www.ajtmh.org/cgi/content/full/72/4/392>
- Keiser J, Singer BH, Utzinger J (2005c) Reducing the burden of malaria in different eco-epidemiological settings with environmental management: A systematic review. *The Lancet Infectious Diseases* 5(11): 695–708.
- Kelsey Jack, B.; Kousky, C.; Sims K.R.E. 2008. Designing payments for ecosystem services: lessons from previous experience with incentive-based mechanisms. *Proceedings of the National Academy of Sciences* 105 (28): 9465–9470. <http://dx.doi.org/10.1073/pnas.0705503104>
- Kerr, J. 2002. Sharing the benefits of watershed management in Sukhomajri, India. In: Pagiola, S.; Bishop, J.; Landell-Mills, N. eds. *Selling forest environmental services: market-based mechanisms for conservation and development*. London: Earthscan.
- Khosh-Chashm, K. 2000. Water-conscious development and the prevention of water misuse and wastage in the Eastern Mediterranean Region. *Eastern Mediterranean Health Journal* 6 (4): 734–745.
- Kijne, J.W.; Baker, R.; Molden, D. eds. 2003. *Water productivity in agriculture: limits and opportunities for improvement*. Comprehensive Assessment of Water Management in Agriculture Series 1. International Water Management Institute, Sri Lanka. 368p. CABI. http://www.iwmi.cgiar.org/Publications/CABI_Publications/CA_CABI_Series/Water_Productivity/Unprotected/0851996698toc.htm
- King, J.; Louw, D. 1998. Instream flow assessment for regulated rivers in South Africa using the Building Block Methodology. *Aquatic Ecosystem Health and Management* 1 (2): 109–124. <http://dx.doi.org/10.1080/14634989808656909>
- King, J.; Brown, C.; Sabet, H. 2003. A scenario-based holistic approach to environmental flow assessments for rivers. *River research and applications* 19 (5–6): 619–639. <http://dx.doi.org/10.1002/rra.709>
- King, J.; Turpie, J.; Brown, C.; Clark, B.; Beuster, H.; Joubert, A. 2010. Pangani river basin flow assessment: Final project summary report. Nairobi: International Union for Conservation of Nature and Pangani Basin Water Board.
- Kirkby, J.; O’Keefe, P.; Timberlake, L. 1995 *The Earthscan reader in sustainable development*. Earthscan Reader Series, 304 pages.
- Kremen, C. 2005. Managing ecosystem services: what do we need to know about their ecology? *Ecology Letters* 8: 468–479. <http://dx.doi.org/10.1111/j.1461-0248.2005.00751.x>
- Kremen, C.; Ostfeld, R. 2005. Measuring, analyzing, and managing ecosystem services. *Frontiers in Ecology and the Environment* 3(10): 540–548. [http://dx.doi.org/10.1890/1540-9295\(2005\)003\[0540:ACTEMA\]2.0.CO;2](http://dx.doi.org/10.1890/1540-9295(2005)003[0540:ACTEMA]2.0.CO;2)

- Kristjansson, P.; Thornton P.; Kruska, R.; Reid, R.; Henninger, N.; Williams, T.; Tarawali, S.; Niezen, J.; Hiernaux, P.; 2004. *Mapping livestock systems and changes to 2050: Implications for West Africa*. http://www.vslp.org/upload/pdf/Pg028_044%20Kristjansson%20and%20Thornton.pdf
- Lal, R. 2010. Enhancing eco-efficiency in agro-ecosystems through soil carbon sequestration. *Crop Science* 50: S-120–S-131. <http://dx.doi.org/10.2135/cropsci2010.01.0012>
- Lehner, B.; Döll, P. 2004. Development and validation of a global database of lakes, reservoirs and wetlands. *Journal of Hydrology* 296 (1–4): 1–22. <http://dx.doi.org/10.1016/j.jhydrol.2004.03.028>
- Lemly, A.D.; Kingsford, R.T.; Thompson, J.R. 2000. Irrigated agriculture and wildlife conservation: conflict on a global scale. *Environmental Management* 25 (5): 485–512. <http://dx.doi.org/10.1007/s002679910039>
- Liu, B.M.; Abebe, Y.; McHugh, O.V.; Collick, A.S.; Gebrekidan, B.; Steenhuis, T.S. 2008. Overcoming limited information through participatory watershed management: Case study in Amhara, Ethiopia. *Physics and Chemistry of the Earth* 33 (1–2): 13–21. <http://dx.doi.org/10.1016/j.pce.2007.04.017>
- Lobell, D.B.; Burke, M.M.; Tebaldi, C.; Mastrandrea, M.D.; Falcon, W.P.; Naylor, R.L. 2008. Prioritizing climate change adaptation needs for food security in 2030. *Science* 319(5863): 607–610. <http://dx.doi.org/10.1126/science.1152339>
- Lukatelich, R.J.; McComb, A.J. 1986. Nutrient levels and the development of diatoms and blue-green algal blooms in shallow Australian estuary. *Journal of Plankton Research* 8 (4): 597–618. <http://dx.doi.org/10.1093/plankt/8.4.597>
- Lundqvist, J.; de Fraiture, C.; Molden, D. 2008. *Saving water: from field to fork: curbing losses and wastage in the food chain*. SIWI Policy Brief. Stockholm, Sweden: Stockholm International Water Institute (SIWI).
- Lundqvist, J.; Gleick P.H. 1997. *Sustaining our waters into the 21st century: Comprehensive Assessment of the Freshwater Resources of the World*. Stockholm: Stockholm Environment Institute, for the United Nations.
- MA (Millennium Ecosystem Assessment). 2005a. *Ecosystems and human well-being: general synthesis*. Washington DC: World Resources Institute.
- MA (Millennium Ecosystem Assessment). 2005b. *Ecosystems and Human Well-being: Opportunities and Challenges for Business and Industry*. World Resources Institute, Washington, DC.
- MA (Millennium Ecosystem Assessment). 2005c. *Ecosystems and Human Well-being: Wetland and Water Synthesis*. World Resources Institute, Washington, DC. Island Press.
- MA – Millennium Ecosystem Assessment (2005d) *Living beyond our means. Natural assets and human wellbeing*. <http://www.millenniumassessment.org/en/index.aspx>
- Makarieva, A.M.; Gorshkov, V.G.; Sheil, D.; Nobre, A.D.; Li, B.-L. 2010. Where do winds come from? A new theory on how water vapor condensation influences atmospheric pressure and dynamics, *Atmospheric Chemistry and Physics Discussions* 10: 24015–24052. <http://dx.doi.org/10.5194/acpd-10-24015-2010>
- Matsuno, Y.; Ko, H.S.; Tan, C.H.; Barker, R.; Levine, G. 2002. *Accounting of agricultural and nonagricultural impacts of irrigation and drainage systems: A study of multifunctionality in rice*. IWMI working paper 43. Colombo, Sri Lanka: IWMI. 36p.
- Matz, M. 2008. Rethinking IWRM under cultural considerations. In Scheumann, W.; Neubert, S.; Kipping, M. eds. *Water Politics and Development Cooperation, Part II*, 176–201. http://dx.doi.org/10.1007/978-3-540-76707-7_8
- Mayers, J.; Batchelor, C.; Bond, I.; Hope, R. A.; Morrison, E.; Wheeler, B. 2009. *Water ecosystem services and poverty under climate change: Key issues and research priorities*. International Institute for Environment and Development, London, UK. Natural Resource Issues No. 17.
- McCartney, M.P.; Boelee, E.; Cofie, O.; Mutero, C.M. 2007. *Minimizing the negative environmental and health impacts of agricultural water resources development in sub-Saharan Africa*. IWMI Working Paper 117, International Water Management Institute, Colombo. <http://dx.doi.org/10.3910/2009.297>
- McCartney, M.; Rebelo, L.M.; Sellamuttu, S.S.; De Silva, S. 2010. *Wetlands, Agriculture and Poverty Alleviation: appropriate management to safeguard and enhance wetland productivity*. IWMI Research Report 137. Colombo: International Water Management Institute (IWMI).
- McCartney, M.; Smakhtin, V. 2010. *Water storage in an era of climate change: addressing the challenge of increasing rainfall variability*. IWMI Blue Paper. Colombo: International Water Management Institute.
- McCartney, M.P.; van Koppen, B. 2004. *Wetland contributions to livelihoods in United Republic of Tanzania*. Food and Agriculture Organisation of the United Nations (FAO) Netherlands Partnership Programme: Sustainable Development and Management of Wetlands. Rome.
- McClain-Nhlapo, C. 2004. *Implementing a human rights approach to food security*. Washington DC: International Food Policy Research Institute.
- McInnes, R. 2010. Urban development, biodiversity and wetland management. Expert workshop report, 16–17 November 2009, Kenya Wildlife Service Training Institute, Naivasha, Kenya. Oxford: Bioscan Ltd., UN Habitat. www.unhabitat.org/downloads/docs/ExpertWorkshopWetlands.pdf

- McIntyre, B.D. et al., 2008. *International Assessment of Agricultural Knowledge, Science and Technology for Development: Global Report*, Island Press, New York, USA.
- Medema, W.; McIntosh, B.S.; Jeffrey, P.J. 2008. From premise to practice: a critical assessment of integrated water resources management and adaptive management approaches in the water sector. *Ecology and Society* 13 (2): 29. <http://www.ecologyandsociety.org/vol13/iss2/art29/>
- Meinzen-Dick, R. 1997. Valuing the multiple uses of water. In Kay, M.; Franks, T.; Smith, L., eds. *Water: economics, management and demand*. London: E&FN Spon. pp 50–58.
- Metz, B.; Davidson, O.R.; Bosch, P.R.; Dave R.; Meyer, L.A. eds. 2007. *Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. http://www.ipcc.ch/publications_and_data/ar4/wg3/en/contents.html
- Mills, D. J.; Westlund, L.; de Graaf, G.; Kura, Y.; Willman, R.; Kelleher, K. 2010. Underreported and undervalued: Small-scale fisheries in the developing world. In Pomeroy, R.S.; Andrew, N. eds. *Small-scale fisheries management frameworks and approaches for the developing world*. London: CABI.
- Molden, D.; de Fraiture, C. 2004. *Investing in Water for Food Ecosystem and Livelihoods*. Comprehensive Assessment of Water Management in Agriculture Blue Paper, International Water Management Institute, Colombo
- Molden, D.; Frenken, K.; Barker, R.; de Fraiture, C.; Mati, B; Svendsen, M.; Sadoff, C.; Finlayson, C.M.; et al. 2007a. Trends in water and agricultural development. In: CA. *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. International Water Management Institute (IWMI), Colombo, Sri Lanka and Earthscan, London, pp 57–89. <http://www.iwmi.cgiar.org/assessment/Publications/books.htm>
- Molden, D.; Oweis, T.; Steduto, P.; Bindraban, P.; Hanjra, M.A.; Kijne, J. 2010. Improving agricultural water productivity: Between optimism and caution. *Agricultural Water Management* 97 (4): 528–535. <http://dx.doi.org/10.1016/j.agwat.2009.03.023>
- Molden, D.; Oweis, T.Y.; Steduto, P.; Kijne, J.W.; Hanjra, M.A.; Bindraban, P.S.; et al. 2007b. Pathways for increasing agricultural water productivity. In CA. *Water for food, water for life: a comprehensive assessment of water management in agriculture*. International Water Management Institute (IWMI), Colombo, Sri Lanka and Earthscan, London, pp 279–310. <http://www.iwmi.cgiar.org/assessment/Publications/books.htm>
- Molden, D.; Tharme, R.; Abdullaev, I.; Puskur, R. 2007c. Irrigation. In Scherr, S.J.; McNeely, J.A. eds. *Farming with nature: The science and practice of ecoagriculture*. Washington, DC, USA: Island Press. pp 231–249.
- Moll, H.A.J.; Staal, S.J.; Ibrahim, M.N.M. 2007. Smallholder dairy production and markets: a comparison of production systems in Zambia, Kenya and Sri Lanka. *Agricultural Systems* 94 (2): 593–603. <http://dx.doi.org/10.1016/j.agsy.2007.02.005>
- Molle, F.; Berkoff, J. 2007. Water pricing in irrigation: the lifetime of an idea. http://www.iwmi.cgiar.org/Publications/CABI_Publications/CA_CABI_Series/Water_Pricing/protected/Molle%20&%20Berkoff_Chap%2001.pdf In: Molle, F.; Berkoff, J. eds. *Irrigation water pricing: the gap between theory and practice*. Comprehensive Assessment of Water Management in Agriculture Series 4. Wallingford, UK: CABI. 2007. pp 1–20.
- Molle, F.; Mollinga, P. 2003. Water poverty indicators: conceptual problems and policy issues. *Water Policy* 5 (5–6): 529–544. <http://www.iwaponline.com/wp/00505/0529/005050529.pdf>
- Molle, F.; Renwick, M. 2005. *Economics and politics of water resources development: Uda Walawe irrigation project, Sri Lanka*. IWMI Research Report 87. International Water Management Institute, Colombo. <http://dx.doi.org/10.3910/2009.087>
- Molle, F.; Wester P.; Hirsch, P. 2010. River basin closure: Processes, implications and responses. *Agricultural Water Management* 97 (4): 569–577. <http://dx.doi.org/10.1016/j.agwat.2009.01.004>
- Morton, J.F. 1987. *Fruits for Warm Climates*. Florida Flair Books
- Mosier, A.R.; Duxbury, J.M.; Freney, J.R.; Heinemeyer, O; Minami, K.; Johnson, D.E. 1998. Mitigating agricultural emissions of methane. *Climatic Change* 40 (1): 39–80. <http://dx.doi.org/10.1023/A:1005338731269>
- Muchena, F.N.; Onduru, D.D.; Gachin, G.N.; de Jager, A. 2005. Turning the tides of soil degradation in Africa: capturing the reality and exploring opportunities. *Land Use Policy* 22: 23–31. <http://dx.doi.org/10.1016/j.landusepol.2003.07.001>
- Mugerwa, S. 2009. Effect of reseeding and cattle manure on pasture and livestock water productivity in rangelands of Nakasongola District, Uganda. MSc Thesis, Makerere University.
- Mukherji, A.; Facon, T.; Burke, J.; de Fraiture, C.; Faures, J.M.; Fuleki, B. et al. 2009. *Revitalizing Asia's irrigation: to sustainably meet tomorrow's food needs*. Colombo, Sri Lanka: International Water Management Institute (IWMI); Rome, Italy: FAO. 39p
- Muli, A. 2000. Factors affecting amount of water offered to dairy cattle in Kiambu District and their effects on productivity. BSc thesis, University of Nairobi (Range Management), Kenya.

- Munro, J.L. Iskandar and Costa-Pierce B.A. 1990. Fisheries of the Saguling reservoir and a preliminary appraisal of management options. In: Costa-Pierce, B.A.; Soemarawoto, O. eds. *Reservoir fisheries and aquaculture development for resettlement in Indonesia*. ICLARM Technical Report 23. Perusahaan Umum Listrik Negara, Jakarta; Institute of Ecology, Padjadjaran University, Bandung, Indonesia; International Center for Living Aquatic Resources Management, Metro Manila, Philippines.
- Muthuri, C.W.; Ong, C.K.; Black, C.R.; Ngumi, V.W.; Mati, B.M. 2005. Tree and crop productivity in *Grevillea*, *Alnus* and *Paulownia*-based agroforestry systems in semi-arid Kenya. *Forest Ecology and Management* 212 (1): 23–39. <http://dx.doi.org/10.1016/j.foreco.2005.02.059>
- Muthuri, C.W.; Ong, C.K.; Craigon, J.; Mati, B.M.; Ngumi, V.W.; Black, C.R. 2009. Gas exchange and water use efficiency of trees and maize in agroforestry systems in semi-arid Kenya. *Agriculture, Ecosystems & Environment* 129 (4): 497–507. <http://dx.doi.org/10.1016/j.agee.2008.11.001>
- Nair, P.K.R.; Gordon, A.M.; Mosquera-Losada, M.-R. 2008. Agroforestry, in Jorgensen, S.E.; Fath, B.D. (eds) *Ecological Engineering*. Encyclopedia of Ecology, Vol. 1. Oxford: Elsevier. pp. 101–110.
- Nair, P.K.R.; Kumar, B.M.; Nair, V.D. 2009. Agroforestry as a strategy for carbon sequestration. *Journal of Plant Nutrition and Soil Science* 172 (1): 10–23. <http://dx.doi.org/10.1002/jpln.200800030>
- Naylor, R.L. 2009. Managing food production systems for resilience. In: Chapin III, F.S. et al. (eds) *Principles of ecosystem stewardship: resilience-based natural resource management in a changing world*. Springer, pp 259–280.
- NRC (National Research Council) 2008. *Lost Crops of Africa: Volume III: Fruits*, National Academy of Sciences
- Nellemann, C.; MacDevette, M.; Manders, T.; Eickhout, B.; Svihus, B.; Prins, A.G.; Kaltenborn, B.P. eds. 2009. *The environmental food crisis – The environment's role in averting future food crises*. A UNEP rapid response assessment. United Nations Environment Programme, GRID-Arendal, www.grida.no
- Nelson, G.C. 2005. Drivers of Ecosystem Change: Summary Chapter. In: Hassan, R.; Scholes, R.; Ash N. eds. *Ecosystems and Human Well-being: Current State and Trends. Findings of the Condition and Trends Working Group*. Millennium Ecosystem Assessment VI. World Resources Institute, Island Press, Washington DC. pp 73–76.
- Nelson, G.C.; Bennett, E.; Berhe, A.A.; Cassman, K.; DeFries, R.; Dietz, T.; Dobermann, A.; Dobson, A.; Janetos, A.; Levy, M.; Marco, D.; Nakicenovic, N.; O'Neill, B.; Norgaard, R.; Petschel-Held, G.; Ojima, D.; Pingali, P.; Watson, R.; Zurek, M. 2006. Anthropogenic drivers of ecosystem change: an overview. *Ecology and Society* 11(2): 29. <http://www.ecologyandsociety.org/vol11/iss2/art29/>
- Newell, F.H. 1916. *Irrigation management*. Appleton & Co. New York, London.
- Nguyen-Khoa, S.; Smith, L. 2008. Fishing in the paddy fields of monsoon Asian developing countries: re-focusing the current discourse on the 'multifunctionality of agriculture'. Paper presented at the INWEPF-ICID workshop of the RAMSAR COP10 meeting.
- Nguyen-Khoa, S.; Smith, L. 2010. A cross-scale approach to multiple use of water. Multiple Use TWG Position Paper. Colombo: Challenge Program on Water and Food.
- Nguyen-Khoa, S.; Smith, L.; Lorenzen, K. 2005. *Impacts of irrigation on inland fisheries: appraisals in Laos and Sri Lanka*. Comprehensive Assessment Research Report 7. Colombo, Sri Lanka: Comprehensive Assessment Secretariat. 36p.
- Nguyen-Khoa, S.; van Brakel, M.L.; Beveridge, M.C.M. 2008. Is water productivity relevant in fisheries and aquaculture? In: Humphreys, E. et al. eds. *Fighting Poverty Through Sustainable Water Use: Proceedings of the CGIAR Challenge Program on Water and Food 2nd International Forum on Water and Food*, Volume 1. The CGIAR Challenge Program on Water and Food, Colombo, Sri Lanka. pp 22–27. www.ifwf2.org/
- Nicholson, E.; Mace, G.M.; Armsworth, P.R.; Atkinson, G.; Buckle, S.; Clements, T.; Ewers, R.M.; Fa, J.E.; Gardner, T.A.; Gibbons, J.; Grenyer, R.; Metcalfe, R.; Mourato, S.; Muûls, M.; Osborn, D.; Reuman, D.C.; Watson, C.; Milner-Gulland, E.J. 2009. Priority research areas for ecosystem services in a changing world. *Journal of Applied Ecology* 46: 1139–1144. <http://dx.doi.org/10.1111/j.1365-2664.2009.01716.x>
- Nielsen, D.C.; Vigil, M.F.; Benjamin, J.G. 2006. *Forage yield response to water use for dryland corn, millet, and triticale in the Central Great Plains*. *Agronomy Journal* 98: 992–998. <http://dx.doi.org/10.2134/agronj2005.0356>
- Noy-Meir, I. 1973. Desert ecosystems: environment and producers. *Annual Review of Ecology and Systematics* 4: 25–51.
- OECD (Organisation for Economic Co-operation and Development) (various years) Glossary of Statistical Terms. <http://stats.oecd.org/glossary/index.htm> (accessed 5 January 2011). Each term has its own year of last update.
- Oenema, O.; Oudendag, D.; Velthof, G.L. 2007. Nutrient losses from manure management in the European Union. *Livestock Science* 112 (3): 261–272. <http://dx.doi.org/10.1016/j.livsci.2007.09.007>

- Oenema, O.; Wrage, N.; Velthof, G.L.; van Groenigen, J.W.; Dolfig, J.; Kuikman, P.J. 2005. Trends in global nitrous oxide emissions from animal production systems. *Nutrient Cycling in Agroecosystems* 72: 51–65.
- Oki, T.; Kanae, S. 2006: Global hydrological cycles and world water resources. *Science* 313 (5790): 1068–1072. <http://dx.doi.org/10.1126/science.1128845>
- Oldeman, L.R.; Hakkeling, R.T.A.; Sombrack, W.G. 1991. World map of the status of human-induced soil degradation. An explanatory note. *Global assessment of soil degradation*. Second revised ed. Wageningen, Netherlands: International Soil Reference and Information Center and United Nations Environment Programme.
- Olsson, L.; Eklundh, L.; Ardö, J. 2005. A recent greening of the Sahel: trends, patterns and potential causes. *Journal of Arid Environments* 63 (3): 556–566. <http://dx.doi.org/doi:10.1016/j.jaridenv.2005.03.008>
- Ong, C.K.; Black, C.R.; Marshall, F.M.; Corlett, J.E. 1996. Principles of resource capture and utilization of light and water. In: Ong, C.K.; Huxley, P. (eds) *Tree-crop interactions: a physiological approach*. Wallingford: CAB International. pp 73–150.
- Ong, C.K.; Black, C.B.; Muthuri, C.W. 2006. Modifying forestry and agroforestry to increase water productivity in the semi-arid tropics. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources* 1 (065): 1–19.
- Ong, C.K.; Leakey, R.R.B. 1999. Why tree–crop interactions in agroforestry appear at odds with tree–grass interactions in tropical savannahs. *Agroforestry Systems* 45 (1–3): 109–129. <http://dx.doi.org/10.1023/A:1006243032538>
- Ong, C.K.; Swallow, B.M. 2003. Water productivity in forestry and agroforestry. P217–228 in: Kijne JW, Barker R, Molden D (eds) *Water productivity in agriculture: limits and opportunities for improvement*. Wallingford: CAB International.
- Oweis, T.; Hachum, A.; 2006. Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa. *Agricultural Water Management* 80 (1): 57–73. <http://dx.doi.org/10.1016/j.agwat.2005.07.004>
- Oweis, T.; Hachum, A. 2009a. Supplemental irrigation for improved rainfed agriculture in WANA region. In: Wani, S.P.; Rockström, J.; Oweis, T. eds. *Rainfed agriculture: unlocking the potential*. Comprehensive Assessment of Water Management in Agriculture Series 7. Wallingford, UK: CABI; Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT); Colombo, Sri Lanka: International Water Management Institute (IWMI). pp 182–196. http://www.iwmi.cgiar.org/Publications/CABI_Publications/CA_CABI_Series/Rainfed_Agriculture/Protected/Rainfed_Agriculture_Unlocking_the_Potential.pdf
- Oweis, T.; Hachum, A. 2009b. Water harvesting for improved rainfed agriculture in the dry environments. In: Wani, S.P.; Rockström, J.; Oweis, T.; eds. *Rainfed agriculture: unlocking the potential*. Comprehensive Assessment of Water Management in Agriculture Series 7. Wallingford, UK: CABI; Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT); Colombo, Sri Lanka: International Water Management Institute (IWMI). pp 164–181. http://www.iwmi.cgiar.org/Publications/CABI_Publications/CA_CABI_Series/Rainfed_Agriculture/Protected/Rainfed_Agriculture_Unlocking_the_Potential.pdf
- Oweis, T.; Hachum, A.; Pala, M. 2004. Water use efficiency of winter-sown chickpea under supplemental irrigation in a mediterranean environment. *Agricultural Water Management* 66 (2): 163–179. <http://dx.doi.org/10.1016/j.agwat.2003.10.006>
- Pachauri, R.K.; Reisinger, A. 2007. *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland: IPCC.
- Pagella, T.F.; Jackson, B.M.; Reynolds, B.; Sinclair, F.L. 2011. Spatially explicit negotiation of ecosystem service synergies and trade-offs: the polyscape approach and tool. College of Natural Sciences, Bangor University, UK. Pangan River Basin Management Project (2010) *Towards Integrated Water Resource Management*. <http://www.panganibasin.com/project/index.html> (accessed 06Oct2010).
- Panigrahi, S.; Acharya, B. C.; Rama Chandra, P.; Bijaya Ketan N.; Banarjee, K.; Sarkar, S.K. 2006. Anthropogenic impact on water quality of Chilika lagoon RAMSAR site: a statistical approach. *Wetlands Ecology and Management* 15 (2): 113–126.
- Parent, G.; Zagré, N.-M.; Ouédraogo, A.; Guiguembé, R. T. 2002. Les grands hydro-aménagements au Burkina Faso contribuent-ils à l'amélioration des situations nutritionnelles des enfants? *Cahiers Agricultures* 11: 51–57.
- Parfitt, J.; Barthel, M.; Macnaughton, S. 2010. Food waste within food supply chains: quantification and potential for change to 2050. *Philosophical Transactions of the Royal Society B* 365: 3065–3081. <http://dx.doi.org/10.1098/rstb.2010.0126>
- Parry, M.L.; Canziani, O.F.; Palutikof, J.P.; van der Linden, P.J.; Hanson, C.E. eds. 2007. *Climate Change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press. 976p. http://www.ipcc.ch/publications_and_data/ar4/wg2/en/contents.html

- Pauly D, 1995. Anecdotes and the shifting baseline syndrome of fisheries. *Trends in Ecology and Evolution* 10: 430.
- Peden, D.; Alemayehu, M.; Amede, T.; Bekele Awulachew, S.; Faki, H.; Haileslassie, A.; Herero, M.; Mapezda, E.; Mpairwe, D.; Tibin Musa, M.; Tadesse, G.; van Breugel, P. 2009a. *Nile Basin livestock water productivity*. Project Number 37. CPWF Project Report. Colombo: Challenge Program on Water and Food.
- Peden, D.; Ayalneh, W.; El Wakeel, A.; Fadlalla, B.; Elzaki, R.; Faki, H.; Mati, B.; Sonder, K.; Workalemahu, A. 2005. *Investment options for integrated water-livestock-crop production in sub-Saharan Africa*. Addis Ababa: International Livestock Research Institute.
- Peden, D.; Tadesse, G.; Haileslassie, A. 2009b. Livestock water productivity: implications for sub-Saharan Africa. *The Rangeland Journal* 31: 187–193. <http://dx.doi.org/10.1071/RJ09002>
- Peden, D.; Tadesse, G.; Misra, A.K.; et al. 2007. Water and livestock for human development. In: CA. *Water for food, water for life: A comprehensive assessment of water management in agriculture*. London, UK: Earthscan; Colombo, Sri Lanka: International Water Management Institute (IWMI). pp 485–514. <http://www.iwmi.cgiar.org/assessment/Publications/books.htm>
- Perry, C.J. 2007. Efficient irrigation; inefficient communication; flawed recommendations. *Irrigation and Drainage* 56 (4): 367–378. <http://dx.doi.org/10.1002/ird.323>
- Pert, P.L.; Butler, J.R.A.; Brodie, J.E.; Bruce, C.; Honzák, M.; Kroon, F.J.; Metcalfe, D.; Mitchell, D.; Wong, G. 2010. A catchment-based approach to mapping hydrological ecosystem services using riparian habitat: a case study from the Wet Tropics, Australia. *Ecological Complexity* 7: 378–388. <http://dx.doi.org/10.1016/j.ecocom.2010.05.002>
- Pimentel, D.; Gatto, M.; de Leo, G. 2001. Pricing biodiversity and ecosystem services. *BioScience* 51(4): 270–272. <http://www.jstor.org/stable/1314071>
- Plusquellec, H. 2002. Is the daunting challenge of irrigation achievable? *Irrigation and Drainage* 51: 185–198. <http://dx.doi.org/10.1002/ird.51>
- Poff, N.L.; Richter, B.D.; Arthington, A.H.; Bunn, S.E.; Naiman, R.J.; Kendy, E.; Acreman, M.; Apse, C.; Bledsoe, B.P.; Freeman, M.C.; Henriksen, J.; Jacobson, R.B.; Kennen, J.G.; Merritt, D.M.; O’Keeffe, J.H.; Olden, J.D.; Rogers, K.; Tharme, R.E.; Warner, A. 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology* 55: 147–170. <http://dx.doi.org/10.1111/j.1365-2427.2009.02204.x>
- Porter, J.; Costanza, R.; Sigsgaard, L.; Sandhu, H.; Wratten, S. 2009. The value of producing food, energy and ecosystem services within an agro-ecosystem. *Ambio* 38: 186–193.
- Power, A.G. 2010. Ecosystem services and agriculture: tradeoffs and synergies. *Philosophical Transactions of the Royal Society B* 365: 2959–2971. <http://dx.doi.org/10.1098/rstb.2010.0143>
- Powell, M.; Pearson, A.R.; Hiernaux, P.H. 2004. Croplivestock interactions in the West African drylands. *Agronomy Journal* 96: 469–483. <http://dx.doi.org/10.2134/agronj2004.4690>
- Pretty, J.; Noble, A.D.; Bossio, D.; Dixon, J.; Hine, R.E.; Penning de Vries, F.W.T.; Morison, J.I.L. 2006. Resource-conserving agriculture increases yields in developing countries. *Environmental Science & Technology* 40(4): 1114–1119. <http://dx.doi.org/10.1021/es051670d>
- Pritchard, L.; Folke, M.; Gunderson, L. 2000. Valuation of ecosystem services in institutional context. *Ecosystems* 3 (1): 36–40. <http://dx.doi.org/10.1007/s100210000008>
- Puskur, R.; Gebreselassie, S.; Ayalneh, W.; Yimegnuh, A.; Peden, D. 2006. Integrating water harvesting and small scale dairy production: Implications for livelihoods. Unpublished report, International Livestock Research Institute.
- Rabia, A.R.; Solowey, E.; Leu, S. 2008. Environmental and economic potential of Bedouin dryland agriculture: a case study in the Northern Negev, Israel. *Journal of Management of Environmental Quality* 19(3): 353–366.
- Rahaman, M.; Varis, O. 2005. Integrated water resources management: evolution, prospects and future challenges. *Sustainability: Science, Practice, & Policy* 1(1): 15–21. <http://ejournal.nbii.org/archives/vol1iss1/0407-03.rahaman.html>
- Raudsepp-Hearne, C.; Peterson, G.D.; Tengö, M.; Bennett, E.M.; Holland, T.; Benessaiah, K.; MacDonald, G.K.; Pfeifer, L. 2010. Untangling the environmentalist’s paradox: why is human well-being increasing as ecosystem services degrade? *BioScience* 60(8): 576–589. <http://dx.doi.org/10.1525/bio.2010.60.8.4>
- Rebello L-M; McCartney, M.P.; Finlayson, C.M. 2010. Wetlands of Sub-Saharan Africa: distribution and contribution of agriculture to livelihoods. *Wetlands Ecology and Management* 18: 557–572. <http://dx.doi.org/10.1007/s11273-009-9142-x>
- Renault, D., and W. Wallender. 2000. Nutritional Water Productivity and Diets. *Agricultural Water Management* 45 (3): 275–296. [http://dx.doi.org/10.1016/S0378-3774\(99\)00107-9](http://dx.doi.org/10.1016/S0378-3774(99)00107-9)
- Reij, C.; Tappan, G.; Belemvire, A. 2005. Changing land management practices and vegetation on the Central Plateau of Burkina Faso (1968–2002), *Journal of Arid Environments* 63: 642–659. <http://dx.doi.org/10.1016/j.jaridenv.2005.03.010>

- Reij, C.; Tappan, G.; Smale, M. 2009. Agroenvironmental transformation in the Sahel, another kind of "green revolution". IFPRI discussion paper 00914, 2020 vision initiative, 43 p.
- Ribot, J.C. 2009. Vulnerability does not just come from the sky: framing grounded pro-poor cross-scale climate policy. In: Mearns, R.; Norton, A. eds. *Social Dimensions of Climate Change: Equity and Vulnerability in a Warming World*. Washington, DC: The World Bank.
- Rockström, J. 1997. On-farm agrohydrological analysis of the sahelian yield crisis: rainfall partitioning, soil nutrients and water use efficiency of pearl Millet. PhD thesis, University of Stockholm, Sweden.
- Rockström, J. 2003. Water for food and nature in drought-prone tropics: vapour shift in rain-fed agriculture. *Royal Society Transactions B: Biological Sciences* 358 (1440): 1997–2009.
- Rockström, J.; Falkenmark, M.; Karlberg, L.; Hoff, H.; Rost, S.; Gerten, D. 2009. Future water availability for global food production: the potential of green water to build resilience to global change. *Water Resources Research* 44: W00A12. <http://dx.doi.org/10.1029/2007WR006767>
- Rockström, J.; Karlberg, L.; Wani, S.P.; Barron, J.; Hatibu, N.; Oweis, T.; Bruggeman, A.; Farahani, J.; Qiang, Z. 2010. Managing water in rainfed agriculture: the need for a paradigm shift. *Agricultural Water Management* 97 (4): 543–550. <http://dx.doi.org/10.1016/j.agwat.2009.09.009>
- Rockström, J.; Lannerstad, M.; Falkenmark, M. 2007. Assessing the water challenge of a new green revolution in developing countries. *Proceedings of the National Academy of Sciences* 104 (15): 6253–6260. <http://dx.doi.org/10.1073/pnas.0605739104>
- Rosengrant, M.W.; Cai, X.; Cline, S.A. 2002. *Global Water Outlook to 2025. Averting an Impending Crisis*. International Food Policy Research Institute, Washington, D.C.
- Roupsard, O. 1997. Ecophysiologie et diversité génétique de *Faidherbia albida* (Del.) A. Chev. (syn. *Acacia albida* Del.), un arbre à Usages Multiples d'Afrique semi-aride. Fonctionnement hydrique et efficience d'utilisation de l'eau d'arbres adultes en parc agroforestier et de juvéniles en conditions semi-contrôlées. Thèse Université H. Poincaré de Nancy I, France.
- Rufino, M.C.; Rowe, E.C.; Delve, R.J.; Giller K.E. 2006. Nitrogen cycling efficiencies through resource-poor African crop-livestock systems. *Agriculture, Ecosystems & Environment* 112 (4): 261–282. <http://dx.doi.org/10.1016/j.agee.2005.08.028>
- Sadras, V.O.; Angus, J.F. 2006. Benchmarking water-use efficiency of rainfed wheat in dry environments. *Australian Journal of Agricultural Research* 57 (8): 847–856. <http://dx.doi.org/10.1071/AR05359>
- Saeed, I.A.M.; ElNadi, A.H. 1997. Irrigation effects on the growth, yield and water use efficiency of alfalfa. *Irrigation Science* 17 (2): 63–68. <http://dx.doi.org/10.1007/s002710050023>
- Saeed, I.A.M.; ElNadi, A.H. 1998. Forage sorghum yield and water use efficiency under variable irrigation. *Irrigation Science* 18 (2): 67–71. <http://dx.doi.org/10.1007/s002710050046>
- Sakthivadivel, R.; de Fraiture, C.; Molden, D.J.; Perry, C.; Kloezen, W. 1999. Indicators of land and water productivity in irrigated agriculture. *International Journal of Water Resources Development* 15 (1/2): 161–179. <http://dx.doi.org/10.1080/07900629948998>
- Sala, O.E.; Parton, W.J.; Joyce, L.A.; Lauenroth, W.K. 1988. Primary production of the central grasslands of the United States. *Ecology* 69 (1): 40–45. <http://dx.doi.org/10.2307/1943158>
- Sanchez, P.A. 1995. Science in agroforestry. *Agroforestry Systems* 30 (1/2): 5–55. <http://dx.doi.org/10.1007/BF00708912>
- Sandhu, H.S.; Wratten, S.D.; Cullen, R. 2010. The role of supporting ecosystem services in arable farmland. *Ecological Complexity* 7 (3): 302–310. <http://dx.doi.org/10.1016/j.ecocom.2010.04.006>
- Saravanan, V.S.; McDonald, G.T.; Mollinga, P.P. 2009. Critical review of Integrated Water Resources Management: Moving beyond polarised discourse. *Natural Resources Forum* 33 (1): 76–86. <http://dx.doi.org/10.1111/j.1477-8947.2009.01210.x>
- Scheffer, M.; Carpenter, S.R.; Foley, J.A.; Folke, C.; Walker, B. 2001. Catastrophic shifts in ecosystems. *Nature* 413 (6856): 591–596.
- Scherr, S.J.; McNeely, J.A. 2008. Biodiversity conservation and agricultural sustainability: towards a new paradigm of 'ecoagriculture' landscapes. *Philosophical Transactions of the Royal Society B* 363: 477–494. <http://dx.doi.org/10.1098/rstb.2007.2165>
- Schmitt, C.B.; Burgess, N.D.; Coad, L.; Belokurov, A.; Besançon, C.; Boisrobert, L.; Campbell, A.; Fish, L.; Gliddon, D.; Humphries, K.; Kapos, V.; Loucks, C.; Lysenko, I.; Miles, L.; Mills, C.; Minnemeyer, S.; Pistorius, T.; Ravilious, C.; Steininger, M.; Winkel, G. 2009. Global analysis of the protection status of the world's forests. *Biological Conservation* 142 (10): 2122–2130. <http://dx.doi.org/10.1016/j.biocon.2009.04.012>
- Schroth, G.; Sinclair, F.L. (eds) 2003. *Trees crops and soil fertility: concepts and research methods*. Wallingford: CAB International.
- Schuman, G.E.; Janzen, H.H.; Herrick J.E. 2002. Soil carbon dynamics and potential carbon sequestration by rangelands. *Environmental Pollution* 116 (3): 391–396. [http://dx.doi.org/10.1016/S0269-7491\(01\)00215-9](http://dx.doi.org/10.1016/S0269-7491(01)00215-9)

- SDC (Swiss agency for Development and Cooperation). 2005. *Gender & Water: Mainstreaming gender equality in water, hygiene and sanitation interventions*. Bern: Swiss Agency for Development and Cooperation.
- Seckler, D.; Molden, D.; Sakhivadivel, R. 2003. The concept of efficiency in water resources management and policy. http://www.iwmi.cgiar.org/Publications/CABI_Publications/CA_CABI_Series/Water_Productivity/Unprotected/0851996698ch3.pdf In: Kijne, J.W.; Barker, R.; Molden, D. eds. *Water productivity in agriculture: limits and opportunities for improvement*. Comprehensive Assessment of Water Management in Agriculture Series 1. Wallingford, UK: CABI; Colombo, Sri Lanka: International Water Management Institute (IWMI). pp 37–51.
- Sengupta, S.; Mitra, K.; Saigal, S.; Gupta, R.; Tiwari, S.; Peters, N. 2003. Developing markets for watershed protection services and improved livelihoods in India. Winrock International India, New Delhi and International Institute for Environment and Development, London (unpublished draft). <http://pubs.iied.org/pubs/pdfs/G00399.pdf>
- Senthilkumar, K.; Bindraban, P.S.; de Boer, W.; de Ridder, N.; Thiyagaran; T.M.; Giller K.E. 2009. Characterising rice-based farming systems to identify opportunities for adopting water efficient cultivation methods in Tamil Nadu, India. *Agricultural Water Management* 96 (12): 1851–1860. <http://dx.doi.org/10.1016/j.agwat.2009.08.007>
- Shah, T. 2007. The groundwater economy of South Asia: an assessment of size, significance and socio-ecological impacts. http://www.iwmi.cgiar.org/Publications/CABI_Publications/CA_CABI_Series/Ground_Water/protected/Giordano_1845931726-Chapter2.pdf In: Giordano, M.; Villholth, K.G.; eds. *The agricultural groundwater revolution: opportunities and threats to development*. Comprehensive Assessment of Water Management in Agriculture Series 3. Wallingford, UK: CABI. pp 7–36.
- Shah, T. 2009. *Taming the anarchy: groundwater governance in South Asia*. Washington, DC, USA: Resources for the Future; Colombo, Sri Lanka: International Water Management Institute (IWMI). 310p.
- Shiferaw, B.A.; Okello, J.; Reddy, R.V. 2009. Adoption and adaptation of natural resource management innovations in smallholder agriculture: reflections on key lessons and best practices. *Environment, Development and Sustainability* 11: 601–619.
- Shiklomanov, I.A. 2000. Appraisal and assessment of world water resources. *Water International* 25 (1): 11–32. <http://dx.doi.org/10.1080/02508060008686794>
- Shiklomanov, I.A.; Rodda, J. 2003: *World Water Resources at the Beginning of the 21st Century*. UNESCO, Paris, France.
- Shmida, A.; Darom, D. 1992. *Handbook of trees and bushes of Israel* (in Hebrew). Jerusalem: Keter Publishing House Ltd. 328 pages.
- Singh, R.P.; Ong, C.K.; Saharan, N. 1989. Above and below-ground interactions in alley cropping in semiarid India. *Agroforestry Systems* 9 (3): 259–274. <http://dx.doi.org/10.1007/BF00141088>
- Singh, O.; Sharma, A.; Singh, R.; Shah, T. 2004. Virtual water trade in dairy economy. irrigation water productivity in Gujarat. *Economical and Political Weekly* 39 (31): 3492–3497.
- Siriri, D.; Ong, C.K.; Wilson, J.; Boffa, J.M.; Black, C.R. 2010. Tree species and pruning regime affect crop yield on bench terraces in SW Uganda. *Agroforestry Systems* 78 (1): 65–77, <http://dx.xoi.org/10.1007/s10457-009-9215-0>
- Smakhtin, V.U.; Anpuithas, M. 2006. *An Assessment of Environmental Flow Requirements of Indian River Basins*. IWMI Research Report 107. Colombo, Sri Lanka: International Water Management Institute. 36 pp
- Smakhtin, V.; Eriyagama, N. 2008. Developing a software package for global desktop assessment of environmental flows. *Environmental Modelling & Software* 23 (12): 1396–1406. <http://dx.doi.org/10.1016/j.envsoft.2008.04.002>
- Smakhtin, V.; Revenga, C.; Döll, P. 2004. *Taking into account environmental water requirements in global-scale water resources assessments*. Comprehensive Assessment Research Report 2. Colombo, Sri Lanka: Comprehensive Assessment Secretariat.
- Smeal, D.; O'Neill, M.K.; Arnold, R.N. 2005. Forage production of cool season pasture grasses as related to irrigation. *Agricultural water management* 76 (3): 224–236. <http://dx.doi.org/10.1016/j.agwat.2005.01.014>
- Smith, K.A.; Cohen, F. 2004. Impacts of land management on fluxes of trace greenhouse gases. *Soil Use and Management* 20: 255–263. <http://dx.doi.org/10.1111/j.1475-2743.2004.tb00366.x>
- Snellen, W.B.; Schrevel, A. 2004. IWRM: for sustainable use of water. 50 years of international experience with the concept of integrated water management. Background document to the FAO/Netherlands Conference on Water for Food and Ecosystems. Wageningen: Ministry of Agriculture, Nature and Food Quality.
- Snellen, W.B.; Van 't Klooster, C.E.; Hoving, I. 2010. Irrigation and water use in agro-production systems. In: De Visser, C et al. eds. *Exploring the potential of high technological and eco-efficient agriculture*. PPO publication 395. Wageningen.

- Solomon, S.; Qin, D.; Manning, M.; Chen, Z.; Marquis, M.; Averyt, K.B.; Tignor, M.; Miller, H.L. eds. 2007. *Climate Change 2007: Working Group I: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press. http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html
- Spergel, B.; Taïeb P. 2008. *Rapid review of conservation trust funds*. Prepared for the CFA Working Group on Environmental Funds. Conservation Finance Alliance
- Springate-Baginski, O.; Allen, D.; Darwall, W.R.T. eds. 2009. *An integrated wetland assessment toolkit: a guide to good practice*. Gland, Switzerland: IUCN and Cambridge, UK: IUCN Species Programme. xv+144p.
- Staal, S.; Owango, M.; Muriuki, G.; Lukuyu, B.; Musembi, F.; Bwana, O.; Muriuki, K.; Gichungu, G.; Omoro, A.; Kenyanjui, B.; Njubi, D.; Baltenweck, I.; Thorpe, W. 2001. *Dairy systems characterization of the Greater Nairobi Milk-shed*. SDP Research Report. Kenya Ministry of Agriculture and Rural Development, Kenya Agricultural Research Institute, International Livestock Research Institute, Nairobi, Kenya
- Steduto, P.; Hsiao, T.C.; Fereres, E. 2007. On the conservative behavior of biomass water productivity. *Irrigation Science* 25 (3): 189–207. <http://dx.doi.org/10.1007/s00271-007-0064-1>
- Steffan-Dewenter, I.; Munzenberg, U.; Tschamtko, T. 2001. Pollination, seed set and seed predation on a landscape scale. *Proceedings of the Royal Society of London B* 268: 1685–1690.
- Steinfeld, H.; Gerber, P.; Wassenaar, T.; Castel, V.; Rosales, M.; de Haan, C. 2006. *Livestock's long shadow: environmental issues and options*. Food and Agriculture Organization (FAO), Rome, Italy.
- Steinmann, P.; Keiser, J.; Bos, R. Tanner, M.; Utzinger J. 2006. Schistosomiasis and water resources development: systematic review, meta-analysis, and estimates of people at risk. *The Lancet Infectious Diseases* 6 (7): 411–425. [http://dx.doi.org/10.1016/S1473-3099\(06\)70521-7](http://dx.doi.org/10.1016/S1473-3099(06)70521-7)
- Stringham, T.K.; Krueger, W.C.; Shaver, P.L. 2003. State and transition modeling: a process based approach. *Journal of Range Management* 56 (2): 106–113.
- Strzepek, K.; Boehlert, B. 2010. Competition for water for the food system. *Philosophical Transactions of the Royal Society B* 365: 2927–2940. <http://dx.doi.org/10.1098/rstb.2010.0152>
- Stuyt, L. C.P. M.; van Bakel, P.J.T.; van Dijk, W.; de Groot, W.J.M.; van Kleef, J.; Noij, I.G.A.M.; van der Schoot, J.R.; van den Toorn, A.; Visschers, R. 2009. *Samengestelde, peilgestuurde drainage in Nederland*. Alterra report.
- Sudarshan, R.M. 2001. Managing Ecosystems for Women's Health and Sustainable Development. An Illustration from the Kumaon, Uttaranchal. *Indian Journal of Gender Studies* 8 (2): 207–222. <http://dx.doi.org/10.1177/097152150100800204>
- Sullivan, C.; Huntingford, C. 2009. *Water resources, climate change and human vulnerability*. 18th World IMACS / MODSIM Congress, Cairns, Australia 13–17 July 2009. <http://mssanz.org.au/modsim09>
- Swallow, B.; Meinzen-Dick, R. 2009. Payment for Environmental Services: interactions with property rights and collective action. In: Beckmann V.; Padmanabhan, M. eds. *Institutions and Sustainability: Political Economy of Agriculture and the Environment*. Springer. pp 243–265.
- Swinton, S.; Lupi, G.; Robertson, P.; Landis, D., 2006. Ecosystem services from agriculture: looking beyond the usual suspects. *American Journal of Agricultural Economics* 88 (5): 1160–1166.
- Swift, M.J.; Izac, M.N.; van Noordwijk, M. 2004. Biodiversity and ecosystem services in agricultural landscapes – are we asking the right questions? *Agriculture, Ecosystems & Environment* 104 (1): 113–134. <http://dx.doi.org/10.1016/j.agee.2004.01.013>
- Szuster, B.; Molle, F.; Flaherty, M.; Srijantr, T. 2003. Socioeconomic and environmental implications of inland shrimp farming in the Chao Phraya Delta. In: Molle, F.; Srijantr, T. eds. *Perspective on Social and agricultural Change in the Chao Phraya Delta*. White Lotus Press, Bangkok, Thailand.
- Tacoli, C. 2011. *Not only climate change: mobility, vulnerability and socio-economic transformations in environmentally fragile areas of Bolivia, Senegal and Tanzania*. Human Settlements Working Paper Series 28. London: International Institute for Environment and Development. <http://pubs.iied.org/10590IIED.html>
- Tarawali, S.; Herrero, M.; Descheemaeker, K.; Grings, E.; Blümmel, M. 2011. Pathways for sustainable development of mixed crop livestock systems: taking a livestock and pro-poor approach. *Livestock Science*, in press. <http://dx.doi.org/10.1016/j.livsci.2011.03.003>
- TEEB (The Economics of Ecosystems and Biodiversity). 2010. *The Economics of Ecosystems and Biodiversity: mainstreaming the economics of nature: A synthesis of the approach, conclusions and recommendations of TEEB*. United Nations Environment Program. <http://www.teebweb.org>
- Tenge, A.J.; De Graaff, J.; Hella, J.P. 2004. Social and economic factors affecting the adoption of soil and water conservation in West Usambara highlands, Tanzania. *Land Degradation and Development* 15 (2): 99–114. <http://dx.doi.org/10.1002/ldr.606>
- Tennant, D.L. 1976. Instream flow regimens for fish, wildlife, recreation and related environmental resources. *Fisheries* 1: 6–10.

- Tharme, R.E. 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications* 19 (5–6): 397–441. <http://dx.doi.org/10.1002/rra.736>
- Thiombiano, L.; M. Malo, M. 2009. Scaling up conservation agriculture in africa: strategy and approaches. *FAO, SFE Technical serie*. 31 p. Rome: Food and Agriculture Organization of the United Nations.
- Thompson, L.; Swatuk, L. 2000. Gender and ecosystems: reframing Southern African “security”. Bellville: University of the Western Cape.
- Thornton, P.K. 2010. Livestock production: recent trends, future prospects. *Philosophical Transactions of the Royal Society B* 365: 2853–2867. <http://dx.doi.org/10.1098/rstb.2010.0134>
- Thornton, P.; Herrero, M. 2001. Integrated crop-livestock simulation models for scenario analysis and impact assessment. *Agricultural Systems* 70 (2–3): 581–602. [http://dx.doi.org/10.1016/S0308-521X\(01\)00060-9](http://dx.doi.org/10.1016/S0308-521X(01)00060-9)
- Thornton, P.K.; Kruska, R.L.; Henninger, N.; Kristjanson, P.M.; Reid, R.S.; Atieno, F.; Odero, A.N.; Ndegwa, T. 2002. *Mapping poverty and livestock in the developing world*. Nairobi: International Livestock Research Institute.
- Tien, N.T.H.; Trang, N.T.; Dang, N.H.; Thinh, D.V.; Phuong, N.T.D. 2010. Situation analysis report on highland aquatic resources conservation and sustainable development in Northern and Central Vietnam. Research Institute for Aquaculture No. 1, Viet Nam.
- TNC (The Nature Conservancy). 2007. World Water Day 2007. Will a dam ruin a river and its communities? <http://www.nature.org/tncscience/worldwaterday/features/honduras.html>
- TNC (The Nature Conservancy). 2008. Brazil's Atlantic Forest: Places we protect. Plant a billion trees for water production. <http://www.nature.org/initiatives/freshwater/work/art24057.html>
- TNC (The Nature Conservancy). 2010. Conservation Partnerships. Learn about our exciting partnerships with government and communities. <http://www.nature.org/partners/commonground/partnership/savannah.html> (accessed 06Oct2010)
- Tschakert, P. 2007. Environmental services and poverty reduction: Options for smallholders in the Sahel. *Agricultural Systems* 94 (1): 75–86. <http://dx.doi.org/10.1016/j.agsy.2005.07.010>
- Tuan, T.H.; Xuan, M.V.; Do Nam; Navrud, S. 2009. Valuing direct use values of wetlands: A case study of Tam Giang–Cau Hai lagoon wetland in Vietnam. *Ocean & Coastal Management* 52 (2): 102–112. <http://dx.doi.org/10.1016/j.ocecoaman.2008.10.011>
- Turner, M.D. 2004. Political ecology and the moral dimensions of “resource conflicts”: the case of farmer-herder conflicts in the Sahel. *Political Geography* 23: 863–889.
- Turner, M.D.; Williams, T.O. 2002. Livestock Market Dynamics and Local Vulnerabilities in the Sahel. *World Development* 30 (4): 683–705. [http://dx.doi.org/10.1016/S0305-750X\(01\)00133-4](http://dx.doi.org/10.1016/S0305-750X(01)00133-4)
- Twomlow, S.; Mugabe F.T.; Mwale, M.; Delve, R.; Nanja, D.; Carberry, P.; Howden, M. 2008. Building adaptive capacity to cope with increasing vulnerability due to climatic change in Africa – A new approach. *Physics and Chemistry of the Earth, Parts A/B/C* 33 (8–13): 780–787. <http://dx.doi.org/10.1016/j.pce.2008.06.048>
- UCC-Water. 2008. Addressing environmental aspects of IWRM. Concepts and Issues Paper No. 1. Horsholm, Denmark: UCC Water.
- UNCCD. 2010. United Nations Decade for Deserts and the Fight against Desertification. Bonn: United Nations Convention to Combat Desertification. <http://undd.unccd.int/>
- UNDP, UNEP, World Bank, WRI. 2000. *World Resources 2000–2001: People and ecosystems: The fraying web of life*. Washington DC: World Resources Institute, United Nations Development Programme, United Nations Environment Programme, World Bank
- UNEP. 2006a. *Marine and coastal ecosystems and human wellbeing: A synthesis report based on the findings of the Millennium Ecosystem Assessment*. Nairobi: United Nations Environment Program. 76 pp.
- UNEP. 2006b. People and forest: forest destruction fuels East Africa's drought. Nairobi: United Nations Environment Program. <http://www.peopleandplanet.net/?lid=28180&topic=23§ion=32>
- UNEP. 2007. *Global Environment Outlook. GEO-4. Environment for Development*. Nairobi: United Nations Environment Program.
- UNEP. 2009a. Ecosystem Management Programme. A new approach to sustainability. Nairobi, United Nations Environment Program. 24 pp.
- UNEP. 2009b. *Water security and ecosystem services. The critical connection*. A contribution to the United Nations World Water Assessment Programme. Nairobi, United Nations Environment Program. 56 pp.
- UNEP. 2010. Blue harvest: inland fisheries as an ecosystem service. Penang: WorldFish Center.
- UNFPA. 2009. *The State of World Population 2009*. Facing a changing world: women, population and climate. United Nations Population Fund: New York, USA

- van Breugel, P.; Herrero, M.; van de Steeg, J.; Peden, D. 2010. Livestock water use and productivity in the Nile Basin. *Ecosystems* 13 (2): 205–221. <http://dx.doi.org/10.1007/s10021-009-9311-z>
- van der Ploeg, S.; de Groot, R.S.; Wang, Y. 2010. The TEEB Valuation Database: overview of structure, data and results. Foundation for Sustainable Development, Wageningen, the Netherlands.
- van der Zijpp, A.J.; Verreth, J.A.J.; Le Quang Tri; van Mensvoort, M.E.F.; Bosma, R.H.; Beveridge, M.C.M. (eds) 2007. *Fishponds in farming systems*. Wageningen Publishers, Netherlands.
- van Koppen B.; Moriarty, P.; Boelee, E. 2006. *Multiple-use water services to advance the millennium development goals*. Research Report 98. Colombo, Sri Lanka: International Water Management Institute, 44p.
- van Koppen, B.; Smits, S.; Moriarty, P.; Penning de Vries, F.; Mikhail, M.; Boelee, E. 2009. *Climbing the Water Ladder : Multiple-use water services for poverty reduction*. The Hague, The Netherlands, IRC International Water and Sanitation Centre and International Water Management Institute. (TP series 52) 213 p. <http://www.irc.nl/page/49660>
- van Noordwijk, M.; Cadish, G.; Ong, C.K. 2006. *Below ground interactions in tropical agroecosystems, concepts and models with multiple plant components*. Wallingford: CAB International. 439 pages.
- van 't Klooster, C.E.; Schrevel, A.; Jansen, H.C.; Froebrich, J. 2010. *How to implement the CSD-17 message on water and agriculture*. Alterra report 2076. Wageningen UR.
- Verdegem, M.C.J.; Bosma, R.H.; Verreth, J.A.J. 2006. Reducing water use for animal production through aquaculture. *Water Resources Development* 22 (1): 101–113. <http://dx.doi.org/10.1080/07900620500405544>
- Vereijken, P. 2003. Transition to multifunctional land use and agriculture. *Netherlands Journal of Agricultural Science* 50 (2): 171–179.
- Vlek, P.L.G.; Le, Q.B.; Tamene, L. 2010. Assessment of land degradation, its possible causes and threat to food security in sub Saharan Africa. In: Lal R.; Stewart, B.A. eds. *Advances in soil science food security and soil quality*. CRC Press, Boca Raton, pp 57–86.
- von Braun, J. 2007. *The world food situation. new driving forces and required actions*. Washington DC: International Food Policy Research Institute.
- Vörösmarty, C.J.; Lévêque, C.; Revenga, C.; Bos, R.; Caudill, C.; Chilton, J.; Douglas, E.M.; Meybeck, M.; Prager, D. 2005. Fresh Water. In: Hassan, R.; Scholes, R.; Ash N. eds. *Ecosystems and Human Well-being: Current State and Trends. Findings of the Condition and Trends Working Group*. Millennium Ecosystem Assessment V1. World Resources Institute, Island Press, Washington DC. pp 165–207.
- Vörösmarty, C.J.; McIntyre, P.B.; Gessner M.O.; Dudgeon, D.; Prusevich, A.; Green, P.; Glidden, S.; Bunn, S.E.; Sullivan, C.A.; Reidy Liermann C.; Davies, P.M. 2010. Global threats to human water security and river biodiversity. *Nature* 467: 555–561. <http://dx.doi.org/10.1038/nature09440>
- Wallace, J.S. 1996. The water balance of mixed tree-crop systems. In: Ong, C.K.; Huxley, P. (eds) *Tree-crop interactions: a physiological approach*. Wallingford: CAB International, pp 189–233.
- Wani, S.P.; Rockström, J.; Oweis, T. eds. 2009a. *Rainfed Agriculture: Unlocking the Potential*. Comprehensive Assessment of Water Management in Agriculture Series 7. Wallingford, UK: CABI; Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT); Colombo, Sri Lanka: International Water Management Institute (IWMI). http://www.iwmi.cgiar.org/Publications/CABI_Publications/CA_CABI_Series/Rainfed_Agriculture/Protected/Rainfed_Agriculture_Unlocking_the_Potential.pdf
- Wani, S.P.; Sreedevi, T.K.; Rockström, J.; Ramakrishna, Y.S. 2009b. Rainfed agriculture: past trends and future prospects. In: Wani, S.P.; Rockström, J.; Oweis, T. eds. *Rainfed agriculture: unlocking the potential*. Comprehensive Assessment of Water Management in Agriculture Series 7. Wallingford, UK: CABI; Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT); Colombo, Sri Lanka: International Water Management Institute (IWMI). pp 1–35. http://www.iwmi.cgiar.org/Publications/CABI_Publications/CA_CABI_Series/Rainfed_Agriculture/Protected/Rainfed_Agriculture_Unlocking_the_Potential.pdf
- Warriner, G.K.; Moul, T.M. 1992. Kinship and personal communication – network influences on the adoption of agriculture conservation technology. *Journal of rural studies* 8 (3): 279–291. [http://dx.doi.org/10.1016/0743-0167\(92\)90005-Q](http://dx.doi.org/10.1016/0743-0167(92)90005-Q)
- Washington-Allen, R.A.; Ramsey, R.D.; West, N.E.; Norton, B.E. 2008. Quantification of the ecological resilience of drylands using digital remote sensing. *Ecology and Society* 13(1): 33. <http://www.ecologyandsociety.org/vol13/iss1/art33/>
- Washington-Allen, R.A.; Salo, L.F. 2007. Meeting review: catastrophic thresholds, perspectives, definitions, and applications. *Bulletin of the Ecological Society of America* 88(2): 219–225. [http://www.esajournals.org/doi/full/10.1890/0012-9623\(2007\)88%5B219%3ACTPDAA%5D2.0.CO%3B2](http://www.esajournals.org/doi/full/10.1890/0012-9623(2007)88%5B219%3ACTPDAA%5D2.0.CO%3B2)
- Watson, R.T.; Noble, I.R.; Bolin, B.; Ravindranath, N.H.; Verardo, D.J.; Dokken, D.J. Eds. 2000. *Land use, land use change and forestry. A Special Report of the IPCC*. Cambridge: Cambridge University Press, 375p. http://www.ipcc.ch/ipccreports/sres/land_use/index.php?idp=0

- WCD (World Commission on Dams). 2000. *Dams and Development: A New Framework for Decision-Making*. Earthscan Publications, London and Sterling, VA.
http://hqweb.unep.org/dams/WCD/report/WCD_DAMS%20report.pdf
- Welcomme, R.L.; Cowx, I.G.; Coates, D.; Béné, C.; Funge-Smith, S.; Halls, A.; Lorenzen, K. 2010. Inland capture fisheries. *Philosophical Transactions of the Royal Society B* 365: 2881–2896.
<http://dx.doi.org/10.1098/rstb.2010.0168>
- Westing, A.H. 1992. Environmental refugees – a growing category of displaced persons. *Environmental Conservation* 19 (3): 201–207. <http://dx.doi.org/10.1017/S037689290003099X>
- Wetlands International (2007) Integrated management of wetlands in Ruoergai Plateau and Altai Mountains to support biodiversity conservation and sustainable development.
<http://www.wetlands.org/Default.aspx?TabId=59&mod=601&articleType=ArticleView&articleId=1954>
 Accessed 06Oct2010.
- WFP (World Food Program). 2010. Hunger stats. <http://www.wfp.org/hunger/stats>, Accessed 24 October 2010.
- WHO (World Health Organization). 2006. *guidelines for the safe use of wastewater, excreta and greywater in agriculture*. Geneva: World Health Organization.
http://www.who.int/water_sanitation_health/wastewater/gsuww/en/index.html
- WHO (World Health Organization). 2007. Buruli ulcer disease (*Mycobacterium ulcerans* infection). Fact Sheet 1999. Geneva: World Health Organization. <http://www.who.int/mediacentre/factsheets/fs1999/en/>
- Wichelns, D. 2010. Virtual water: a helpful perspective, but not a sufficient policy criterion. *Water Resources Management* 24 (10): 2203–2219. <http://dx.doi.org/10.1007/s11269-009-9547-6>
- Wilson, M.; Carpenter, S. 1999. Economic valuation of freshwater ecosystem services in the United States: 1971–1997. *Ecological Applications* 9 (3): 772–783.
[http://dx.doi.org/10.1890/1051-0761\(1999\)009\[0772:EVOFES\]2.0.CO;2](http://dx.doi.org/10.1890/1051-0761(1999)009[0772:EVOFES]2.0.CO;2)
- Wilson, T. 2007. Perceptions, practices, principles and policies in provision of livestock–water in Africa. *Agricultural Water Management* 90 (1–2): 1–12. <http://dx.doi.org/10.1016/j.agwat.2007.03.003>
- Wittemyer, G.; Elsen, P.; Bean, W.T.; Burton, C.O.; Brashares, J.S. 2008. Accelerated human population growth at protected area edges. *Science* 321 (5885): 123–126. <http://dx.doi.org/10.1126/science.1158900>
- Wolters, W. 1992. *Influences on the efficiency of irrigation water use*. ILRI Publication 51. Wageningen: International Institute for Land Reclamation and Improvement.
<http://content.alterra.wur.nl/Internet/webdocs/ilri-publicaties/publicaties/Pub51/Pub51.pdf>
- Wood, S.; Sebastian, K.; Scherr, S.J. 2000. *Pilot analysis of global ecosystems: Agroecosystems*. Washington, DC, International Food Policy Research Institute and World Resources Institute.
<http://www.wri.org/publication/pilot-analysis-global-ecosystems-agroecosystems>
- Wood, A.; van Halsema, G.E. 2008. *Scoping agriculture-wetland interactions. Towards a sustainable multiple response strategy*. FAO Water reports 33. Rome: Food and Agriculture Organization of the United Nations.
<http://www.fao.org/nr/water/docs/WaterReports33.pdf>
- Woomer, P.L.; Touré, A.; Sall, M. 2004. Carbon stocks in Senegal's Sahel transition zone. *Journal of Arid Environments* 59 (3): 499–510. <http://dx.doi.org/10.1016/j.jaridenv.2004.03.027>
- World Bank. 2003. *Reaching the Rural Poor*. Module 9: Investments in agricultural water. Washington D.C.
<http://go.worldbank.org/NPZZQF6190>
- World Bank. 2008. *Investment in agricultural water for poverty reduction and economic growth in sub-Saharan Africa. Synthesis report*. A collaborative program of AFDB, FAO, IFAD, IWMI, and the World Bank. Washington: the World Bank. <http://www.fanrpan.org/documents/d00508/>
- World Bank. 2009. *Minding the stock: bringing public policy to bear on livestock sector development*. The World Bank, Agriculture and Rural development Department. Washington, DC.
<http://siteresources.worldbank.org/INTARD/Resources/FinalMindingtheStock.pdf>
- WRG. 2009. *Charting Our Water Future: Economic Frameworks to Inform Decision-making*, The 2030 Water Resources Group. http://www.2030waterresourcesgroup.com/water_full/Charting_Our_Water_Future_Final.pdf
- WRI (World Resources Institute). 1998. *World Resources 1998–99: environmental change and human health*. Washington DC: World Resources Institute, the United Nations Environment Programme, the United Nations Development Programme, and The World Bank.
<http://www.wri.org/publication/world-resources-1998-99-environmental-change-and-human-health>
- WRI (World Resources Institute). 2005. *World resources 2005 – The wealth of the poor: managing ecosystem to fight poverty*. Washington DC: World Resources Institute. 255 pp.
http://archive.wri.org/population/pubs_pdf.cfm?PubID=4073
- WWA (World Water Assessment Programme of the United Nations). 2006. *Water, a shared responsibility (WWDR2)*. 2nd United Nations World Water Development Report. Paris: UNESCO, New York: Berghahn Books. <http://www.unesco.org/water/wwap/wwdr/wwdr2/>

- WWA (World Water Assessment Programme of the United Nations). 2009. *Water in a changing world (WWDR3)*. 3rd United Nations World Water Development Report. Paris: UNESCO Publishing, London: Earthscan.
<http://www.unesco.org/water/wwap/wwdr/wwdr3/>
- WWF (World Wildlife Fund). 2009a. Wetland restoration: Sand River, South Africa. http://wwf.panda.org/who_we_are/wwf_offices/south_africa/index.cfm?uProjectID=ZA0313 Accessed 06Oct2010.
- WWF (World Wildlife Fund). 2009b. Freshwater conservation programme – Phase II.
http://wwf.panda.org/who_we_are/wwf_offices/brazil/index.cfm?uProjectID=BR0939 accessed 06Oct2010.
- WWF (World Wildlife Fund). 2009c. Managing community resources in the Peruvian Amazon.
http://wwf.panda.org/es/sala_redaccion/proyectos/index.cfm?uProjectID=PE0867 accessed 06Oct2010.
- WWF (World Wildlife Fund). 2010a. Payments for Ecosystem Services.
<http://www.worldwildlife.org/science/projects/ecosystemserv/item1987.html> accessed 10Mar2010.
- WWF (World Wildlife Fund). 2010b. Monitoring the glaciers of the Himalayas.
http://wwf.panda.org/who_we_are/wwf_offices/nepal/index.cfm?uProjectID=NP0898 accessed 06Oct2010.
- Xu, Z.; Bennett, M.T.; Tao, R.; Xu, J. 2004. China's Sloping Land Conversion Programme four years on: current situation, pending issues. *International Forestry Review* 6(3–4): 317–326.
- Zhang, W.; Ricketts, T.H.; Kremen, C.; Carney, K.; Swinton, S.M. 2007. Ecosystem services and dis-services to agriculture. *Ecological Economics* 64 (2): 253–260. <http://dx.doi.org/10.1016/j.ecolecon.2007.02.024>
- Zomer, R.J.; Trabucco, A.; Coe, R.; Place, F. 2009. *Trees on farm: analysis of global extent and geographical patterns of agroforestry*. ICRAF Working Paper no. 89. Nairobi: World Agroforestry Centre.
<http://www.worldagroforestrycentre.org/downloads/publications/PDFs/WP16263.PDF>
- Zygmunt, J. 2007. *Hidden waters: a briefing*. London: Waterwise.
http://www.waterfootprint.org/Reports/Zygmunt_2007.pdf

APPENDICES

1 – Ecosystem Management (UNEP)	111
2 – Water for food and ecosystems (FAO 2005)	114
3 – Ecosystems and human well-being (MA 2005a)	115
4 – Environment for development (GEO4)	116
5 – Water for food, water for life (CA 2007)	117
6 – Water in a changing world (WWDR3)	119
7 – International Assessment of Agricultural Knowledge, Science, and Technology for Development (IAASTD)	120
8 – Impact of agriculture on climate change	121
9 – From farming systems to agroecosystems	122
A9.1. Classification and numbers	122
A9.2. Livestock systems and drivers	123
A9.3. Agroecosystems: towards a broader vision of production systems	125
A9.4. Anthropogenic biomes	127
10 – Food from non-agricultural ecosystems	128
A10.1. Protecting wetlands in Madagascar	128
A10.2. Small-scale highland fisheries enhancement in Asia	128
11 – Regulatory ecosystem services in a watershed	130
12 – Ecosystem services: values and trade-offs	131
A12.1. Ecosystem services in the Mississippi River Delta	131
A12.2. Global values of ecosystem services	131
A12.3. Polyscope tool for comparing impacts on ecosystem services	134
A12.4. Potential benefits of multifunctional agriculture in Minnesota	135
13 – Opportunities and trade-offs between animal production, ecosystems, and livelihoods	137
A13.1. Exploring trade-offs between livestock, livelihoods, and ecosystems	137
A13.2. Opportunities for sustainable livestock systems	140
A13.3. Integrated watershed management for improved water productivity and ecosystem services in Ethiopia	140
14 – Options for sustainable agriculture in arid environments	141
A14.1. Low tillage and other soil improvement measures	141
A14.2. Sustainable crop selection for arid agroecosystems	142
A14.3. Arboreal pastures	144
A14.4. Examples of water collection in arid areas	144
15 – Wetlands	146
A15.1. Integrated wetland assessment in Cambodia and Tanzania	146
A15.2. Integrated management of wetlands in China	146
A15.3. Wetlands and livelihoods in South Africa	147
16 – Integration of aquaculture in agroecosystems	149
A16.1. Aquaculture in rice fields	149
A16.2. From enhanced fisheries in wetlands to horizontally integrated land-based (marine) aquaecosystems	151
A16.3. Aquaculture in irrigation schemes	152

17 – Ecological agriculture	154
A17.1. Conservation farming	154
A17.2. Small-scale sustainable agriculture in Kenya	155
18 – Water calculations: footprints, availability, requirements, and efficiency	156
A18.1. Calculation with PODIUM	156
A18.2. Water footprints and virtual water trade	156
A18.3. Irrigation efficiency	157
A18.4. Livestock water productivity (LWP) in the Nile Basin	158
A18.5. Increasing water use efficiency in aquaculture	159
19 – Agroecosystems, water, and health	162
20 – Role of technology	164
21 – Payments for ecosystem services (PES)	165
A21.1. Water services in Sukhomarjri, India (FAO 2007b)	165
A21.2. China’s Grain for Green program (FAO 2007b)	165
A21.3. Forest reserve water fund in Guatemala	165
A21.4. Brazil’s Water Producer Program	166
22 – Integrated Water Resources Management	167
A22.1. IWRM Process Cycle	167
A22.2. Regulatory instruments in IWRM	168
A22.3. National basin dialogue in Jordan	169
23 – Catering for climate change	170
A23.1. River forest action plan in the United States	170
A23.2. Monitoring glaciers in Nepal	170
A23.3. Freshwater conservation program for Brazil	171
24 – Environmental flows	173
A24.1. Calculation of environmental water requirements (EWR)	173
A24.2. Pangani River Basin Management Project in Kenya and Tanzania	173
A24.3. Assessing environmental flows in Honduras	174
A24.4. Sustainable Rivers Project USA – Savannah River	174
A24.5. Environmental flow assessment in Vietnam	175
25 – Ecosystem restoration	177
A25.1. River restoration in Jordan	177
A25.2. Managing community resources in the Peruvian Amazon	177
A25.3. Restoration of the Chilika Lagoon, India	178

Appendix 1

Ecosystem Management (UNEP)

The UNEP Ecosystem Management Programme (UNEP 2009a; <http://www.unep.org/ecosystemmanagement/>) strives to change the sectoral approach to environmental management and move to an integrated approach towards sustainable management of forests, land, freshwater, and coastal ecosystems. UNEP identified 11 threatened ecosystem services as priorities within its mandate (Figure A1), with the top six in the center: climate regulation, water regulation, natural hazard regulation, energy, freshwater, nutrient cycling.

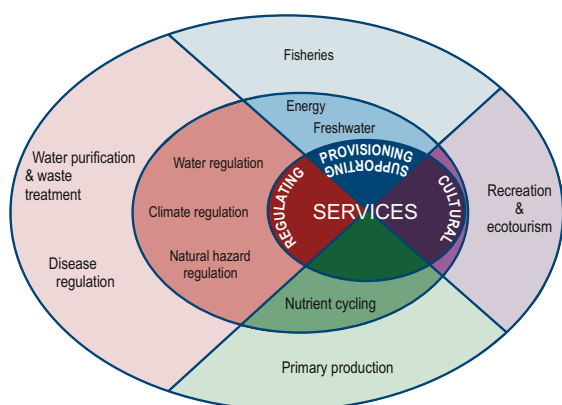


Figure A1. Eleven ecosystem services categories prioritized by UNEP. The lopsided diagram illustrates UNEP's role as being most significant in the regulating (regulatory) services and with the six priority services closest to the centre and five secondary services at the periphery.

UNEP's Ecosystem Management Programme takes a holistic view of the links between ecosystem services and human well-being, considering ecosystem concerns in relation to development concerns, recognizing the interdependence of ecosystem services and human needs, and acknowledging the diverse effects on various social groups of declining ecosystem services. This approach invites all the relevant stakeholders to take part in collaborative decision making, priority setting and conflict resolution. The Ecosystem Management Programme is guided by five interlinked elements that each offers an entry point for UNEP intervention: human well-being, indirect drivers of change, direct drivers of change, ecosystem functioning and ecosystem services (Figure A2).

Using an ecosystem approach, natural resource managers can analyze the drivers shaping an

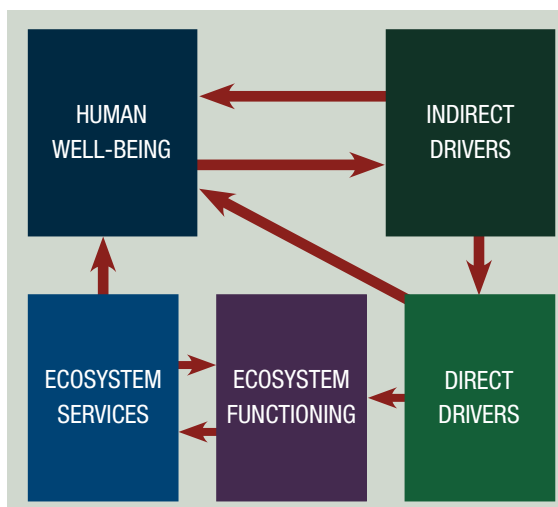


Figure A2. Conceptual framework of the Ecosystem Management Programme.

ecosystem, followed by design and implementation of appropriate action. Successful implementation would make the case, generate knowledge, turn knowledge to action and be followed up by monitoring, evaluation and feedback:

- *Step 1: Making the case towards understanding and accepting an ecosystem approach.* Most countries measure development and wealth in economic terms without considering the value that ecosystems provide towards overall human well-being. A new organizational mindset, coupled with institutional changes to facilitate collaboration between sectors, may be required for countries to fully understand, adopt and implement the ecosystem approach. Countries and other stakeholders have to be involved in a dialogue on ecosystems and development through workshops on ecosystem management; rapid assessments of the linkages between ecosystem services and human well-being; accessible guidelines for various groups of stakeholders; and dissemination of key messages.
- *Step 2: Generating knowledge,* aimed at the maintenance and resilience of ecosystem functioning. The Ecosystem Management Programme will support this by establishing net

works for data and information exchange on ecosystem services; facilitating ecosystem level assessments; identifying relevant ecosystem services and their relation to human well-being; identifying direct and indirect drivers of ecosystem change; developing plausible scenarios based on the impacts of direct and indirect drivers over time; and building capacity to undertake economic valuation of ecosystem services.

- *Step 3: Turning knowledge to action* to improve delivery of ecosystem services and change the way we manage ecosystems. This step aims at improving ecosystem functioning and resilience by addressing the drivers of change and ensuring equitable access to ecosystem services. Building on step 1 and 2, data and knowledge will be used to determine which services have priority; to develop effective intervention strategies; and to ensure equitable access and use of ecosystem services by all stakeholders. The Ecosystem Management Programme will focus on building local capacity at local, national and trans-boundary level to assess and analyze ecosystems and make decisions relating to the optimal delivery of ecosystem services.
- *Step 4: Monitoring and evaluation* to refine intervention strategies. The delivery of ecosystem services is a complex process involving many factors. Hence the Ecosystem Management Programme adopts a new approach to monitoring and evaluation by using overall delivery of ecosystem services as a measuring stick rather than impacts on specific drivers. To ensure the optimal delivery of ecosystem services, UNEP will offer technical support for the development and review of indicators of ecosystem service delivery; facilitate review of the delivery of ecosystem services against established baselines; and facilitate and build capacity to develop and implement feedback mechanisms into steps 1 to 3 above.

The environmental food crisis (Nellemann et al. 2009)

In the same year that UNEP launched its Ecosystem Management Programme, an important publication was brought out on the role of the environment in averting future food crises (Nellemann et al. 2009). It discussed the recent surge of 50–200% in food

prices and the huge impacts these food prices had as they drove 110 million people into poverty and left 44 million more undernourished. The report discusses the status of food production related to population growth, signaling stabilization of yields in cereals, after several decades of steady increase, and reduced fish harvests. The authors relate this to lack of investments in agricultural development but also to the results of environmental degradation.

The natural environment as the basis for food production is threatened by land degradation, urban expansion and conversion of crops and cropland for non-food production, such as biofuels. The combined effects of climate change, land degradation, cropland losses, water scarcity and species infestations may cause projected yields to be 5–25% short of demand by 2050, with prices expected to rise by another 30–50%. Without policy intervention, the combined effects could result in a substantial increase in the number of undernourished people. Hence new ways for increasing food supply are required. Rather than focusing solely on increasing production, food security can be increased by optimizing food energy efficiency, which would enhance supply. Optimizing food energy efficiency means minimizing the loss of energy in food from harvest potential through to processing and actual consumption and recycling. By optimizing this chain, food supply can increase with much less damage to the environment. Nellemann et al. (2009) thus propose 7 options for improving food security without compromising environmental sustainability:

Options with short term effects:

1. Price regulation on commodities and larger cereal stocks to buffer the tight markets of food commodities and the subsequent risks of speculation in markets.
2. Removal of subsidies and blending ratios of first generation biofuels, which would promote a shift to other types of biofuels based on waste (if this does not compete with animal feed), thereby avoiding the capture of cropland.

Options with mid-term effects:

3. Reduction of the use of cereals and food fish in animal feed and development of alternatives to

animal and fish feed, such as recycling waste and using fish discards.

4. Support to farmers in developing diversified and resilient eco-agriculture systems that provide critical ecosystem services (water supply and regulation, habitat for wild plants and animals, genetic diversity, pollination, pest control, climate regulation), as well as adequate food to meet local and consumer needs.
5. Increased trade and improved market access by improving infrastructure and reducing trade barriers, but also reducing armed conflict and corruption.

Options with mid-term effects:

6. Limiting global warming, including the promotion of climate-friendly agricultural production systems and land-use policies at scales to help mitigate climate change, especially with regard to water resources of the Himalayas.
7. Raised awareness of the pressures of increasing population growth and consumption patterns on sustainable ecosystem functioning.

Blue Harvest (UNEP 2010)

Another synthesis report addressed the importance of inland fisheries as an ecosystem service, the pressures upon them, and management approaches to sustain them (UNEP 2010). Rivers and lakes in Africa, Asia and Latin America provide food and employment for tens of millions of people. They provide 33% of the world's small scale fish catch and employ over 60 million people, of whom 33 million are women. The supply of fish from inland waters is critically important for human nutrition, especially in Africa and parts of Asia. Over 200 million of Africa's 1 billion people regularly consume fish and nearly half of this comes from inland fisheries.

The policy implications of UNEP's ecosystem approach applied to inland fisheries include:

- *Participation of key stakeholders*, especially those concerned with land and water management, and economic development such as en-

ergy, trade and agriculture, but also with stakeholders in other sectors that draw upon services provided by aquatic ecosystems, including water supply, conservation and tourism.

- *Agreement over future scenarios* and management objectives among stakeholders.
- *Management for resilience*. Because multiple drivers impact inland fisheries and there are complex interactions between these, managing these systems requires investment to maintain resilience and multiple options for future sustainability and productivity. Resilience is fostered by investments that maintain ecosystem functioning, reduce vulnerability, and build adaptive capacity in the face of unforeseen and unforeseeable threats.
- *Pursue adaptive learning* within the complexity of social and institutional environments by adopting an effective process of adaptive learning.
- *Plan and manage catchments for inland fisheries* to sustain fisheries productivity, by investing in maintaining healthy catchments with appropriate land use, and sustaining the quality and quantity of water flow into lakes and rivers. This requires engaging with land and water management processes at multiple scales through strategic environmental assessment, integrated planning at the basin scale, and design of environmental flow regimes for fisheries.

This approach can be supported by:

- Improved understanding of the vulnerability to environmental change of inland fisheries.
- The development of viable options for addressing the environmental change threats to inland fisheries.
- Capacity building among key stakeholder groups to increase resilience of inland fisheries at local, national and regional scales as well as capacity to sustain and enhance social benefits from these resources.
- Improved governance of inland fisheries and their ecosystems.

Appendix 2

Water for Food and Ecosystems (FAO 2005)

Sustainable use of water is fundamental for production functions and well-functioning ecosystems. However, unsustainable water use is common as population growth and increased water use per capita put increasing pressure on the availability and quality of water resources and on the ecosystems which are key to regulation, supply and purification of water. The poor are the first to suffer from this as the satisfaction of basic food needs is often obtained at the expense of the natural environment, which in turn threatens the very basis of future food production. FAO recognizes this and calls for an integrated approach to water resources and ecosystems at the river basin level.

By identifying best practices and generic lessons the FAO/Netherlands Conference Water for Food and Ecosystems (FAO 2005; <http://www.fao.org/ag/wfe2005/>) aimed at facilitating the implementation of existing international commitments on sustainable water use in relation to food and ecosystems. The conference provided a high-level platform for governments to 1. identify management practices; 2. analyze practical lessons learned; and 3. develop the necessary enabling environments, all leading to sustainable water use at the river basin level and the harmonization of food production and ecosystem management:

1. *Fostering implementation: know-how for action.* Increased knowledge, reliable information and greater awareness of the complex interactions between water for food and ecosystems, will help improve the capacity of stakeholders and ensure that sound decisions are made. Focusing on best practices can contribute, in a practical way, to implementing governments' commitments to effectively balance water for livelihoods and resilient ecosystems. Key questions include:
 - How to enhance effective stakeholder involvement?
 - How to integrate and apply knowledge for managing the intertwined relation between water for food and ecosystems?
2. *"New economy" for water for food and ecosystems.* Inputs, services and impacts must be analyzed in terms of their social, economic, and environmental values for each stakeholder. The goal is to help all involved stakeholders make well informed, transparent decisions on the allocation of natural resources, and ensure that their decisions are consistent with higher level (national/cross boundary) priorities. This will lead to a new prospect, "a new economy" of water for food and ecosystems. Key questions include:
 - How to assess the various positive and negative externalities of water use?
 - How to ensure that the diverse value of water is included in decision making processes by stakeholders?
3. *The enabling environment.* Promising institutional and managerial arrangements must be adopted at local and national/cross boundary levels to enable sustainable water management for food and ecosystems, equitable representation of all stakeholders in the decision making process, and consistency at all levels. Key questions include:
 - What institutional arrangements and policies help to enable local stakeholders to manage their resources and to accommodate the diverse users and uses of water?
 - How can institutions and organizations offer a platform for joint decision making/negotiation – involving fishers, pastoralists, rainfed agriculturists, and industries – that includes the specific needs of nature and environment?

Appendix 3

Ecosystems and Human Well-being (MA 2005a)

Key messages synthesized from the Millennium Ecosystem Assessment (<http://www.maweb.org/en/Index.aspx>).

“Initiated in 2001, the objective of the Millennium Ecosystem Assessment was to assess the consequences of ecosystem change for human well-being and the scientific basis for actions needed to enhance the conservation and sustainable use of those systems and their contribution to human well-being.” The MA was an enormous undertaking that sought to catalogue the state of the environment and the changes taking place, as well as produce recommendations for actions. The MA has involved the work of more than 1,360 experts worldwide. Their findings on the condition and trends of ecosystems, scenarios for the future, possible responses, and assessments at a sub-global level are set out in technical chapters grouped around these four main themes. In addition, a general synthesis draws on these detailed studies to answer a series of core questions posed at the start of the MA. The practical needs of specific groups of users, including the business community, are addressed in other synthesis reports. Each part of the assessment has been scrutinized by governments, independent scientists, and other experts to ensure the robustness of its findings.

The Millennium Ecosystem Assessment includes a series of “Key Messages,” which can be stated generally: Everyone depends on the environment in countless ways, and that dependence has resulted in massive changes to ecosystems. It also said that people, mainly through conversion of land to more or less intensive agriculture, are the single largest contributor to reduced regulation and supporting ecosystem services. These changes have improved the lives of billions, but have caused significant environmental damage that has caused the extinction thousands of species and weakened many ecosystems to a breaking point. It points out that to prevent more damage and start to repair the damage that has already occurred, coordinated conservation efforts must prevail over unchanging attitudes and ignorance. The MA made popular the paradigm of *environmental*

(or ecosystem) services, which was used in a nearly every environmental assessment published since.

The MA is broken into five synthesis reports, in addition to the general synthesis (<http://www.maweb.org/en/Synthesis.aspx>):

- Ecosystems and human well-being: biodiversity synthesis
- Ecosystems and human well-being: desertification synthesis
- Ecosystems and human well-being: opportunities and challenges for businesses and industry (MA 2005b)
- Ecosystems and human well-being: wetlands and water (MA 2005c)
- Ecosystems and human well-being: health synthesis

Each of these synthesis reports is a result of a much larger report that was produced by a set of experts. In the report on “wetlands and water” the focus is on the challenges faced by wetlands and the services they provide. Through the lens of wetlands, it examines topics ranging from climate change, population growth, water scarcity, and ecosystem services among others. It goes on to suggest cross-sectoral and ecosystem based approaches to water management that take into account drivers outside of the traditional water sector.

Furthermore, a set of three global Assessment Reports was produced (<http://www.maweb.org/en/Global.aspx>) that provide a synthesis of the information gained from the Millennium Ecosystem Assessment and organize it conceptually in a way that is most useful to policymakers. Hence separate reports have been published under the titles; Current state and trends (Hassan et al. 2005), Scenarios, and Policy responses. In addition, various multi-scale assessments are available (<http://www.maweb.org/en/Multiscale.aspx>).

Appendix 4

Environment for Development (GEO4)

Key messages synthesized from the Global Environmental Outlook 4 (GEO-4: UNEP 2007), see <http://www.unep.org/geo/geo4.asp>.

Published in 2007, the GEO-4, places sustainable development at the core of the assessment, particularly on issues dealing with intra- and intergenerational equality. The analyses include the need and usefulness of valuation of environmental goods and services, and the role of such services in enhancing development and human well-being, and minimizing human vulnerability to environmental change.

The GEO-4 uses a “drivers-pressures-state-impacts-responses (DPSIR)” framework for analyzing environmental change. It privileges human well-being and ecosystem services as key concepts, but moves away from an exclusive focus on ecosystems to look at the entire set of interactions between society and the environment.

The GEO-4 is composed of 6 parts:

A. *Overview* presents the changes that have occurred in the environment and our understanding of it that have occurred in the last 20 years.

B. *State-and-Trends of the Environment: 1987–2007* presents trends in each of four areas: Atmosphere, Land, Water, and Biodiversity.

C. *Regional Perspectives* focuses on regional changes since 1987

D. *Human Dimensions of Environmental Change* is split into two parts: vulnerabilities of people and the environment, and governance for sustainability.

E. *The Outlook – Towards 2015 and Beyond* presents four scenarios for the future of the environment.

F. *Sustaining Our Common Future* presents a number of options for action.

The GEO-4 section on water looks at a variety of different topics, including: drivers of change, ocean and aquatic ecosystem health, freshwater availability for human use and well-being, implementation of IWRM, the effects of water quality degradation on human and ecosystem health, water for food, and tries to establish balanced solutions to these problems.

Appendix 5

Water for Food, Water for Life

Key messages synthesized from the Comprehensive Assessment of Water Management in Agriculture (CA 2007).

Published in 2007, the Comprehensive Assessment of Water Management in Agriculture (CA) was hailed by many as one of the most important documents focusing on water ever to be produced. It begins with the question: “Is there enough land, water, and human capacity to produce food for a growing population over the next 50 years—or will we ‘run out’ of water?” The answer of the CA is that it is possible to produce the food—but it is probable that today’s food production and environmental trends, if continued, will lead to crises in many parts of the world. Only if we act to improve water use in agriculture will we meet the acute freshwater challenges facing humankind over the coming 50 years. It approaches this problem from the view that agriculture is responsible for the vast majority of freshwater withdrawals, so improving water efficiency in agriculture is the best way to affect the water sector. After integrating over 5 years of work by over 700 scientists, the Comprehensive Assessment produced 8 policy actions that then formed the basis for the structure of the rest of the report.

The Comprehensive Assessment argues that the greatest hope for meeting the food and water demands of the world 50 years from now lies in increasing agricultural productivity for many of the least productive areas. Because of massive disparities between technology and technique, many farmers have not increased their productivity for thousands of years. It argues that 75% of the additional food we need could be met by increasing the productivity of low-yield farmers to 80% of the productivity that high-yield farmers get from comparable land. The largest potential increases that the Comprehensive Assessment outlines are in rainfed areas, which is where many of the world’s poorest people live. Rainfed agriculture had long been written off by many as low-yield and less important

than its irrigated counterpart. The Comprehensive Assessment changed the way that many in the water field thought about rainfed agriculture.

Policy actions recommended by the Comprehensive Assessment of Water Management in Agriculture were (CA 2007):

- *Change the way we think about water* – This entails several things. Instead of focusing only on obvious water sources like rivers and groundwater, rain should be viewed as the ultimate source of all fresh water. It also argues that we should not use standard solutions. Rather, solutions should be crafted based on the political, social, and economic context. Lastly, agriculture should be viewed as its own multiple use system and ecosystem.
- *Fight poverty by improving access to agricultural water and its use* – This involves improving water access through legal (water rights) and infrastructure (storage, etc.) reforms. This also includes building infrastructure and promoting pro-poor technologies that target multiple-use systems.
- *Manage agriculture to enhance ecosystem services* – This action aims to recognize the benefits that the agroecosystem can provide, as well as showing that water for agriculture does not have to trade off with other services. However, it notes that there will be changes and careful and informed decisions must be made.
- *Increase the productivity of water* – Increasing water productivity shows incredible potential for helping all areas of the water sector—from environmental flows to crop productivity and poverty reduction.
- *Upgrade rainfed systems* – By improving soil water soil moisture conservation and providing

some supplemental irrigation, rainfed systems hold the potential to lift the greatest number of people out of poverty and increase water productivity where it is needed most.

- *Adapt yesterday's irrigation to tomorrow's needs* – Expansion of irrigated land has begun to reach its limits in certain parts of the world, so adapting current infrastructure to increasing needs is one of today's great challenges. Better technology, integration with agriculture, and better water management all show potential to help.
- *Reform the reform process—targeting state institutions* – Water institutional reform is important to facilitate better water management. Involving a variety of actors and tailoring solutions to specific situational needs are important for crafting solutions to water problems.
- *Deal with trade-offs and make difficult choices* – Engaging all stakeholders to make difficult decisions is an important part of the solution to the coming water crisis.

Appendix 6

Water in a Changing World (WWDR3)

Key messages synthesized from the third World Water Development Report (WWDR3: WWA 2009).

The goal of the WWDR is “getting out of the water box. Many paths to sustainable development are linked to water, but the decisions that determine how water resources are used or abused are not made by water managers alone”. Currently most international reports and suggestions have water managers as a target audience. This report acknowledges that in fact, civil society actors, political actors, and businesses and economic actors all have a large influence on the water sector. They are responsible for many drivers of change, and control access to most of the response options.

While this approach defines the way that the WWDR looks at the water sector, the report also has a number of other focal points. It seeks to provide a comprehensive assessment of the state of the world’s water resources, and tries to apply a new approach to water supply and demand that links them to other global dynamics. This approach demands more recognition of the fact that water is vitally important for a number of other global dynamics including poverty, and the achievement of all eight millennium development goals.

The WWDR is divided into 4 parts:

- *Understanding what drives the pressures on water* – This part focuses primarily on drivers, including demographic, economic, social, technological, legal and political, and climatic.
- *Using water* – The second part first focuses on the importance of water and its wide scale application in areas from economic development through ecosystem services. Then it outlines the evolution of water use, the impacts of water use on the environment, and begins to address how to manage water competition.
- *State of the resource* – Part 3 begins by examining the global water cycle and the changes that have recently begun to speed that cycle up. It then looks at specific changes that have occurred and the challenges that those changes represent. Finally, it analyzes the state of hydrological observations.
- *Responses and choices* – This part looks at potential solutions to water problems. First it notes responses from inside the “water box,” but then spends more time evaluating responses that differ from traditional water solutions. Finally, it looks at solutions that integrate water decision-making with broader planning and management decisions.

The WWDR devotes two chapters and nearly 30 pages to effects of water sector changes on the environment. The focus of the report is on water for agricultural productivity, and the effects that pollution and overuse have on ecosystem services and environmental flows. The report views non-agricultural ecosystems as ‘other’ water users, and tries to manage water demand within this framework. It also primarily views the importance of ecosystems in terms of ecosystem services that they provide.

Appendix 7

International Assessment of Agricultural Knowledge, Science, and Technology for Development (IAASTD)

Key messages synthesized from the IAASTD (McIntyre et al. 2008; www.agassessment.org).

The project to complete the IAASTD was initiated by the Food and Agriculture Organization (FAO) and the World Bank, and was eventually sponsored by a variety of organizations including UNEP. Its goals were to assess the impacts of past, present, and future agricultural knowledge, science, and technology on; i) the reduction of hunger and poverty, ii) the improvement of rural livelihoods and human health, and iii) equitable, socially, environmentally and economically sustainable development.

While the report does not focus explicitly on water or the environment, it is nevertheless a particularly important document for this study to include. It has helped to define the current understanding of how agriculture works in the world, and has helped to motivate significant changes in agricultural practice. Hopefully, this trend will continue into the future and the IAASTD will keep helping to alleviate poverty.

The IAASTD argued that agriculture is multifunctional—that it fills many more roles than simply providing food. It provides fiber, fuel, a variety of other goods, ecosystem services, a social center, employment, and a transmission of cultural practices. It accounts for the livelihood of 40% of Earth's population. It acknowledges that any scale of farming can be either sustainable and highly productive, or highly vulnerable. It seeks to push agriculture towards sustainability and productivity through the application of Agricultural Knowledge, Science, and Technology (AKST). Furthermore, it aims at reducing agriculture's role in poverty. It focuses on the relations between the environment and agriculture, and the relations between agriculture and social equity issues. Finally, it examines drivers of change, including climate change, land degradation, reduced access to natural resources, and several other issues.

The IAASTD has eight chapters:

- *Context, conceptual framework and sustainability indicators*, which focuses on setting up a framework for the data and arguments provided in the rest of the report,
- *Historical analysis of the effectiveness of AKST systems in promoting innovation*, which sets the potential for change and guides the goals of the report based on the historical effectiveness of other strategies,
- *Impacts of AKST on development and sustainability goals*, which looks at past AKST advances and the impacts that they have had,
- *Outlook on agricultural changes and its drivers*, which examines the drivers and the changes that they will produce,
- *Looking into the future for agriculture and AKST*, which examines possibilities for positive change as a result of AKST,
- *Options to enhance the impact of AKST on development and sustainability goals*, which seeks to make improve the use and uptake of AKST to improve development,
- *Options for enabling policies and regulatory environments*, which is about institutional solutions to water problems, and
- *Agricultural knowledge, science and technology: Investment and Economic Returns*, which addresses the economic aspects of implementation of the IAASTD's suggestions.

The IAASTD spends a significant amount of its pages on improving water efficiency in agriculture as a key driver of overall water use. Furthermore, it seeks to view agriculture as a part of the environment, identifying and basing actions on the linkages between it and other ecosystems. This approach has gained traction and now helps define how people look at agriculture's interaction with ecosystems.

Appendix 8

Impact of Agriculture on Climate Change

While climate change can be seen as a driver of food and water security, influencing the role of ecosystems, agricultural food production has its own effects on climate change too. Livestock production, especially cattle, has a negative effect on climate change by producing greenhouse gases. Its contribution has been estimated at 18% of the global anthropogenic greenhouse gas (GHG) emissions through methane (25–30%), CO₂ (30%) and N₂O (25–30%) (Steinfeld et al. 2006). However, more recent estimations suggest that the agricultural sector as a whole accounts for roughly 14 percent of global greenhouse gas (GHG) emissions, of which three quarters come from developing countries (Parry et al. 2007; FAO 2009d).

Stored manure and rice grown under flooded conditions also contribute methane to the atmosphere (Mosier et al. 1998), while over-application of fertilizer results in emission of nitrous oxide (Oenema et al. 2005; Smith and Cohen 2004). Carbon dioxide (CO₂) is released largely from microbial decay or burning of plant litter and soil organic matter (Janzen 2004). On the other hand, many ecosystems absorb carbon dioxide and thus serve as carbon 'sinks', decreasing the CO₂ present in the atmosphere and thereby potentially slowing down climate change. For example, the world's forests are an important carbon sink influencing the global carbon cycle (Lobell et al. 2008). The world's

grazing lands store 10 to 30% of total soil carbon (Schuman et al. 2002). Sahelian rangelands are highly degraded, but with proper management could potentially annually capture 0.77 tons of carbon per hectare (Woomer et al. 2004).

Overall, terrestrial ecosystems have taken up approximately 25% of anthropogenic carbon in the last century (WWA 2009). However, destruction of ecosystems as a result of population growth and other drivers is limiting the buffering capacity of those ecosystems. Agriculture, or rather, sound management of agroecosystems, can play its part in reducing ecosystem degradation and in turn reduce greenhouse gas emissions through improved crop and grazing land management (to improve soil carbon storage), and improved rice cultivation and fertilizer application techniques (Metz et al. 2007). Most (70%) of the technical and economic mitigation potential is in developing countries (FAO 2009d). However, the impact of carbon fertilization is uncertain. Atmospheric carbon stored into (agricultural) plants is quickly cycled back into the atmosphere through harvesting, human consumption, and decomposition. Further changes in the composition of the atmosphere could result in crop yield increases as a result of CO₂ fertilization and improvements in the efficiency of water uses, but could also increase pollution (FAO 2009d).

Appendix 9

From Farming Systems to Agroecosystems

In this document, agriculture is considered as a continuous range of agroecosystems determined by the environment (e.g. climate and soil type) in which they are situated, but also by the farming system used. This appendix illustrates various types of farming systems (according to FAO's classification), with particular attention to livestock-based systems, followed by some background on how agricultural production systems evolve and the introduction of a new concept of 'anthropogenic biomes' (Ellis and Ramankutty 2008).

A9.1. Classification and numbers

The Food and Agriculture Organization of the United Nations (FAO) developed a classification of farming systems of developing regions based on the available natural resource base and the dominant pattern of livelihoods and farm activities. Inputs are physical, such as climate, soil, altitude, as well as human, such as availability of labor, market access, cost of land, tradition, demand for products, capital. Arable processes include plowing, harvesting and weeding, while grazing, shearing and milking are pastoral processes. Outputs can be crops, animals and animal products. Hence eight broad categories of farming systems were distinguished (Dixon and Gulliver 2001):

- *Irrigated* – small holders, medium and large systems
- *Wetland rice-fish integrated farming* – dependent on monsoon rains and supplementary irrigation
- *Rainfed in humid areas* – small scale and commercial (tree) crop cultivation, mixed crop-livestock systems
- *Rainfed in steep and highland areas* – often mixed crop-livestock systems
- *Rainfed in dry or cold areas* – mixed crop-livestock systems and pastoral systems
- *Dualistic* – including large commercial farms and smallholders
- *Coastal artisanal fishing* – often combined with farming
- *Urban-based* – focused on horticulture and livestock

Each category includes a number of separate farming systems and has its own issues of vulnerability and poverty (Table A1). Like any classification system, especially one trying to divide a global continuum of agroecosystems into only 8 categories, it fails to capture diversity. For the sake of this publication, and particularly due to its focus on water, livestock numbers have been added because livestock farms are such large users of land and water.

Table A1. Categories of farming systems in developing countries with some characteristics and estimated livestock units (LU) (adapted from Dixon and Gulliver 2001 with livestock data calculated by An Notenbaert on the basis of FAO 2007c).

	Irrigated	Wetland rice-based	Rainfed humid	Rainfed highland	Rainfed dry/cold	Dualistic large/small	Coastal artisanal fishing	Urban based
No. of farming systems	3	3	11	10	19	16	4	6
Total land (m ha)	219	330	2013	842	3478	3116	70	
Cultivated area ^a (m ha)	15	155	160	150	231	414	11	
Irrigated area (m ha)	15	90	17	30	41	36	2	
Agric. population (m)	30	860	400	520	490	190	60	40
Market surplus	high	medium	medium	low	low	medium	high	high
Poultry (m LU)	1.2	22.4	17.4	18.4	15.8	20.1	0.4	
Pigs (m LU)	0.6	34.7	17.0	35.6	6.6	24.6	0.1	
Small ruminants (m LU)	3.2	15.2	19.0	16.5	56.5	15.8	0.6	
Cattle (m LU)	8.4	81.5	105.0	73.1	118.6	202.4	2.0	

^aCultivated area refers to both annual and perennial crops

A9.2. Livestock systems and drivers

Livestock production is the single largest land user globally, with overall 45% of the global surface area dedicated to livestock production (Herrero et al. 2009). Grassland covers 25% of the land surface and land dedicated to feed crops occupies one third of the global cropped area. Livestock production contributes 53 and 33% of the agricultural gross production in industrial and developing countries respectively. Developing countries produce 50% of the beef, 41% of the milk, 72% of the lamb, 59% of the pork and 53% of the poultry globally. Mixed crop-livestock systems produce close to 50% of the global cereals. The importance of the livestock sector is also clear from the value of production as milk has the highest value of production of all commodities globally. After rice (second), meat from cattle, pigs and poultry are next in order of importance. In the least developed countries, the value of the livestock

industry is around 1.4 trillion dollars, excluding the value of infrastructure or land (Herrero et al. 2009).

In terms of cattle numbers, the mixed rainfed systems have a 40% share of the total cattle herd in the world's drylands, followed by grazing systems (31%) and mixed irrigated systems (29%). In terms of livestock density in dryland environments, mixed irrigated systems have the highest animal density with 39 tropical livestock units per square kilometer (TLU/km²) followed by mixed rainfed (20 TLU/km²) and grazing systems (3 TLU/km²). In general, the combined livestock densities decrease with increasing aridity, because of concomitant decreases in primary productivity and carrying capacity (Thornton et al. 2002). Rainfed areas of the Nile River Basin with relatively high annual rainfall per capita (1000 m³) were dominated by livestock production systems while areas with lower rainfall per capita mainly had mixed crop-livestock systems (Peden et al. 2009a; Table A2).

Table A2. Annual rainfall per capita in livestock dominated and mixed crop-livestock production systems of the Nile River Basin.

Production system	Hyper-arid	Arid and semi-arid	Humid	Temperate
Livestock dominated	4	52	191	6
Mixed crop-livestock	-	23	9	8

Growth in the industrial pig and poultry sectors in South America and Asia will create the need for more grain for feed: by 2050, more than 40% of the global cereal use will be for feed purposes (Herrero et al. 2009). Because rich countries already consume high amounts of livestock products, the growth in demand is predominantly a developing country phenomenon (Table A3), where some 1 billion poor people are supported by livestock.

Table A3. Current and project consumption of animal products (Herrero et al. 2009).

Countries	Year	Annual per capita consumption		Total consumption	
		Meat (kg)	Milk (kg)	Meat (Mt)	Milk (Mt)
Developing	2002	28	44	137	222
	2050	44	78	326	585
Developed	2002	78	202	102	265
	2050	94	216	126	295

For poor smallholder farmers, livestock provide diverse products and services and an insurance against various shocks. Livestock are also an income source, provide livelihood diversification and improved nutrition (Table A4). In addition to urbanization and changes in diet, other drivers affect livestock production and illustrate how food security and consumption may drive agriculture and influence management of agroecosystems (Table A5).

Table A4. Energy and protein sources in developing countries, by sub-region (Herrero et al. 2009).

Region	% of energy from cereals, roots, tubers	% of energy from livestock	% of protein from livestock
West Africa	66	5	16
Central Africa	69	4	19
East Africa	63	11	26
Southern Africa	72	12	36
India	64	8	16
Bangladesh	54	2	6

Table A5. Balancing food production, maintenance of ecosystems service and poverty reduction in livestock systems of the developing world through policy, investment and technology (adapted from Herrero et al. 2009, 2010).

Drivers and pressures	Policy needs	Investment needs	Technology needs
Agro-pastoral systems			
Significant rural – urban migrations, more conflicts, higher numbers of vulnerable people, increases in livestock numbers in some places, significant impacts of climate change in places, resource degradation	Frameworks for diversifying income sources including payments for ecosystem services and others, insurance-based schemes	Roads, livestock markets, health and education establishments, development of water sources, food storage systems, telecommunications	Matching livestock breeds to the agroecosystems, livestock species changes in some places, suitable crops if required, early warning systems, mobile phone based telecommunication products: prices information and others
Extensive crop-livestock systems			
Manageable increases in population density but significant rural-urban migrations, potential for increased crop and livestock production through intensification, and though large impacts of climate change in some places	Policies to create incentives and an enabling environment to produce food in these regions, appropriate credit, land tenure rights, incentives for public-private partnerships, service and support institutions	Infrastructure: roads, post-harvest storage systems, water sources and storage, health and education establishments, markets, development of value chains, involvement of the private sector, product processing plants, telecommunications	Crop varieties suitable for the agroecosystem, fertilizers and agricultural inputs, livestock feeds, breeding systems, livestock vaccines and health management
Intensive crop-livestock systems			
Large increased population densities, reductions in the primary productivity of crops, water scarcity or soil fertility constraints, large increases in livestock numbers, increases in food prices, potential food insecurity, environmental degradation, increases in zoonotic and emerging diseases	Regulations for intensification / de-intensification, monitoring and evaluation frameworks for assessing environmental impacts. Appropriate regulatory frameworks for global food trade	Infrastructure to support value chains: ports, railways, cold chains, processing plants, supermarkets and storage facilities. Human capacity development to improve management skills	Options with high efficiency gains: more crop per drop, more crop per unit of fertilizer, species or animals with improved conversion efficiencies of feed into milk and meat
Industrial landless systems			
Most growth in monogastric production, heavy dependence on grains as feed, expansion into areas further away from centers of demand as transport efficiency develops	Regulations for intensification / de-intensification, monitoring and evaluation frameworks for assessing environmental impacts. Appropriate regulatory frameworks for global food trade	Infrastructure to support value chains: ports, railways, cold chains, processing plants, supermarkets and storage facilities	Animals with improved conversion efficiencies of feed into milk and meat, more efficient diet formulation, technologies for waste disposal

A9.3. Agroecosystems: towards a broader vision of production systems

While analyses generally assume average conditions (such as average temperature and average monthly rainfall) and equilibrium states, deviations of the mean better represent reality as systems are continuously adjusting towards an equilibrium that may never be reached. Buffering mechanisms to mitigate shocks should therefore be put in place in the entire food chain, for instance through storage and processing. Sufficient storage capacity should be maintained in agroecosystems to sustain long term use of natural resources and to provide buffering mechanisms to mitigate fluctuations in production due to environmental variability, especially of rainfall, that are expected to increase. Without such measures, the frequency

with which shocks occur is likely to increase, while the intensity might be higher. This will likely worsen food security of the most vulnerable under conditions of tightening supply and demand of food, and high concentrations of people.

Historically, intervention measures have been continuously implemented to “control” the production conditions for food to reduce risk and uncertainty. Development of the agricultural sector faces severe limitation if control measures to mitigate variability are inadequate, such as in many countries in sub-Saharan Africa. A rather basic concept underlying the success of the various agricultural revolutions in Europe and the United States, Asia and Latin America holds universally: enabling technologies should be designed to suit local biophysical and social conditions to lift productivity (Figure A3).

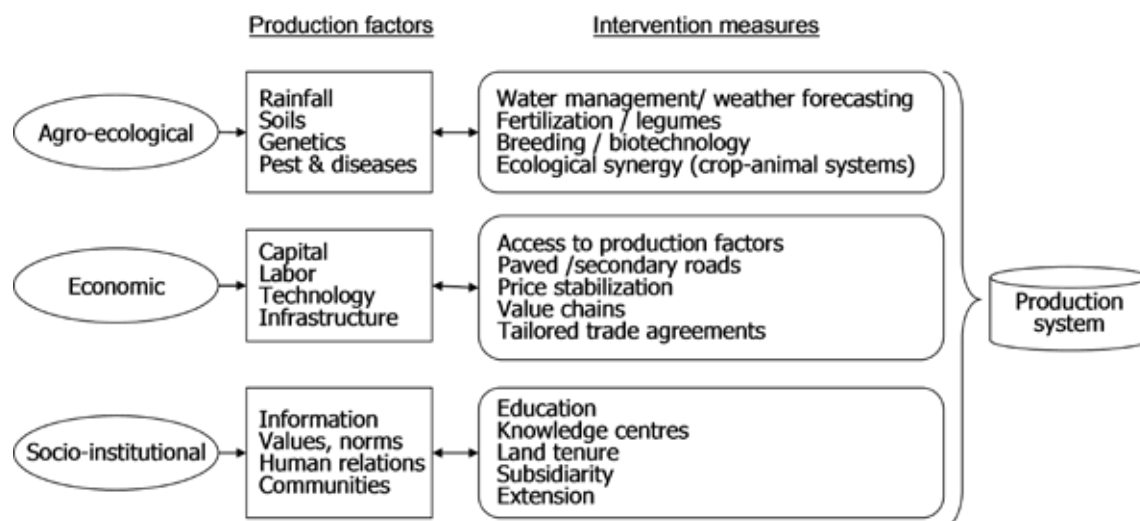


Figure A3. Production systems are a consequence of complex interaction of agroecological and economic conditions within a socio-institutional environment (Bindraban et al. 2009b).

The above concept emphasizes intervention measures at the farm scale and seeks to secure food availability and livelihood for the farmer and her/his family. While farming systems should be well embedded in the social and economic conditions they operate in, we increasingly realize the necessity for them to be sustainably embedded in their eco-regional setting as well. While excessive use of water may reduce farmers' risks as in rice production, collective demand for water may call for optimized use of water (Senthilkumar et al. 2009). Also, resource allocation for ecosystems to function properly and for ecosystems to provide the necessary services to maintain human activity should be explicitly accounted for.

Agroecosystems are continuously evolving due to changing external conditions. Changing norms, values or international competition lead to adjustments in production systems. For European agriculture, Vereijken (2003) classified production systems that have evolved over the past decades based on their core objectives (Figure A4). Starting off as systems to secure food production along with work and income, integrated systems have evolved to take ecosystem issues into consideration. With improving wealth and increasing societal demand for non-food products and a broader range of ecosystem services, along with policies to revitalize the dwindling rural economies, agricultural systems have evolved with multiple functions embedded in a mixed landscape.

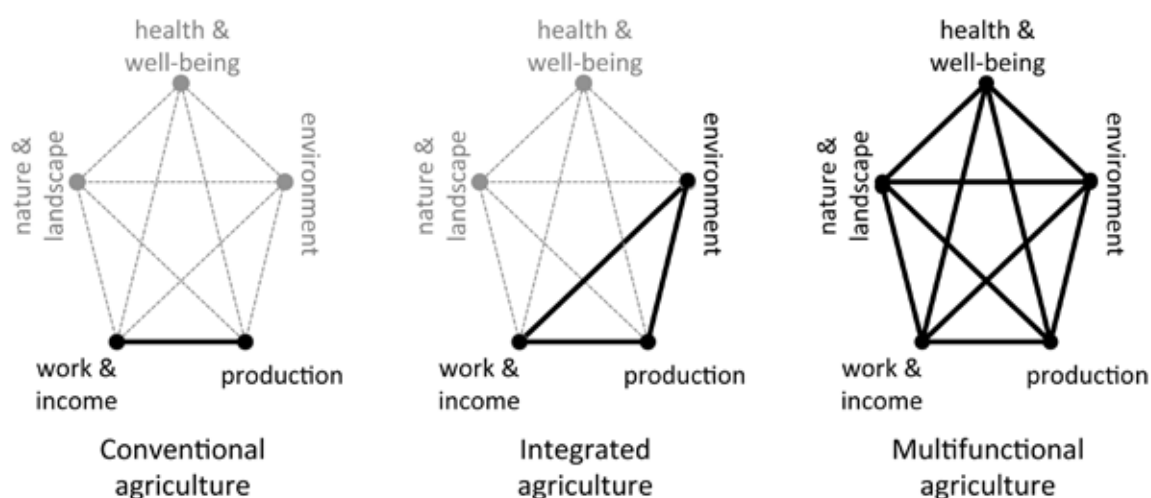


Figure A4. The multiple functions of agriculture and land use systems to meet ever more rural functions as societal objectives (Modified from Vereijken 2003).

A9.4. Anthropogenic biomes

A relatively new concept is that of 'anthropogenic biomes', which offers a new view of terrestrial ecosystems (Ellis and Ramankutty 2008), embedding a range of agroecosystems. The authors recognize the impact of human residence and agriculture, proposing a mosaic of 21 categories in 6 groups: wildlands to forested, rangelands, croplands, villages and dense settlements (Table A6).

Table A6. Biomes with their population and land cover (Ellis and Ramankutty 2008).

Biome	Area		Population	
	million km ²	%	million people	%
Wildlands	29.4	22.5	0	0
Forested	25.3	19.3	40	0.6
Rangeland	39.7	30.4	280	4.3
Croplands	27.3	20.8	930	14.5
Villages	7.7	5.9	2,560	40.2
Dense settlements	1.5	1.1	2,570	40.3
Global total	130.9	100.0	6,380	100.0

Appendix 10

Food from Non-Agricultural Ecosystems

Probably the most documented type of food collection from non-agricultural ecosystems is fisheries (UNEP 2010). However, other wild plants and animals also play an important role in food security and merit attention (Foresight 2011). In many cases, ecosystems are actively managed to facilitate hunting and gathering (Bharucha and Pretty 2011). Integrated management of agroecosystems can support ecosystem services that are important for biodiversity and contribute to safeguarding 'wild food'. The three mentioned publications provide a wealth of information on the importance of food from non-agricultural ecosystems, so here we present only two examples of ecosystem management that enhance the sustainability of fishing and other ways of collecting food from ecosystems.

A10.1 Protecting wetlands in Madagascar

The Mahavavy-Kinkony Wetlands Complex covers an area of 268,236 hectares in Madagascar. Lakes, rivers, marshes, shorelines and mangroves in this area are home to 12 globally threatened species of birds, reptiles and fishes, including the endangered Madagascar teals and Madagascar sacred ibises. Hunting, overfishing and wetland conversion to agribusiness are the main threats to this freshwater ecosystem. BirdLife International (2007) developed a model for managing these wetlands by actively involving local communities, governmental institutions and industrial food producers established in the area. Various activities were launched in collaboration with the local communities and local large private sector food producers, such as ecotourism, community-based fisheries management, and controlled hunting activities. Local associations were developed so that they were able and legally eligible to take on management of natural resources in the wetlands. In January 2007, local achievements were further strengthened when the government of Madagascar included the Mahavavy-Kinkony Wetlands Complex

in the declaration of an additional 1 million hectares of new protected areas in the island nation.

A10.2 Small-scale highland fisheries enhancement in Asia

Assessments of small-scale fisheries in Bangladesh, China and Vietnam (Ahmed et al. 2011; Cai et al. 2010; Tien et al. 2010) have shown they are an important component of local livelihoods and food security. Globally such fisheries produce several million tons of catch annually and provide employment for millions of people. Surveys and co-monitoring with fishers on the Brahmaputra River, Mymensingh, Bangladesh indicated that professional, seasonal and subsistence fishers went fishing on average 290, 179 and 187 days per year and landed 1–1.3 kg per day (Ahmed et al. 2011). Although landings by individual fishers may be relatively small, national level estimates suggest over one million tons of fish are landed by inland capture fisheries in Bangladesh (DOF 2009).

Overfishing of what are perceived to be common property resources combined with habitat loss and pollution has led to significant declines in the once abundant freshwater fisheries of Bangladesh. Capture fishery returns from the Beijiing River, China declined significantly between the 1950s and 2000 from around 8,000 to 2,000 tons per year (Cai et al. 2010). In northwest Vietnam a decline of around 50% in capture fisheries yields was found in the Da River since the 1980s (Tien et al. 2010). Declining fish stocks in China and Vietnam have been blamed on overfishing, pollution, sand mining, and dam construction for irrigation purposes and hydro-electricity generation (Cai et al. 2010; Tien et al. 2010).

Community-based management could enhance decision-making and the enforcement of fisheries regulations, promote broader environmental awareness and contribute to better pollution control

and planning and management of proposed conservation areas (Ahmed et al. 2011). Another option is aquaculture development, this has been proposed as one means to supplement fish supplies in Shaoguan City, China and northern Vietnam, even though environmental and social concerns have been noted. Under these development projects culture-base fisheries are promoted with several million Common carp (*Cyprinus carpio*) and Crucian carp (*Carassius carassius*) being stocked annually from fry release platforms moored in Shaoguan City. Bioeconomic modeling is employed as part of the HighARCS project to better understand the socio-

economic impact of such restocking programs and alternative livelihood strategies and conservation plans. In addition, action is taken to conserve and restore wild fish stocks and a number of aquatic conservation areas have been established under Shaoguan City with objectives including protection of spawning areas and conservation of rare species. Insights from the planning and management of these aquatic conservation areas would be useful in guiding the establishment of proposed protected freshwater areas in Bangladesh and potentially throughout Asia.

Appendix 11

Regulatory Ecosystem Services in a Watershed

Tibet supplies an important ecosystem service in the form of fresh water to a large part of Asia. During the monsoon months the water supplied by the Tibetan plateau is a negligible fraction of the total river flows. However, at the end of the winter and in early spring, glacial melt from the Tibetan plateau is the major water source for agriculture in the downstream agricultural areas during a crucial period of the growing season. In Tibet, the main crop is spring barley, which has been its staple food crop for centuries. Over 80% of the catchment consists of extensive grasslands used for yak herding.

The increased demand for agricultural production in Tibet, the expected impacts of climate change and the need to sustain the water flow to downstream areas challenge policy makers to make the most

appropriate trade-offs between agriculture and the environment. Immerzeel et al. (2008) assessed whether it would be technically and economically feasible to pay farmers to reduce water consumption by changing from irrigated to rain-fed crop production and thus secure the water tower of Tibet. The analysis shows that it is theoretically possible to increase discharge out of the catchment in the critical months April–June by 11% on average. When farmers are provided with a sufficiently high economic incentive the river discharge in the critical pre-monsoon period can be increased significantly even if the percentage of irrigated lands is relatively low. Accumulated over larger areas this could provide a significant increase in total upper discharge of some of the major rivers (Immerzeel et al. 2008).

Appendix 12

Ecosystem Services: Values and Trade-Offs

A12.1. Ecosystem services in the Mississippi River Delta

A recent detailed evaluation was carried out by Batker et al. (2010) to value various ecosystem services in the Mississippi Delta. Table A7 shows a summary of the ranges of values found for a selection of ecosystem services. Wetlands especially have very high potential values, largely because of their crucial role in storm surge and cyclone protection and in water flow regulation, but also because of their role in food provision, which is much more than that of forests. Interestingly, the value of food production for agricultural land is reported to be higher only when compared to open fresh water and upland forest, while all types of wetland yield more value in food production, most of which comes from fisheries (Table A7).

Upstream water management has been the major driver of adverse ecosystem change in the Delta. In particular dam construction and the resulting changes in hydrology have reduced sediment transportation and affected the functioning of wetlands in the Delta. This has increased the financial costs for maintenance of physical water and land infrastructure and reduced the ability of wetlands to protect the area from storms. Despite agriculture having relatively low ecosystem service value in the Delta it has dominated water allocation policy. The result has been an increase in food production and reduction in water risks for farmers but an exponential escalation of environmental risks downstream, such as higher vulnerability to extreme meteorological events as in the devastating hurricanes of 2005 (Batker et al. 2010).

A12.2. Global values of ecosystem services

When compared to other groups of ecosystems, or biomes, the total value of ecosystem services from cropland is relatively low, even for food production. For example, Costanza et al. (1997) suggest that, in comparison to croplands, wetlands provide more valuable food per hectare annually, resulting in some 84.5 billion dollars in food, while four times the area in cropland produce only 75.6 billion dollars globally (Table A8). Graphically these findings are even more striking (Figure A5), though the values in this study are rough estimates only. However, part of the difference could be explained by the much higher price of wetland food products such as fish and shrimps, as compared to grain or pulses. Nevertheless, the paper sparked worldwide discussions and has since then been followed by many site-specific and more accurate studies and global analyses (e.g. Balmford et al. 2009; Batker et al. 2010; TEEB 2010; van der Ploeg et al. 2010). Interestingly, TEEB (van der Ploeg et al. 2010) found similar values for lakes and rivers (7,433) and for wetlands (15,752 both in Int.\$/ha/year – 2007 values) as Costanza et al. (1997), who reported 8,498 and 14,785 USD/ha/year – 2004 values, respectively. For other biomes, such as forests and grassland, the values were much higher (Costanza et al. 1997; van der Ploeg et al. 2010).

Table A7. Estimation of the average value of ecosystem services of various land cover types in the Mississippi River Delta (in range of US\$/ha/year – 2004 values, adapted from Batker et al. 2010). Empty cells mean that no data were available.

Ecosystem services	Wetland (fresh & intermediate) ^a	Wetland (brackish & saline) ^a	Wetland (wooded) ^b	Open water ^c	Wooded upland ^d	Agricultural land/pasture
Provisioning services						
Food production	145-3,346	145-3,346	145-3,346	57	70	85
Water supply	115-308	115-308	115-308	45-1,137	24-1,044	
Raw materials	12-13	12	12		35	
Cultural services^e	693-2,183	693-2,183	511-1,602	17-3,978	18-4,408	70
Regulatory services						
Water flow regulation	1,013-9,865	349-1,513	1,513-16,159		4	
Storm protection	3783	3783	3783		3	
Other ^f	1,220-4,217	1,521-5,259	1,420-5,353	931	336-628	39-64
Supporting services^g	503-1,201	503-1,201	503-1,201	3-903	274-1,377	1
Total	7,483-24,914	7,121-17,603	8,001-31,762	1,053-7,006	765-7,569	195-220

^aWeighed (by area size) average of the two types of wetland. Throughout the table, in cases where the value was given for only one type of land use, that value was taken.

^bWeighed (by area size) average of shrub-scrub wetland and forested wetlands.

^cAverage of open fresh water and open estuarine water.

^dAverage of upland shrub-scrub and upland forest.

^eCultural services include recreation and aesthetic value.

^fOther regulatory services include carbon sequestration, gas regulation, waste treatment, pollination, erosion control, and biological control.

^gSupporting services include soil formation, nutrient cycling, genetic resources and habitat refugia.

Table A8. Estimation of the average global annual value of ecosystem services of terrestrial biomes (in 1994 US\$/ha, adapted from Costanza et al. 1997).

Ecosystem services	Forests	Grass	Wetlands	Lakes and rivers	Cropland
Provisioning^a					
Food production	43	67	256	41	54
Water supply	3	0	3,800	2,117	
Other provisioning	138		106		
Cultural^b	68	2	1,455	230	
Regulatory^c					
Water flow regulation	2	3	15	5,445	
Extremes ^e	2		4,539		
Other regulatory	326	171	4,310	665	38
Supporting^d	387	1	304		
Total (US\$/ha/year)	969	232	14,785	8,498	92
Area (10 ⁶ ha)	4,855	3,898	330	200	1,400
Total global value (10⁹ US\$)	4,706	906	4,879	1,700	128

^aProvisioning services: water supply, food production, and raw materials.

^bCultural services include recreation and other cultural services.

^cRegulatory services such as gas regulation, climate regulation, disturbance regulation (extreme events such as floods, droughts and storms), water flow regulation, erosion control, waste treatment, pollination, and biological control.

^dSupporting services: soil formation, nutrient cycling, habitat refugia, and genetic resources.

^eRegulation of extreme environmental fluctuations, including flood control, drought recovery and storm protection.

An interesting exercise would be to use the values from Costanza et al. (1997) to estimate the increase in ecosystem services in the hypothetical case that croplands were managed for multiple functions rather than solely for food production. In some cases it seems easy as several ecosystem services had not been assessed at all in the original studies. But in most cases, naturally this can only give a very coarse idea as the global

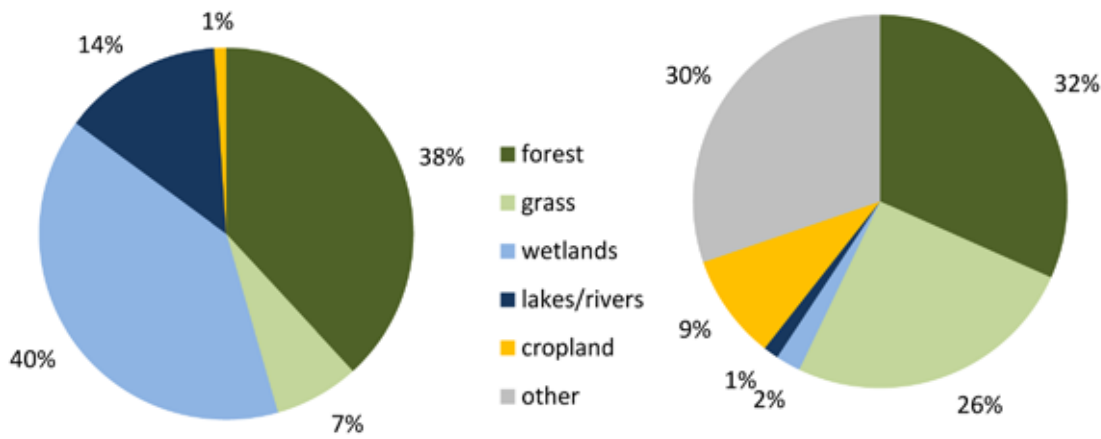


Figure A5. Global distribution of terrestrial biomes (groups of ecosystems), by area (left) and by their contribution to the total annual value of terrestrial ecosystem services as estimated by Costanza et al. (1997) in 1994 US\$. The category 'other' includes desert, tundra, ice/rock and urban, for which annual values of ecosystem services are either unknown or negligible. Freshwater ecosystems in particular provide high value ecosystem services as the contribution of 530 million hectares of wetlands, lakes and rivers (3% of the land) makes out more than half (53.4%) of the global value of ecosystem services.

values are rough estimates and their extrapolation only hypothetical. What if, for example, food production could be enhanced by integrating tree-crop-livestock-aquaculture systems? Perhaps this would increase productivity so much, especially for high value products such as animal protein, that it would be acceptable to take the average value of all productive biomes from Table A8. And what if the current 10% tree cover in half of the croplands (Zomer et al. 2009) could be increased to 15%? By using mainly multipurpose trees that provide fruits, fodder and timber products, this 15% tree cover would provide not all, but perhaps two thirds of the ecosystem services provided by forests, i.e. 10%. Applied to half of the cropland area, it might be justified to then add 5% of the value of forests to cropland. More attractive agroecological landscapes may have higher cultural value, but lacking reliable data on this, a safe assumption could be to estimate this at 1% of the value of forest or wetland (taking the average of the two). Since all measures for increasing water productivity will improve water regulation, agroecological landscapes should provide better water regulation services, at least similar to the average of forest and grassland. Better soil and water management, combined with intercropping (especially when using perennial crops), should also reduce erosion; for this we could use the value of grassland (29 USD/ha/year). Reduction of waste and increased

resource recovery will enhance the waste treatment potential of cropland, possibly to a similar level as grassland and forest (both the same value of 87 USD/ha/year in Costanza et al. 1997). Finally, with increased productivity and better soil nutrient management, reduced losses, introduction of buffer strips and habitat corridors, and much higher biodiversity, various supporting ecosystem services could increase. Soil formation could be the same as under grasslands, i.e. 1 USD/ha/year. A low estimate for the other supporting services could be to take 1% of the forest value for nutrient cycling (3.6 USD/ha/year), 2% of the habitat value of wetlands (6.1 USD/ha/year) and 1% of the genetic resources value of forests (0.2 USD/ha/year) (Costanza et al. 1997). All other values would remain the same, though there might be beneficial impacts on other ecosystems. Table A9 combines all these estimates into one, bringing the total potential value of ecosystem services of cropland from 92 to 278 USD/ha/year. If 10% of this increase could be achieved, or all of it on 10% of the area, then the value of the benefits would theoretically increase by 19% to USD 154 billion globally, if all the above hypotheses are true. However, the global values from Costanza et al. (1997) are very coarse and the hypothetical projection is even coarser, so these values are only illustrative. Higher and more realistic projections are discussed in Appendix 12.4 for two Minnesota watersheds (Boody et al. 2005).

Table A9. Estimated (Costanza et al. 1997) and potential extrapolated (own calculations) average global annual value of ecosystem services of cropland that could be achieved by taking an ecosystem approach to agricultural production, creating agroecological landscapes (values in 1994 USD/ha).

	Estimated value	Potential value
Provisioning services		
Food production	54	92.2
Water supply	0	0
Other	0	6.9
Cultural	0	4.4
Regulatory services		
Water regulation	0	2.5
Disturbance regulation	0	0
Other	38	154
Supporting services	0	10.9
Total value (USD/ha/year)	92	270.9

A12.3 Polyscape tool for comparing impacts on ecosystem services

One of the new tools under development for assessing ecosystem services is the polyscape tool (adapted from Pagella et al. 2011). It allows quantification of trade-offs and synergies among impacts of land use interventions such as changing tree cover. Small catchment maps indicate with colors where new tree cover is most desirable to enhance woodland habitat connectivity, reduce flow accumulation, have minimum impact on farm productivity, and reduce sediment transport (Figure A6). Green (trees desirable) via orange to red (trees not wanted) all denote degrees of impact. When the four benefits are traded off in the large map, there is only a small area of the catchment (green) where tree placement benefits all goals. To substantially enhance some ecosystem services by increasing tree cover, farmers would need to be well compensated for loss of production; for others only certain farms in the landscape are important and different bits of the landscape have different value for each service considered.

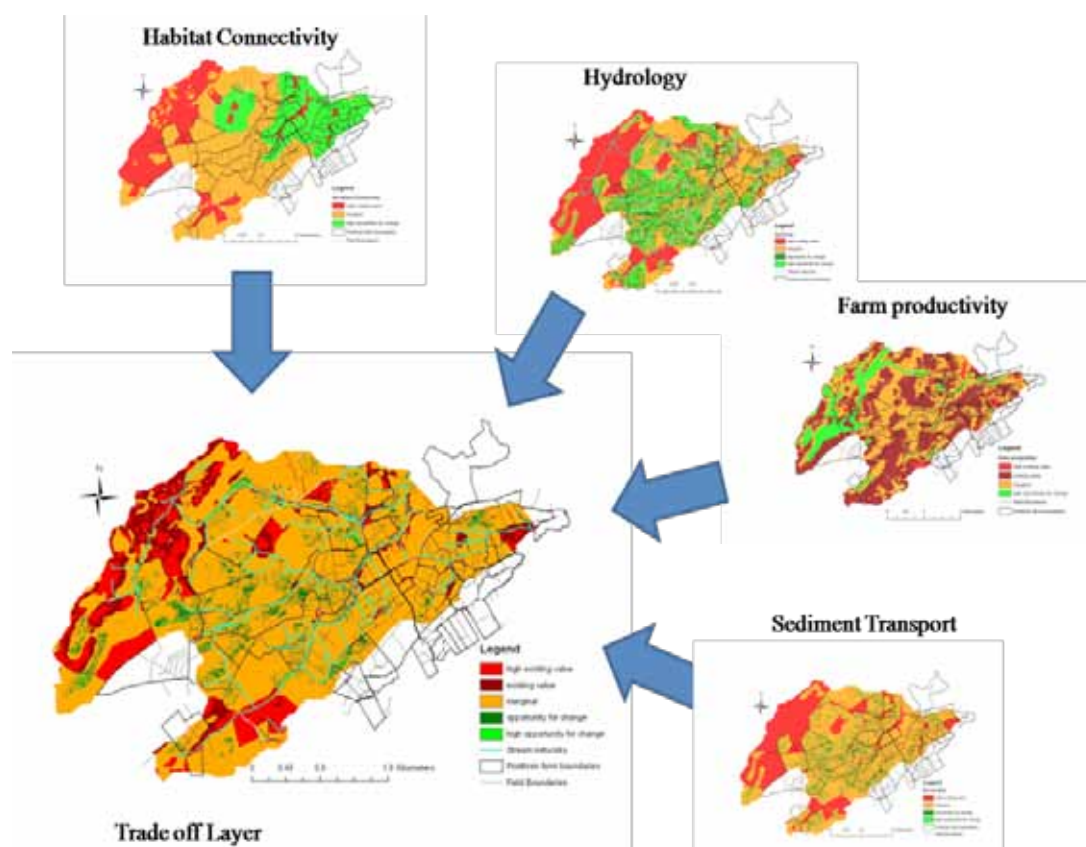


Figure A6. Example of the application of the polyscape tool (adapted from Pagella et al. 2011) to explore trade-offs and synergies of impacts of tree cover on ecosystem services.

A12.4 Potential benefits of multifunctional agriculture in Minnesota

Scientists, farmers and other residents of Wells Creek and Chippewa River watersheds in Minnesota, USA, developed four scenarios to learn how farming policy and practices would lead to various environmental and economic impacts (Boody et al. 2005). Under scenario A, current practices continued and a trend towards fewer farms with increased cultivation of corn and soybean was projected. Scenario B envisages the introduction of Best Management Practices such as conservation tillage, 30 m riparian buffers alongside streams and no over-application of fertilizers. Scenario C aims at maximizing diversity as well as profitability, adding to scenario B wetland restoration, increased crop diversity (including less than 5% organic farming), perennial crops, and rotation of crops as well as grazing. The five year crop rotation included small grains and alfalfa, leading to a reduction in the area currently under corn and soybean rotations. Scenario D further extended this by increasing vegetation cover, especially perennial grassland,

extension of the riparian buffer strips to 90 m, and the use of cover crops (green manure).

In both watersheds, ecosystem services such as erosion control (reduction in sediment and phosphorus outflow), soil carbon storage, and days without lethal fish effects increased with increased sustainable practices (Figures A7 and A8). Interestingly, net farm income was also highest under the most environmentally sustainable scenario (D). Part of the costs of the transition from a series of intensive production systems to a multifunctional agroecological landscape, were envisaged to come from public funds for nature conservation. While the funds were especially high for scenario D, these were compensated by the reduced need for commodity subsidies for corn and soy bean that are of a higher level altogether (Table A10). In Wells Creek, greenhouse gas emissions would be higher under scenario D (7,705 MTCE) than the baseline (5,003 MTCE), because of the higher numbers of livestock. This would largely, but not entirely, be compensated by the increased carbon storage in the soil (7,258 metric tons/year)

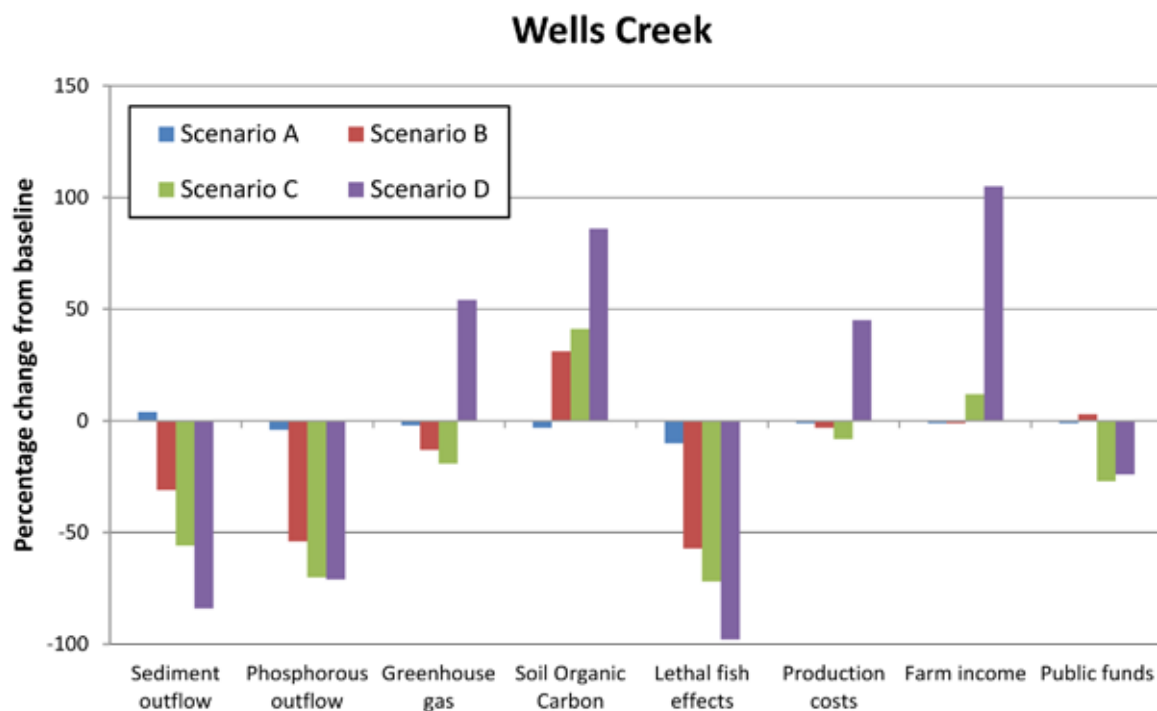


Figure A7. Projected changes (in %) in selected ecological and environmental indicators as compared to the baseline (Table A10) in Wells Creek watershed under scenario A current practices, B best management practices, C maximizing diversity and profitability and D increased vegetative cover (adapted from Boody et al. 2005).

Chippewa River

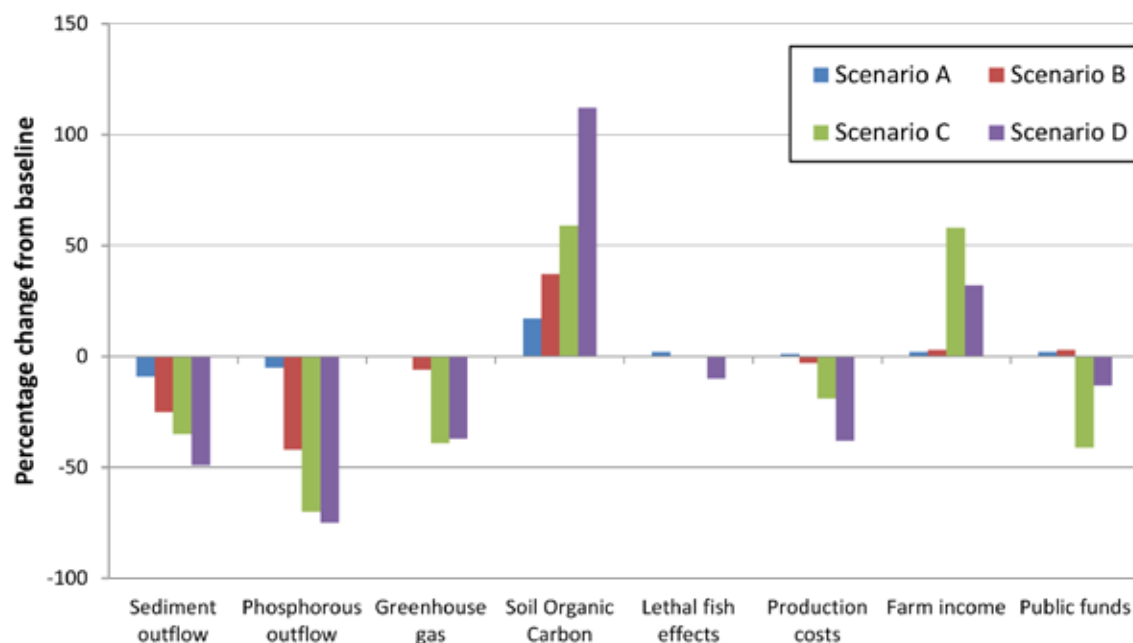


Figure A8. Projected changes (in %) in selected ecological and environmental indicators as compared to the baseline (Table HH) in Chippewa River watershed under scenario A current practices, B best management practices, C maximizing diversity and profitability and D increased vegetative cover (adapted from Boody et al. 2005).

Table A10. Baseline values of the indicators in Figures FF and GG for Wells Creek and Chippewa River watershed in Minnesota, USA (adapted from Boody et al. 2005; dollars are based on 1999 values).

Indicator	unit	Baseline values	
		Wells Creek	Chippewa River
Sediment outflow	000 kg/year	36	1.8
Phosphorus outflow	kg/year	3,430	2,322
Greenhouse gas	metric tons carbon equivalent	5,003	2,065
Soil Organic Carbon	metric tons/year	3,902	4,792
Lethal fish effects	days/year	6.7	11.2
Production costs	000 USD/year	13,522	9,202
Farm income (net)	000 USD/year	2,089	979
Public funds			
Conservation Reserve Program	000 USD/year	115	306
Commodity payments	000 USD/year	1,370	1,386

Appendix 13

Opportunities and Trade-offs Between Animal Production, Ecosystems, and Livelihoods

A13.1 Exploring trade-offs between livestock, livelihoods, and ecosystems

In response to several future scenarios, the MA concludes that in the next 50–100 years, major agricultural decisions will come in the form of trade-offs, especially “between agricultural production and water quality, land use and biodiversity, water use and aquatic biodiversity, and current water use for agricultural production” (Nelson 2005). The accelerating demand for livestock products is increasingly being met by intensive (industrialized) production systems, especially for chicken and pigs in Asia (Thornton 2010). These systems have contributed to large increases in production: over the last decade, bovine and ovine meat production increased by about 40%, pig meat production rose by nearly 60%, and poultry meat production doubled (Steinfeld et al. 2006). However, intensified livestock production poses serious waste problems and puts increased pressure on cultivated systems to provide feed inputs, with consequent increased demand for water and nitrogen fertilizer.

Whereas the negative impact of these systems on ecosystem services are well known, it is harder to find suggestions for changes that would allow these production systems to make a positive contribution to ecosystem services. The focus is mainly on mitigation of the negative impacts of these systems, for example through recovery of nutrients from manure. In general, producing in a more sustainable and less polluting way, while still meeting the demands, will require an investment by the producer, at least in the short term. For instance, recovery of nutrients from manure, an important contribution to the supporting ecosystem service of nutrient cycling, is highly variable and depends significantly on infrastructure and handling (Herrero et al. 2009). Approximately 65% of manure

nitrogen is recovered from (industrialized) intensive systems in Europe. Almost 30% of this is lost during storage and maximum cycling efficiencies as nitrogen available to crops is around 52%, though with large differences between countries (Oenema et al. 2007). In developing countries as well there is a large range of variation in nitrogen-cycling efficiencies in manure management systems (Rufino et al. 2006). Manure handling and storage and synchrony of mineralization with crop uptake, hence fine tuning of nutrient cycling in the soil, are key ways of increasing nitrogen cycling efficiencies in mixed intensive systems, thus contributing to better regulation of water quality.

Yet, there are also examples of situations where co-benefits emerge between agricultural outputs and maintenance of ecosystem services. These examples may not be readily available as they require in-depth analysis of scientific as well as indigenous evidence and thus come at a (knowledge intensive) cost. Some guiding questions on livestock, ecosystems and livelihoods have been formulated by Herrero et al. (2009):

General questions

- Can we meet the demand for livestock products in an environmentally sustainable way or will the demand for livestock products will be forced down as trade-offs for resources increase livestock product prices?
- Will reductions in demand for livestock products in the developed world lead to higher environmental sustainability? What will be the effects on producers?
- Can livestock product prices be maintained at low levels while accounting for the full environmental costs of livestock production? What will be the impacts on the poor?

- Will livestock systems evolution lead to more sustainable livestock benefits for society?
- Can the limits to sustainable intensification be adequately defined and indicators for measuring it be developed and monitored in livestock systems?

Pastoral and agro-pastoral systems

- Can the increased global demand for livestock products lead to increased incomes of livestock keepers?
- Will increases in extensive livestock production to meet demands increase deforestation in the neotropics?
- Can we increase grassland productivity through management and fertilizer inputs without increasing the environmental impacts of livestock production?
- A significant carbon sequestration potential exists in pastoral systems in Africa and Latin America, but can simple and transparent systems of payments for environmental services (measurements, monitoring, and payments) be developed and implemented?
- Can pastoralists really reap the economic benefits of livestock/wildlife co-existence under increasing human population density, agricultural intensification and increasing rangeland fragmentation?

Mixed crop-livestock systems

- Intensifying the diets of ruminants can decrease methane production, but can this be done without increasing the demand for grains?
- Intensification of production may increase food production in parts of the developing world but can this be done without eroding the diversity of animal and plant genetic resources as more productive animals and plants are sought?
- In Africa sustainable intensification of mixed extensive areas is possible but significant in-

vestments are required in services and markets. How do we increase productivity and incomes in African smallholder farming systems without significantly reducing soil fertility? Can the role of livestock be re-defined?

- How will ruminants in Asia be fed in irrigated systems as water tables drop and land use is devoted to the production of staple crops?
- Mixed systems in North America are gaining significant research interest but will these systems remain as productive and economically viable as their more industrialized counterparts?

Industrial systems

- Demand for livestock products has significantly increased the production of monogastrics like chicken and pigs. This has reduced prices of meat for poor consumers but at the same time has caused pollution problems in places.
- High efficiency (output per unit of feed) is possible in the productivity of monogastrics, but dependence on concentrates will increase demands for feed grains, possibly fuelling deforestation in the neotropics. Can grain use for animal production be reduced while maintaining the economic viability and efficiency of these systems?
- Systems in North America and Europe are heavily subsidized to maintain certain environmental and landscape benefits but at the same time this creates demand for feed (grains) and resources elsewhere. Is this sustainable?

A13.2 Opportunities for sustainable livestock systems

It is important to distinguish extensive and intensive livestock production. Livestock grazing is the single largest user of land globally in terms of area, but most of the world's animal production comes from intensive industrialized production in developed countries, closely followed by rainfed mixed crop-livestock systems in developing countries. These intensively farmed areas land areas are the focal points for ecosystem degradation. For example in

Table A11. Estimated major sources of soil loss from different land-use practices in Ethiopia and implied major sources of sedimentation of water bodies in Ethiopia (Hurni 1990).

Land use or cover	Area of country (%)	Estimated soil loss (tons/ha/year)	Total soil loss	
			(million tons/year)	(% of total)
Annual crops	13	42	672	45
Grazing and browse	51	5	312	21
Wood and bush-land	8	5	49	3
Forests	4	1	4	<1
Other	24	-	457	30
Total	100		1,493	100

Ethiopia, 45% of the soil loss occurs on the 13% of country under cultivation, while grazing lands covering about half of the country account for only 21% of the soil loss (Hurni 1990; Table A11).

Livestock keeping creates multiple impacts on both the carbon and the nitrogen cycles, thus impacting climate change. Luckily, this also implies that there are multiple options for mitigation within the livestock sector (World Bank 2009). Livestock production systems offer significant potential in carbon sequestration, for instance in improved pastures, and in reversing deforestation for the production of feed stuffs through increased agricultural productivity (Watson et al. 2000). Some livestock herding systems in Africa have managed large areas in semi-natural status, maintaining vegetation cover and indirectly preserving vital ecosystem services. With respect to reduced emissions, much can be done by keeping fewer, but more productive animals through better nutrition, animal health, breeding and husbandry techniques (Tarawali et al. 2011). To mitigate greenhouse gas emissions from animal waste, options lie in increased feed digestibility, storage and treatment of the waste and appropriate waste applications (World Bank 2009).

Land degradation is linked with low water productivity and impaired ecosystem services (Bossio et al. 2008). Land degradation is often associated with high population pressure. However, the extent of land degradation and its causative mechanisms are highly site-specific (Muchena et al. 2005). One way of dealing with this is to facilitate outmigration of people from vulnerable areas, through the provision of education and credit

services offering alternative livelihoods (World Bank 2009). However, high population pressure and market demand can in itself trigger investments in labor-intensive conservation practices and natural resources management (Nelson 2005). Solutions tackling land degradation lead to improved water productivity and environmental health (Descheemaeker et al. 2009), without reducing the water availability for food and feed production.

With respect to nutrient cycling, adjustments are needed both in nutrient-deficient systems, where soil fertility is being depleted, and nutrient-loaded systems, where groundwater contamination, surface-water eutrophication and soil pollution are major problems (World Bank 2009). Technical solutions to reduce the quantity of animal waste and facilitate its proper management and application have to be supported by regulatory measures and financial instruments, such as subsidies and taxes. In nutrient-deficient systems, proper integration of livestock and crop production components in mixed and agro-pastoral systems can alleviate nutrient export through the application of manure and urine to cultivated areas (Powell et al. 2004).

Sustainable growth and intensification of livestock production systems will be required to cater for opportunities of increasing demands for livestock products, while mitigating the negative effects of the sector (Tarawali et al. 2011). Substantive investments and policies are essential to implement the measures above (World Bank 2009). With more sustainable livestock production systems, the increased demands for animal products could be satisfied while maintaining environmental flows and services.

A13.3 Integrated watershed management for improved water productivity and ecosystem services in Ethiopia

Example based on Descheemaeker et al. (2010b).

Crop-livestock farming is an important livelihood strategy for smallholder farmers in water scarce areas of Ethiopia, which are characterized by land degradation, low agricultural productivity, food insecurity and increasing population pressure. Integrated watershed management has become a popular way to tackle the inter-related problems of land degradation, low productivity, institutional and organizational constraints and poverty (German et al. 2007; Shiferaw et al. 2009). Community-based integrated watershed management, through exclosures and water harvesting ponds, was implemented in the water scarce LencheDima watershed in the northern highlands of Ethiopia (Liu et al. 2008).

With the overall aim to rehabilitate the degraded hill slopes in the watershed, exclosures (areas closed for grazing and agriculture) were established. In these closed areas contour trenches were made for improved water infiltration and multipurpose trees were planted at the time of closing. This enhanced regulatory (water regulation) and supporting (soil formation) ecosystem services. The community was responsible for the protection of the area and this was institutionalized through written bylaws. Provisioning services were enhanced as herbaceous and woody biomass production in exclosures recovered drastically (Figure A9) and farmers harvested the grass for haymaking. Exclosures led to improvements

in livestock water productivity (Descheemaeker et al. 2009): by protecting about 40% of the rangelands in the watershed, the water productivity of the feed increased by 18 to 49%, depending on the amount of hay produced in the exclosures. As a result, the livestock production per unit of water depleted also increased (Descheemaeker et al. 2010b). Long-term environmental benefits (observed runoff reduction, groundwater recharge and protection of downstream cropland from peak flows) and increased woody biomass production from exclosures contribute to improved ecosystem services in the watershed.

The second intervention consisted of dome-shaped water harvesting structures in the farmers' homesteads. Farmers used on average 50% of the water to irrigate fruit trees and vegetables planted in their homesteads. Domestic uses accounted for about 20% of the water use, and livestock drinking for the remaining 30%, mostly in the dry period. The effect of water harvesting structures on livestock water productivity was brought about through the reduction of the energy spent by animals for walking to the drinking points in the dry season (about 11% of their annual energy budget). The energy saved could potentially be used for productive purposes such as milk production (Descheemaeker et al. 2010a). Other studies (Muli 2000; Staal et al. 2001; Puskur et al. 2006) found that water harvesting structures enabled farmers to combine vegetable production with small scale dairy, which significantly increased milk production and farmers' income. While animals were kept in the homestead for drinking, the pressure on the rangelands was also reduced, avoiding land degradation and disruption of environmental flows.



Figure A9. Degraded open access grazing land (left) and protected exclosures, three years after closing (right).

Appendix 14

Options for Sustainable Agriculture in Arid Environments

A14.1 Low tillage and other soil improvement measures

Amending cultivation methods to fit the landscape is not a new idea. Sir Alfred Howard, whom many credit with the invention of organic agriculture¹³, talked about farming to fit the land in his 1943 book, *An Agricultural Testament* (Howard 1943). In this book, Sir Alfred describes in detail the damage done to soil structure by excess tillage: each plowing simplifies the soil, taking away part of its crop capacity. Plowing breaks up the intricate structure of living soil and exposes the microflora and fauna to the sun and the drying air. Deprived of these vital organisms, the soil loses its ability to 'clump' or form colloids of soil and organic matter. This clumping leaves air channels throughout the soil; when clumping does not occur water has no way to penetrate and soils lose their ability to retain moisture. Plowed soil may then compact into cement-like surfaces or turn into fine dust that can easily be blown or washed away by weather events. Taking all this into consideration, Sir Albert's ideal format for rainy England was almost a no till format depending very much on pasture and animal husbandry, woodlots, hedgerows and orchards.

The amount of topsoil lost varies from crop to crop. The rich soils of the American prairie have been farmed for a hundred or so years, losing one third of the topsoil and approximately half of the soil's fertility. Topsoil is a non-renewable resource, once lost; it may take hundreds of years to regenerate naturally. However, with adequate management it is possible to build an arable layer in 10 years and thus enhance the supporting and regulatory services of an agroecosystem. This would involve maintaining groundcover and steadily increasing the amount of organic material in the soil, which then increases its structure, water storage capacity and fertility (Lal

2010). Increasing soil organic matter is extremely hard and the very slow accumulating effect can easily be disturbed by plowing, especially in arid areas.

To keep soil in dry areas healthy and intact, long cycle crop rotations and long fallows are necessary. Alan Grainger describes such systems in his book, *The Threatening Desert* (Grainger 1990):

"Traditional farming in arid and semi-arid areas was designed to reduce risk of crop failure by planting a variety of crops with different water requirements so that there was a good chance that one would survive if rains were late or limited. Essential components of this crop system were drought-resistant food crops. More profitable and demanding crops such as cotton or groundnuts could be planted in years when rains were plentiful. Long fallows were used so that fertility could regenerate. After four or five years of continuous cropping on one plot, farmers would move to another, leaving the first plot idle or to be used as pasture for up to five years. In some areas, *Acacia senegal* trees were allowed to invade the fallow plot and when mature they were tapped for Arabic gum, a highly profitable commodity, for about seven years. During this fallow period, soil was protected from erosion by tree cover, falling leaves built up a litter layer so that vital nutrients and humus accumulated in the topsoil and fertility was also enriched by nitrogen fixing bacteria in the tree roots. Finally the trees were felled and burned and the land was cultivated for food crops once more."

These systems were highly effective examples of biomimicry and sustainability in traditional agriculture (Benyus 1997). The vegetation introduced was diverse (see also A14.2) and required different amounts of moisture at different times and from different soil layers. The water used was the water that collected in wadis (temporary rivers) or alluvial fans from the irregular rains. The cultivars were a mixture of annual food crops, useful bushes and perennial indigenous trees, similar to

¹³ Organic or ecological agriculture do not necessarily or always imply low or no tillage.

the vegetation that grows in such areas with no human intervention. Wood, cereal, herbs, gum, fodder, shade, shelter and charcoal were among the benefits reaped from these traditional systems.

Approaches like this can be applied in areas where pressure is low. However, when population pressure increases these farming systems either collapse or, with increased value of the land, may become more sustainable. The greening of the Sahel after successive droughts was not only attributed to increased rain, but also to widespread adoption of sustainable farming practices (Herrmann et al. 2005; Reij et al. 2005, 2009).

Since desert soils are generally poor, attention must also be paid to available plant nutrients. Nitrogen can be increased by the planting of nitrogen-fixing trees and legumes, or by the application of animal manure. Potassium is made available by the breakdown of leaf litter and the addition of composted material to the areas under cultivation. Phosphorus on the other hand, cycles in and out of plant-available states, which makes it a difficult nutrient to manage. Most soils contain phosphorus in unavailable forms: in acidic soils phosphorus binds to aluminum and iron, in alkaline soils it binds to calcium, and even with relatively neutral pH soils phosphorus can become immobile, lost to erosion, or trapped in clay-humus complexes. It is possible to add phosphorus in the form of powdered rock phosphate or rock dust but the release of the nutrient depends on biological activity in the soil. Acids produced by bacteria and mycorrhizal fungi act upon soil phosphorus and change it to available forms. Therefore phosphorus availability is not just a function of supply and demand but also of starting and maintaining high levels of biological activity in the soil, which illustrates the importance of nutrient cycling as a supporting ecosystem service.

A14.2 Sustainable crop selection for arid agroecosystems

A combination of farming practices (including soil management), animal husbandry and agroforestry can make dry agroecosystems more productive and sustainable, thus improving livelihoods at the local level. There may be opportunities for trading and sale of some percentage of the harvest, for small

scale production, and for increasing the amount of usable materials for the desert household. These goals can be supported by the cultivation of a diverse and sustainable crop repertoire.

An investigation of local plants in each candidate site helps to identify which local plants may be a valuable source of food for the human population and which can be utilized to support the flocks and herds (Danin 1983). There are usually both seasonal and constant resources among local species. Many suitable crops might be found among the local perennial plants (Shmida and Darom 1992). Perennial plants and their longer cycles of living and yielding are much more suitable to the desert than annual crops. Perennial plantations need little tillage allowing for natural regeneration of soil structure. Desert perennials are more water thrifty; each liter of water invested in a perennial is converted to long-lived plant tissue, fruit, seeds and leaves, an investment not only in yield for the season but in future yields. Perennial plants allow for more ecological agriculture; the long slow breakdown of organic matter and release of minerals in the arid zones is suitable for the soil of long-lived plantations. Perennial plants are both the agents and the beneficiaries of such cycles.

Table A12 lists several local crop candidates from a zone of hyper-aridity shared by Israel and Jordan. The advantages of using such desert-adapted plants include the water-thrifty nature of the germplasm, the availability of fresh genetic material with no need for quarantine, local knowledge and familiarity relative to the plant material and possibly existing systems for utilization of the plant products. They are all physiologically appropriate for arid and hyper-arid areas and multipurpose, producing food and material for sale and trade and improving the organic matter content of poor soils and the soil's permeability. Hence these plants perform better and provide more benefits to a population living in a hyper-arid area.

Finally, perennial plantations, ideally made up of various species, such as in many oases, are regenerative-friendly. They may make best use of the available water and even help generating supporting and regulatory ecosystem services. Trees shade and protect the soil from the sun, lowering

soil temperatures and thus regulating the micro-climate. Fallen leaves produce natural mulch and encourage colonization of beneficial soil organisms. Trees and perennial plants are sanctuaries and nesting places for birds, hunting grounds for insectivores, feeding areas for pollinating insects. Their roots are highways into the earth for ants, beneficial nematodes, beneficial fungi and mycorrhizza, as well as conduits for sparse and precious rainfall. When perennial plantations are established, their mitigating presence allows for the integration of some annual plants to utilize the runoff from the irregular rains. Hence a balanced agroecosystem can be established, with a wealth of regulatory and supporting ecosystem services, safeguarding the delivery of food and other provisioning services. In semi-arid areas, well-managed rangelands could have similar impacts.

Local species may provide some of these perennial and annual elements as appropriate choices for biodiversity resources. The annual plants may include grass for grazing, medicinal herbs for use or cottage industry and leafy vegetables to improve the diet of the farmer and herder. Perennial trees would ideally be multipurpose, providing fruits, shade, fodder, wood

and more. A good example of such a multipurpose tree is the *Argania spinosa* in southern Morocco that produces hard wood for tool manufacture when coppiced, can be a source of browsing for goats, a source of nectar and pollen for honey bees, an anti-erosive tree in areas with seasonal flooding, but is most of all a source of edible oil, soap and cosmetic oil for the local people. Argania oil is added to porridge (semetar), nut butter (amalou) and used very much like olive oil in the Moroccan kitchen (Morton 1987). Another interesting tree is the *Lalob* or *Balanites aegypticus* which supplies browse for goats and camels, fruit pulp for fermentation, medicinal sap, oil of good quality for illumination and firewood and can serve as an anti-erosive (NRC 2008). Members of the *Prosopis* family of trees are all nitrogen fixers. These trees can supply browse, high quality protein food from pods, firewood, syrup and non-gluten flour for human consumption, shade and shelter for the flocks, wind-break and building material. Especially in the dry season, the trees provide high quality feed for livestock. Unfortunately several *prosopis* species have a tendency to invasiveness that needs to be carefully managed and thinned to allow for the planting or emergence of other species.

Table A12. Crop candidates and the potential contributions of their germplasm to ecosystem services in a desert area shared by Israel and Jordan.

Crop Candidate	Provisioning services	Regulatory services ^a	Supporting services ^b
<i>Atriplex</i>	Flowers, pasture, medicinal	apiary	
<i>H. salicornia</i>	Browse, flowers, oil	apiary	reclamative, pioneer
<i>Marula</i>	Fruit, oil, timber, liquor, browse	shade	reclamative
<i>Balanites</i>	Fruit, oil, flowers, sap, leaves, medicinal, poles, fence, browse	shade	
<i>Commiphorasap</i>	Sap, smoke wood, flowers, medicinal	xerophyte, apiary	reclamative
<i>Boswellia sp.</i>	Sap, incense, smoke wood, medicinal	apiary	reclamative
<i>Acacia</i>	Sap, pods, wood, browse	xerophyte, apiary	pioneer
<i>Achillea</i>	Essential oil, flowers, medicinal	apiary	pioneer
<i>Argania</i>	Nuts, oil, wood, poles, browse	apiary	reclamative
<i>Capers</i>	Buds, medicine, cosmetics, liquor	apiary	ground cover
<i>Terebinth</i>	Resin, wood, browse, rootstock	shade, windbreak	reclamative
<i>Zisiphus</i>	Fruit, poles, liquor, juice, browse	living fence, windbreak	
<i>Cassia</i>	Flowers, leaves, pods	apiary	ground cover, reclamative
<i>Saxaul</i>	Browse, sap, flowers	dune stabilization	reclamative
<i>Prosopis</i>	Browse, wood, poles, pods	stabilization, apiary, windbreak	reclamative
<i>Zyglrophyllum</i>	Browse, sap, flowers, pasture, medicinal		pioneer
<i>Artemisia</i>	Essential oil for medicinal use (antimalarial)	apiary	

^aApiary plants are important habitats for bees, hence contribute to pollination. Shade and windbreaks plays a role in climate regulation. Xerophytes use very little water hence help regulate water flows. Living fence and (dune) stabilization are important in erosion regulation.

^bReclamative plants and ground cover (also through nutrient cycling) help soil formation. Pioneer plants contribute to climate change mitigation.

A14.3. Arboreal pastures

Another potential intervention in harmony with the harsh environment of arid areas is the establishment of arboreal pastures. The first aspect of the planting of arboreal pastures is their influence on the merciless wind and water erosion rampant in the parts of the arid world that have been overgrazed and damaged by centuries of neglect, then made worse by wasted run-off and non-sewage saline water. The second aspect of the planting of arboreal pastures is that it helps to mitigate the problem of fierce competition between local animal herders over the rights to graze sheep and goats on the vegetation that remains.

The goal of arboreal pasture planting is to stop the erosion by reclaiming and reusing the water resources to plant native trees and plants. These plants should be planted in sufficient format and quantity to regenerate the chosen sites and produce more biomass for grazing. The competing factions, who may be communities, institutions or even commercial stakeholders, in all sites must agree to work together towards this goal, and share the task of planting and site care and pledge to share the pasture areas in a sustainable manner for summer grazing after the trees and plants are mature. The immediate objectives of arboreal pasture planting are the establishment of systems to reclaim and use the wastewater and runoff that are currently damaging factors and to turn them into water resources for the deliberate increase of native vegetation, thereby halting the ongoing land degradation. The ultimate goal is an increase of vegetation for grazing, the establishment of partnerships for sustainable grazing sites between former rivals and hopefully the creation of examples that can be emulated in other contested, arid and desolate grazing areas to the benefit of all stakeholders (Even-Ari et al. 1982).

Runoff water from non-sewage or saline wastes is used to nourish indigenous wild trees and shrubs on rehabilitated ancient terraces. Supporting measures include fencing the plantings until the trees are mature enough to be grazed. Various factors are monitored, such as plant growth, the weather, the amount of runoff water and other environmental factors, including biomass, the effect on soil temperature and the amount of organic material and available nutrients in the soil. This will allow

for an accurate evaluation of the development of the species in the context of the available water resources. Once the trees are big enough, animals are introduced to the mature planting to observe their behavior and preferences during grazing and to reach an approximation of number of trees and combination of native plants that will be needed per head of sheep and goats for sustainable grazing. Arboreal pasturage can thus provide a wide range of ecosystem services in addition to grazing grounds, such as erosion control and enrichment of the soil by leaf litter and nitrogen-fixing of appropriate tree species (Rabia et al. 2008).

A14.4 Examples of water collection in arid areas

Runoff water can be directed after collection, via a division box, to lateral canals, especially across the face of a slope, to allow for storage in that slope or into small depressions or limans in more level areas. These features can be produced by hand labor with simple tools. Both slopes and limans can be planted with low water use perennials and heavily mulched to prevent evaporation. Water can also be stored in berms and swales by directing the water into loading ditches on the upslope side of the features. A swale planted with grass or a fodder crop will wick the water laterally across its face. A planted berm formation will absorb the water upward into its core.

A sound combination of interventions could also help protect against wind and water erosion. An example of a dual strategy would be an upslope catchment area and a berm planted with water thrifty trees. The water would be slowed by the catchment area, stored in the berm and so kept from creating a damaging gully. The trees on the berm would be supported by the collected water, and grow strong and tall enough to break the wind.

These principles have been applied in a rainwater harvesting project managed by the Arava Institute for Environmental Studies (AIES) in the Negev, Israel. Nir Moshe is the site of AIES's largest rainwater collection experiment in the Negev, with an average annual rainfall of 250 mm. There are 20,000 m² of berms and contour furrows in this project that collect rainwater from a series of nearby slopes. The berms were formed by use of

a bobcat tractor and hand work to create a series of five curving berms whose nesting concave sides face the slopes and whose lower points drain into a roadside ditch that leads to a pond. The berms have been planted with drought tolerant trees, including cassia, moringa, albitzia, carob, argania and leucaeno. A pond has been created at what was once the lowest point of a gully caused by erosion. It has been closed at one end, graveled and lined so that it can accommodate several thousand cubic meters of water. By the end of January 2010, after

one winter in operation, two thousand five hundred cubic meters (2,500,000 liters) of water were collected on this site by the catchment furrows and stored in tree covered berms. The runoff water was drained into the small pond. This was the biggest rainwater harvested at this site since it was created four years ago, feeding an agroecosystem that provides a range of provisioning (food, fodder and other products from the trees), regulatory (water and erosion regulation) and supporting (nutrient cycling) ecosystem services.

Appendix 15

Wetlands

A15.1 Integrated wetland assessment in Cambodia and Tanzania

Example based on the application of IUCN's Integrated Wetland Assessment toolkit (Springate-Baginski et al. 2009).

Wetlands contain biodiversity of exceptional conservation significance, comprising many unique ecosystems and a wide array of globally-threatened species. At the same time they typically form an essential component of local, national and even regional economies, as well as underpinning the livelihoods of many rural communities. Yet, despite their importance, they are under increasing pressure. Weak consideration of wetlands in decision-making remains one of the major factors leading to their degradation. Management decisions affecting wetlands rarely consider the wider biological, ecological, development or economic values of wetlands as they are. IUCN developed a toolkit of methodologies to assess the value of wetland biodiversity to livelihoods, particularly of the poorest, and to find ways to clearly present this information to decision makers (Springate-Baginski et al. 2009). The methodologies are integrated and incorporate biodiversity, economics and livelihoods approaches. The toolkit was put in practice in two demonstration sites: Stung Treng Ramsar Site in Cambodia and Mtanza-Msona Village in Tanzania (Allen and Springate-Baginski 2008).

Following initial scoping exercises to generate broad basic data, capacity and awareness on wetland values within the demonstration sites, fieldwork was completed and integrated reports on the livelihood, biodiversity and economic values of the areas were prepared. These assessments yielded detailed scientific and management information, including GIS maps and databases, which document key values and overlaps between threatened species and areas of high human dependence. Information obtained in the Stung Treng Ramsar site was included

in the management and zoning plan for this site, supporting pro-poor wetland conservation and sustainable use to the benefit of local livelihoods and biodiversity. Data obtained in the second demonstration site helped local communities to understand the importance of wetlands resources in their livelihoods. The main output of the project is "An Integrated Wetland Assessment Toolkit: A guide to good practice" (Springate-Baginski et al. 2009). This guideline provides a set of integrated assessment methods that combine and investigate the links between biodiversity, economics and livelihoods, with a particular focus on strengthening pro-poor approaches to wetland management. It aims to assist in overcoming the current methodological and information gaps in wetland planning, factor wetland values into conservation and development decision-making and management planning, and assist in identifying areas of potential conflicting priorities. It is expected to be of use by wetland site managers, conservation and development planners, and researchers from both natural and social science disciplines. The studies in Cambodia and Tanzania brought experts from the social, ecological and economic background to work together. It was not easy to convince them of the value of the work in each of the other two disciplines. For example, it was challenging but ultimately successful to convince the social scientists of the value of biodiversity assessment and vice-versa and it was challenging to find good models and tools as examples of integrated work (Allen and Springate-Baginski 2008).

A15.2 Integrated management of wetlands in China

Example based on Wetlands International (2007).

China has about 6 million hectares of mountain wetlands of which the largest majority is peatlands. They provide key habitats for endangered wildlife and plant species and they also maintain water levels in streams, rivers and adjacent grasslands.

Peatlands also provide important ecosystem services in storing and sequestering huge amounts of carbon. However, they are negatively impacted by unsustainable farming practices (drainage, over-grazing), mining and infrastructure development, and by climate change. Wetlands International has set out to involve different stakeholders from various sectors and government levels (central, provincial, prefecture, county and community) to support the integrated management of mountain peatlands. The work is being conducted in the Ruergai Marshes on the Qinghai Tibetan Plateau and the Altai Mountains in northwestern China. In these locations, practical ways in which biodiversity conservation and provision of ecosystem services can be supported by different economic sectors and local communities are being tested.

After various meetings with all stakeholders to enhance understanding of the project and the importance of biodiversity conservation, biodiversity and socioeconomic data was collected in the two sites. In 2007, field activities such as peat land surveys were initiated by training key local personnel in the Ruergai Plateau and Altai. Based on collated and field data, various strategies for the protection and sustainable use of the Altai mountain wetlands were reviewed and a rapid assessment report prepared. This report was presented to all stakeholders and their input considered in its final version. Solutions proposed for the integrated management of peatlands focused on changes in infrastructure planning and grazing management. Techniques for restoring peatlands damaged by old drainage schemes were also included in the plan. Currently, other conservation strategies are under development with collaboration of local governments. The next steps will be the implementation of solutions and monitoring of the impacts on ecosystem services.

A15.3 Wetlands and livelihoods in South Africa

Example based on WWF (2009a).

Wetlands are important ecosystems for water security because of their role in water regulation and water quality moderation. Additionally, they possess unique biodiversity and offer important

livelihood benefits. However, in many areas the use of wetlands for small-scale farming is eroding the wetland integrity and associated ecosystem services, through unsustainable practices. This is the case of the Sand River's upper catchment wetlands in South Africa's Limpopo Province. These wetlands are within densely populated communal lands. The wetland farmers, 90% of whom are women, are among the poorest of the country and depend on these freshwater ecosystems as their only source of food. But their farming practices, passed from generation to generation, are causing increased erosion, increased desiccation, poor soil fertility and low productivity. In partnership with the Association for Water and Rural Development (AWARD), the WWF South Africa Program Office started a project to recovery the ecological functions of the Sand River's wetlands while improving the livelihoods of the communities living in this area. The project aims to promote awareness of the value of wetlands goods and services in providing livelihood security to poor rural communities, and to develop good agricultural practices among wetlands' farmers and harvesters in the Sand River Basin.

The project started by evaluating the nature and intensity of farming practices in the wetlands; detailed and rapid appraisals on 60 plots were completed using interviews, field assessments and documentary photographs. The appraisals confirmed erosion, desiccation and poor soil fertility as the main negative outcomes from farming practices. Because wetlands farmers relied very much on the wetlands for their livelihoods, it was assumed that they understood their value. However, this was not true and getting farmers to change their practices and think about long term management of the wetlands was a challenge.

Based on this information, all 60 farmers were grouped on the basis of shared issues and engaged in a series of workshops and field visits, whereby they were introduced to basic wetland concepts, conservation tillage methods and good wetland practices. During these workshops, discussions about the need for change were carried out so that farmers could understand the connection between their livelihoods and long term wetland security and functioning. Farmers then designed their own action plans as well as impact indicators.

These actions were implemented and their impact on agricultural practices and the state of the wetlands was determined using the indicators. An obstacle for this was the poor communication and lack of self-organization amongst farmers. Poor trust hampered knowledge exchange about the implemented actions. However, with the support of the project team, farmers understood with time the importance of working together to find ways

to use the wetlands more sustainably. They also became aware that a number of the problems they faced had their origins in the micro-catchment and that working with other stakeholders was needed. Hence they started working on reducing livestock damaging crops, preventing gully erosion and managing the large quantities of water entering the wetland from the surrounding villages.

Appendix 16

Integration of Aquaculture in Agroecosystems

Livestock, agriculture, horticulture, aquaculture and fisheries production have been closely integrated in iconic farming systems for hundreds of years; e.g. dike-pond farming in the Pearl River Delta and rice-fish culture in Zhejiang Province, China; canal-dike culture in Thailand and Vietnam; *chinampa* cultivation in Mexico; and taro cultivation with fishponds in Hawaiian *apupua'a* agroecosystems. Several of these traditional systems have virtually disappeared and most are now under immense pressure to change, owing to greater concentration on high-value, cash crop production supported with external technology (formulated feeds, inorganic fertilizer, agrochemicals, mechanical pumps, aerators and filters and agricultural machinery). Promising approaches to productive multiple-use of water resources that persist include rice-fish farming and integration of aquaculture and culture-based fisheries in reservoirs and these are discussed further below. Negative environmental externalities associated with intensive farming become more apparent and the full cost of external feed, fertilizer, fuel and technology inputs are accounted for in cost-benefit assessments. Together this is likely to influence policy-making and consumer attitudes and may signal a renaissance for traditional resource efficient and conserving farming systems. Therefore it is important to preserve knowledge and ideally examples of such integrated systems to guide and inform emerging ecocultures. This appendix summarizes conditions, constraints, and water use efficiencies in various aquaculture-agroecosystem combinations (Table A13). Stocking aquatic animals in predominantly aquatic agroecosystems, with interconnected field and pond systems, may make a significant contribution to farm household and local community food security and nutrition. Appropriate

management and governance arrangements are required, however, to ensure costs and benefits are distributed equitably and that impacts of proposed changes in access arrangements on poor and landless groups are considered.

A16.1 Aquaculture in rice fields

A special case that has a long tradition is fish keeping in rice fields. In the discussion on wetlands (Appendix 15) it is also important to recognize the synergies between fisheries and rice cultivation that are being practiced in South East Asia and elsewhere. These practices may create agroecosystems that have higher biodiversity and increased water productivity.

Culturing fish in rice fields can help control pests and weeds, promote nutrient availability to rice plants and enhance nutritional benefits and financial returns from what are widely regarded as low input, environmentally friendly and more sustainable farming systems. Integrating fish culture in irrigated and rainfed rice fields also makes more effective use of appropriated water resources. Culturing fish in rice fields is considered a traditional practice in China, Japan, and Java; more recently rice-fish culture has been introduced by development agencies and extension services to many countries in Asia and a growing number in Africa. However, integrated culture of rice and fish requires refined farm management approaches with increased dependency on reliable water supply and farmers having to coordinate rice production and fish culture practices. Often this lack of expertise combined with poor quality and unreliable fish seed production has constrained widespread and long-lasting adoption.

Table A13. Integration of aquaculture practices with other activities to optimize efficiency and increase water productivity (adapted from Bunting, in press).

Integration	Management practices	Constraints and conditions	Potential water use efficiency outcomes
Livestock-aquaculture	Ducks and geese foraging on ponds Wildfowl and poultry housed over fishponds Waste from pigs and cattle directed to fishponds for treatment and nutrient recycling Plant and fish biomass cultivated using solid and liquid waste fed to livestock	Possible pathogen and disease transfers within integrated systems Chemical treatments and dietary supplements for livestock may affect production and accumulate in aquaculture components Excessive waste loadings or perturbations affecting the ecological-balance of the pond can result in low oxygen levels and fish health problems and mortality	Multiple products from ponds and lakes with lower water footprints Enhanced environmental protection of receiving waters through better on-farm waste management and nutrient recycling Aquaculture of biomass and fodder crops helps avoid public health risks and consumer acceptance of aquatic products grown using waste resources.
Aquaculture in irrigation and water management schemes	Fish cages in irrigation channels in India and Sri Lanka Culture-based fisheries in domestic supply and irrigation reservoirs Aquaculture in traditional irrigation structures within micro-catchments in Sri Lanka Fish culture in irrigated rice-fields and farmer managed systems in Africa and Asia	Excessive flow rates can impact on animal welfare and make food unavailable Debris can block mesh reducing flow rates and cause physical damage to cages Management must balance irrigation and aquaculture demands New structures may be needed to sustain fish populations during low-water periods Agrochemicals in extended irrigation systems and adjacent areas can affect aquaculture productivity and may constitute a public health concern	Nature of aquaculture means water is conserved, potentially with higher nutrient content, enhancing crop production Aquatic species may predate on disease vectors and crop pests and weeds Integration of aquaculture activities may enhance nutrient cycling and uptake by plants under irrigation
Aquaculture in water storage reservoirs	Fish cages in reservoirs for hydroelectric power generation Culture-based fisheries in water storage and hydroelectric reservoirs Polyculture in urban and peri-urban water-bodies primarily for floodwater discharge and amenity	Inappropriate reservoir bed preparation, presence of submerged structures and drowned trees and routine dropdown may reduce the area suited to aquaculture development Rapid dropdown may damage physical cage structures Changes in access and use rights associated with aquaculture development may cause social problems	Multiple-use of water in reservoirs could contribute to increased revenue generation and alternative livelihoods for displaced or marginal communities Appropriate species selection for aquaculture could contribute to weed control and enhance water quality in reservoirs.
Aquaculture in saline drainage and wastewater	Aquaculture in saline groundwater evaporation basins in Australia Fish culture in saline wastewater from industrial processes and desalination	Variation in salinity levels and possible extremes may constrain species selection or culture duration Low production rates as compared with prevailing commercial operations suggest need for further assessment of financial and economic attributes	Exploitation of saline water resources through integration of aquaculture can contribute to overall farm productivity and generate new income streams Economic benefits of integrating aquaculture, salt tolerant crop production and salt harvesting could help offset costs of controlling saline groundwater problems
Aquaculture in thermal effluents and cooling water	Production of juvenile fish in cooling water effluents from nuclear power stations in France Farming marine worms in thermal effluents in the UK	Chemicals used to clean power station and variations in water temperature may affect growth and product quality Farming species for human consumption may pose unacceptable health risks or not gain consumer acceptance	Retention of thermal effluents for aquaculture production can facilitate heat dissipation and contribute to meeting statutory discharge standards Exploitation of thermal effluents can help avoid greenhouse gas emissions associated with heating water for culturing cold intolerant species
Urban and peri-urban aquaculture	Fish cages in canals and lakes in Bangladesh and Vietnam Fish culture in canals, lakes, ponds and borrow-pits in peri-urban areas throughout Asia Macrophyte cultivation in drainage canals and low-lying water bodies e.g. Bangkok, Hanoi, Phnom Penh Aquaculture exploiting food and drink production and processing by-products	Multiple-use of urban and peri-urban water bodies may mean hydrology is out of the control of aquaculture producers and associated operational constraints result in sub-optimal management Risks from pollution and poaching may constrain aquaculture development Insecure land tenure and pressure from urban residential and industrial development may constrain investment in aquaculture systems	Floodwater storage and groundwater recharge associated with extensive wastewater-fed aquaculture operations can contribute to stabilizing local hydrological conditions Vigilance of aquaculture producers helps in monitoring pollution and safeguarding water quality for other users
Aquaculture in multi-purpose household ponds	Fish culture in small ponds used primarily for domestic and agricultural purposes Composite fish culture in rainwater-harvesting structures	Introduction of aquaculture can cause conflicts with other agricultural and domestic uses of household ponds Inclusion of aquaculture in rainwater harvesting ponds may constrain the use of water use for other crops and financial risks	Appropriate integration of aquaculture in household ponds can contribute to food security and livelihood outcomes without reducing water availability for other purpose Aquaculture in ponds can help reduce pressure on provisioning ecosystem services of natural water bodies

Integration	Management practices	Constraints and conditions	Potential water use efficiency outcomes
Wastewater-fed aquaculture	<p>Intentional use of wastewater to supply water and nutrients for aquaculture</p> <p>Lagoon-based sewage treatment systems incorporating fishponds developed under the Ganges Action Plan initiative, India</p> <p>Fish culture in 3900 ha of ponds in the East Kolkata Wetlands, West Bengal, India</p> <p>Duckweed cultivation on wastewater in UK for processing to biofuel</p>	<p>Health risks posed by wastewater use for aquaculture demand that appropriate treatment and control measures are adopted</p> <p>Consumer perceptions, prevailing beliefs and institutional barriers may constrain development</p> <p>Land area required for combined wastewater treatment and reuse through aquaculture may prohibit development</p>	<p>Management of wastewater promoted by integration of aquaculture can help operators meet statutory discharge standards and help safeguard public health</p> <p>Wastewater reuse through aquaculture can help protect the quality of water bodies receiving discharge from the system</p> <p>Exploitation of wastewater flows for biomass production could help alleviate pressure on freshwater resources</p>

Rice-fish culture was adopted widely in northeast Thailand and West Java, Indonesia and it has been shown to make an important contribution to incomes and food security in poor and marginal farming communities. A large proportion of global rice production is not under irrigation, and integrating fish culture in rain-fed fields unsuited to intensive rice cropping can help in developing more sustainable livelihoods for farming communities. Collection of wild food from rainfed rice fields has been shown to be important but is often overlooked. Perceived declines in the availability of wild fish and well developed trading networks for fish seed from private hatcheries stimulated the adoption of rice-fish culture in northeast Thailand.

As concern grows over the sustainability of high input, irrigated, monoculture rice production and farmers face increasing bills for fertilizers and pesticides to maintain yields, the viability of low-input rice-fish culture measured in conventional financial terms and based on standard risk assessment criteria is likely to increase. Farmers should be supported in assessing their prospects with regards adopting rice-fish culture and where demand exists action should be taken to ensure an enabling institutional environment exists. Successful development of rice-fish culture has been attributed to: adaptation of traditional water management approaches to accommodate fish culture; appropriate extension services, training and capacity-building; access to quality fish seed of appropriate species.

A16.2 From enhanced fisheries in wetlands to horizontally integrated land-based (marine) aquaecosystems

As stated in sub-sections 3.3.2 and 3.3.4, fisheries and aquaculture are very important sources of food from wetland systems. In many wetlands, interventions such as stocking fish and other aquatic organisms have blurred the difference between capture fisheries and aquaculture. However, no systematic impact assessment of this emerging aquatic resource management strategy has been undertaken. According to Gurung (2002) carp have been stocked in several lakes in upland areas of Nepal to enhance production and reduce fishing pressure on 'thinly populated native species' while safeguarding employment and income for traditional fishing communities 'until measures for conservation practices of locally vulnerable species are developed'. When planning and implementing such a strategy appropriate risk assessments and control measures should be employed to protect native fish populations and ensure other species are not negatively affected. Potential social, cultural, and environmental impacts of such interventions also demand careful assessment prior to implementation. As an alternative to stocking natural water bodies and in response to environmental concerns over degradation of open water aquaculture, horizontally integrated land-based marine aquaculture systems have been developed.

Responding to concerns over possible environmental degradation associated with open-water marine aquaculture and competition for space and resources with other coastal zone users several bodies have advocated the development of horizontally integrated or multi-trophic land-based marine aquaculture systems. Within such systems farmers use formulated feeds specific for each species. E.g. fish, shrimp or abalone, are cultured together with other organisms, notably microalgae, shellfish, and seaweed that convert nutrients released from the fed component to harvestable biomass, either for use as a supplementary food source, hence reducing the demands for feed, or to generate additional revenue, thereby increasing efficiency and productivity of the system. Other combination aquaculture systems have similar potential and risks (Table A13).

In Israel tank-based culture systems have been developed combining for instance fish or abalone with seaweed; abalone, fish and seaweed; fish and shellfish; fish, microalgae and shellfish; fish, shellfish, abalone, and seaweed. Constructed wetlands planted with samphire (*Salicornia* spp.) that can be harvested for use as a vegetable, forage or bio-fuel have been evaluated to a limited extent for additional ecosystem services, including nutrient cycling (Bunting and Shpigel 2009), but further work is required to assess likely production from commercial scale systems, labor demands associated with management and harvesting, market perceptions and risks associated with this strategy.

Integrated systems permit the generation of higher revenues and more regular cash-flows from water pumped ashore or from underground, or available via tidal exchange. A pond-based system combining fish, microalgae and shellfish developed on the Atlantic coast of France received water from a tidally filled reservoir. However, the capacity of the reservoir limited the biomass of fish and consequently limited the integrated production that could be maintained in the systems. In tropical coastal areas integrated farming systems combining pond-based fish and shrimp production with shellfish and seaweed production have been developed. However, high suspended solids concentrations can constrain shellfish growth and high turbidity

and grazing can limit algae production. Mangrove stands have been used to condition incoming water and treat aquaculture wastewater.

Economies of integration associated with horizontally integrated systems, using the same water, feed inputs, infrastructure, equipment, and labor to produce multiple crops, appear to offer a potential advantage over monoculture systems as they provide a wider range of ecosystem services. Opportunities to develop comparable systems in freshwater settings could be explored, as well as assessments to determine the impact on the aquaecosystem on ecosystem services within and outside the system. However, integration places new demands on farmers in terms of skills and knowledge requirements, results in additional risks, in particular related to engineering requirements and pests and disease and poses new and poorly defined statutory and marketing challenges.

A16.3 Aquaculture in irrigation systems

New capture fisheries are often cited as a secondary benefit associated with reservoirs developed for irrigation purposes. However, timely colonization by species suited to reservoir conditions and valued by fishermen is not guaranteed. Furthermore, unrestricted and unregulated fishing could limit the establishment of a substantial, self-reproducing stock of a desirable species (Munro et al. 1990). Consequently, establishing a culture-based fishery or fish culture in pens or cages may be proposed as a solution. Construction of pens and cages can be used to partition the available water resource, potentially enabling displaced or landless peoples to gain some form of employment and security; however, the costs of constructing and stocking such structures can be prohibitive, often leading to rich individuals and commercial enterprises dominating the available resources.

In Southeast Asia cages in inland waters are traditionally between 10 and 100 m² (Beveridge and Muir 1993). However, smaller 1 m² cages have been developed in Bangladesh, for example, primarily to permit poor people to engage in cage-culture (Brugere et al. 2001). The two major categories of cages utilized are fixed and floating,

fixed cages being generally smaller and used in shallow areas (<10 m depth). Management and input requirements for cage culture can be extensive, semi-intensive, or intensive. In tropical fresh waters the most commonly practiced form of cage culture is semi-intensive (Beveridge 2004). Tilapia species and common carp are often used for cage aquaculture in freshwater reservoirs. Cages can also be deployed in irrigation canals, but flow-rates and regimes must be suitable and the requirements of cage operators must be considered in the overall planning and management of the irrigation system.

Rapid uncontrollable expansion of aquaculture in larger irrigation reservoirs could potentially result in access to fishing grounds and navigational routes

being disrupted and this could in turn lead to social tension (Beveridge and Phillips 1993). Drawdown and the presence of submerged trees can restrict the area available for cage-based aquaculture development (Table A13). Fast drawdown can also cause physical damage to cages and lead to upwelling of deoxygenated hypolimnetic waters which could cause mortalities in overlying fish cages. Fluctuating water levels can be a serious problem in reservoirs used for irrigation and hydroelectric power generation. Uncontrolled development of aquaculture and associated waste discharges can lead to serious water quality problems (Beveridge and Muir 1993) and this can be compounded by reduced water exchange owing to the physical presence of pen and cage structures.

Appendix 17

Ecological Agriculture

One of the recommendations of UNEP for dealing with the environmental food crisis is to support farmers in developing diversified and resilient eco-agriculture systems (Nellemann et al. 2009). This is not exactly the same as agroecosystems that can include any type of agricultural ecosystem. Ecoagriculture is one of many approaches towards sustainable farming and highlighted in the main document (Sections 3.4 and 5.4) because of its landscape scale and its compatibility with modern high input agriculture.

A recent special issue of *Critical Reviews in Plant Sciences* (2011, Vol.30, Nr.1–2) provides a wealth of background on various ways agriculture could be made more sustainable. In this appendix other examples of non-conventional agriculture are given that provide critical ecosystem services (water supply and regulation, habitat for wild plants and animals, genetic diversity, pollination, pest control, climate regulation) in addition to adequate food and improved livelihood perspectives. These may be locally successful but not necessary suitable for up – and out-scaling. Moving from conventional agricultural and environmental management practices to non-conventional ones such as conservation agriculture represents a great challenge in terms of changing habits and minds (Table A14).

A17.1. Conservation farming

As an example of local initiatives in Africa, PELUM Association (www.pelumrd.org) is a network of 207 civil society organizations in Eastern, Central, and Southern Africa, working towards poverty eradication and food security through sustainable agriculture. It aims at building the capacity of farming and rural community groups to accumulate skills, stimulate farmer learning, and inspire experimentation and innovation in their quest to achieve food security. In this it builds on the potential of indigenous knowledge and indigenous farming and cropping patterns.

As an example, a study by PELUM on 15 small farms and two commercial farms before and after conversion towards conservation farming in Zambia showed that it can be an important first step to enable smallholder farmers to get out of poverty and towards sustainable farming:

- Conventional small-scale farming in Zambia was a failure with a nationwide average yield of 1.1 metric tons/ha and mostly economic deficits because of high costs related to inputs like tillage and fertilizer.
- 30% of all fields were abandoned at the time of harvest every year, because inputs (labor, plough, fertilizer) were not available at the right time.

Table A14. Comparison of conventional farming with conservation agriculture (Thiombiano and Malo 2009).

	Conventional farming	Conservation agriculture	Rationale
Tillage	Farmers plough and hoe to improve the soil structure and control weeds	Direct planting without prior inversion of the soil Planting on the rip line or making holes for planting with a hoe	Ploughing in the long term destroys the soil structure and contributes to declining fertility and organic matter levels.
Crop Residue	Farmers remove or burn residue or mix them into the soil with plough or hoe	Crop residue left on the field Planting of cover crops	Crop residues improve soil structure Cover crops protect soil from erosion and limit weed growth.
Mix and rotate crops	Monocultures or crop rotations in a tillage framework where the soil is inverted with a mouldboard plough or similar implements	Crop rotation or intercropping is a permanent feature of the cropping system	Helps to maintain soil fertility Breaks disease cycles

- In the 'worst' sub-village a pilot project with technical support from PELUM achieved a 70% increase of yield and profit after 6 days of training and individual coaching.
- A comparison between various plowing techniques and implements showed that:
 - Plowing led to lowest yields (average 2.4 tons/ha)
 - Ripping was better (about 4 tons/ha)
 - Hand hoed had the best results (5–8 tons/ha)
 - The highest yields of 8 tons/ha were only reached by farmers who used manure (chemical fertilizers showed lower yields).

Sustainability of farms was measured before and after conversion to conservation farming. Profit was the indicator for economic sustainability while for ecological sustainability carbon dioxide (CO₂) equivalents were used. In Zambia, conservation farming proved to be significantly more profitable (70% more profit after one to two years after conversion) than conventional farming. This applied to small and large farms applying zero-tillage and direct drilling into the stubble. While ecosystem services were not explicitly measured by PELUM, it appears, in any case, that the supporting service of soil formation was enhanced.

A17.2. Small-scale sustainable agriculture in Kenya

Since 1993, SACDEP (sustainable agriculture community development programme, see <http://sacdepkenya.org/>) trained over 40,000 farmers in 14 districts in Kenya. During those years, the strategies of sustainable agriculture have been refined. While conventional agriculture is only about increased production and incomes, SACDEP uses 4 principles to guide sustainable agriculture: economic feasibility, environmentally friendly, social justice and culturally acceptable. In order to make these principles practically operational, necessary pillars of sustainable agriculture were defined. The pillars are based on farmer working groups, low-cost external inputs, organic agriculture, ability of communities to mobilize finances, renewable energy, farmers' participation in conservation, processing and value adding, as well as in marketing decisions (including pricing) and in the formulation of policies for agricultural and rural development. SACDEP had successful projects in Kenya on organic products, draft animal power, low cost livestock such as dairy goats, wind energy, Direct Organic Markets and high value alternative and emerging crops. It would be interesting to measure the impact of the combined interventions on ecosystem services, particularly regulatory and supporting services, such as ecosystem resilience.

Appendix 18

Water Calculations: Footprints, Availability, Requirements, and Efficiency

A18.1 Calculation with PODIUM

Can water productivity be increased to such an extent that food security can be achieved without increasing (on a global scale) the withdrawal of water for agriculture – thereby contributing significantly to achieving environmental security as well? An analysis of such a global challenge, using the IWMI's Podium Model (<http://podium.iwmi.org/podium/>), yields the following results. In the scenario where the population grows as per the UN Medium population growth forecast to 7.8 billion in 2025, there is a moderate expansion of 3% of the harvested area, and 10% of irrigated area. But the withdrawals by irrigation are constrained to decrease by about 10%. The only way that enough food can be grown is then by increases in water productivity on rainfed and irrigated land. For the period between 2000 and 2025, we have estimated that an annual growth rate of about 1.8% or roughly a 60% percent increase for the period, on irrigated land, and 1.0%, or a 30% increase on rainfed land in water productivity would be required. This significant increase in water productivity is roughly double the increase expected in business as usual scenarios. If food and environmental security are to be achieved simultaneously, then this is the challenge.

18.2 Water footprints and virtual water trade

The concept of the water footprint is based on the notion that to provide just about any product requires a certain amount of water. Water footprints are then used as a measure of the total volume of freshwater used to produce a product, measured over the whole of the supply chain from primary production, processing, packaging, and transport, to consumption and disposal or recycling (Hoekstra 2009). It has been estimated that, on average, our food actually only contains 35% of the water

that it took to produce (Zygmunt 2007), though the variety of water use in fields, production processes, consumption, and disposal is so high between regions and value chains, that averages have to be used with extreme caution only. When compared to water productivity, water footprints tend to give higher values of water use, not only because they include the entire value chain, but also because water footprints cannot account for multiple uses of water. For instance, water for grain production will yield grain for food, but also stover for feed and it is hard to determine which part of the water is used for what¹⁴.

The methodology used for calculating water footprints can be quite elaborate and considers 'green', 'blue', and 'grey' components that are all specified geographically and temporally (Hoekstra et al. 2011). 'Green' refers here to the consumption of rainwater during the supply chain process, 'blue' refers to surface or groundwater, and 'grey' refers to the volume of water required to assimilate the load of pollutants to existing ambient water quality standards (Hoekstra 2009). This is somewhat different from how others refer to these sources of water¹⁵.

Water footprints can be used to calculate the water use of producing and processing different goods at the same location, or the same goods at different locations, which can consequently be used to make strategic comparisons and trade-offs. This could be applied to help producers make their value chain

14 Stover is not by definition a by-product as in many cases, farmers base their choice of crop or variety on the potential value of the entire plant for livestock, soil fertility, or other uses. Crop selection has consequences for water use and productivity.

15 Other authors label water in the soil as 'green' and call only surface water 'blue'. Aquifers (also called groundwater, where the soil is saturated with water) may be called 'green' or 'blue'. Similarly, 'grey' water (also written as 'greywater') is often used for lightly polluted water itself, to distinguish it from 'black' or fecally contaminated wastewater. In order to avoid confusion, this document refrains from the use of color labels as much as possible.

from field to consumer more water-efficient. It would be hard to use water footprints in making decisions on which crops should (or should not) be grown in certain areas as other environmental costs and impacts on livelihoods are not considered. It would be even harder to base policy decisions regarding domestic production or importation of water-intensive products on these calculations.

Theoretically, water could be saved globally by growing products that need a lot of water in highly productive areas, where farmers can get the best out of every drop, rather than cultivating these crops in areas where even more water is required to make these products. This idea prompted some authors to look at global trade in terms of moving (virtual) water (Allan 1998, 2003). Growing food in rainfed areas and moving it to areas that rely on irrigation would then reduce pressures on rivers and groundwater systems in water scarce areas (Chapagain and Hoekstra 2008). For example, from a water use perspective it could be wiser to grow rain-fed wheat in the relatively cool Ethiopian highlands rather than in arid Egypt, where transpiration of the plants is higher and water has to be transported a long way for irrigation, evaporating underway in reservoirs and canals. In practice, water use efficiency hardly plays a determining role in either crop selection or trade. The benefits of virtual water trade may not be significant (de Fraiture et al. 2004).

A18.3. Irrigation efficiency

In reviews on *irrigation efficiency*, Israelsen (1932) is commonly credited as the first to have defined the concept (Wolters 1992; Perry 2007; Jensen 2007), stringing together the various steps in the trajectory of the irrigation flow between the point of water diversion and the atmosphere (Snellen et al. 2010). The expression irrigation efficiency (E_i) is here defined as the water transpired by the crops of an irrigation farm or project to the water diverted from a river or other natural water source into the farm or project canal or canals' (Israelsen 1932). This (overall) efficiency (E_i) is the product of the component efficiencies (or output/input ratios) for these three steps of the water movement:

- *The conveyance and delivery efficiency (E_c)*, the ratio of the volume of water delivered to the farms and the volume diverted from the river;

- *The water application efficiency (E_a)*, the ratio of the volume of irrigation water stored in the soil and the volume delivered to the farm;
- *The consumptive-use efficiency (E_u)*, the ratio of the volume transpired by the crop and the volume of irrigation water stored in the soil.

In practice, overall irrigation efficiencies are surprisingly low, as was shown by the International Commission on Irrigation and Drainage (ICID) in two worldwide surveys on irrigation efficiency (Table A15). The order or magnitude (23–51%) hardly changed in the 20 years between the surveys.

Table A15. Overall irrigation efficiencies from ICID surveys (Bos and Nugteren 1974; Wolters 1992).

Group	Number of schemes	Average overall efficiency (%)	Source
Arid and semi-arid regions	33	37-42	Wolters 1992
Humid regions	30	23	Wolters 1992
Surface irrigation	38	25-29	Bos and Nugteren, 1974
Sprinkler irrigation	6	51	Bos and Nugteren 1974

When designing the canal system for an area of a given size, the designer wants to have an idea of irrigation efficiency in order to calculate either the canal capacities and the size of the flow that needs to be diverted at the source, or the area that can be irrigated with a given flow size. In both cases, improving irrigation efficiency saves costs. In the period 1950–2000, irrigation and drainage investments absorbed 30–33% of total lending for rural development (World Bank 2003). In order to achieve the rate of return required by the Bank, planners of new irrigation projects tried to save on investment costs. Planners achieved considerable cost savings by leaving out the end part of the delivery system; instead of bringing the water to the individual farm, a delivery point is shared by a group of farmers. This approach is at the expense of individual control over soil moisture conditions, considered a key attribute of irrigated agriculture (Newell 1916). The limitations of this approach were also expressed by irrigation experts within the World Bank (e.g. Plusquellec 2002). Other consequences of the investment criterion were preferences for arid and semi-arid regions, because the difference in agricultural production *with and without* the project is higher compared to areas

with more rainfall; and for perennial irrigation, because providing irrigation water throughout the year produces the highest return on investment. The consequence, however, is that large amounts of irrigation water are used in dry locations or seasons, where transpiration efficiency and therefore water productivity tends to be low (van 't Klooster et al. 2010).

Once planners had arrived at a rate of return that made the irrigation system eligible for funding, the permission for withdrawing the water was more or less automatically given, especially in the case of public irrigation systems. It is only in the last decades of the previous century, that water came to be considered as valuable, even when it did not fulfill some well-defined productive function such as for agriculture, industry, urban water supply, navigation, etc. By the time that people realized that irrigation used 70–80% of total water withdrawals (Bhatia and Falkenmark 1992), many countries had already allocated the major part of their water resources to irrigation on the basis of earlier studies that never considered the value of water and water productivity.

A18.4 Livestock water productivity (LWP) in the Nile Basin

Based on a basin-wide assessment of livestock water use and productivity, van Breugel et al (2010) concluded that the total water need for feed production in the basin was roughly 94 billion m³, which amounts to approximately 5% of the total annual rainfall (68 billion m³ or 3.6% of total annual rainfall when excluding water for residues). In most areas of the basin, LWP is less than 0.1 USD/m³, with only few areas showing a LWP of 0.5 USD/m³ and higher (Figure A10). Livestock water productivity is on average low, but large differences exist across the basin, both within and between livestock production systems. These differences suggest that there is scope for improvement of LWP, which could lead to significant reduction of water use at the basin level while maintaining current levels of production. In line with the large scale analysis, community and household level analyses indicated that in the Ethiopian highlands, LWP ranges from 0.09 to 0.69 USD/m³ (Haileselassie et al. 2009b; Descheemaeker et al. 2010a), whereas in animal

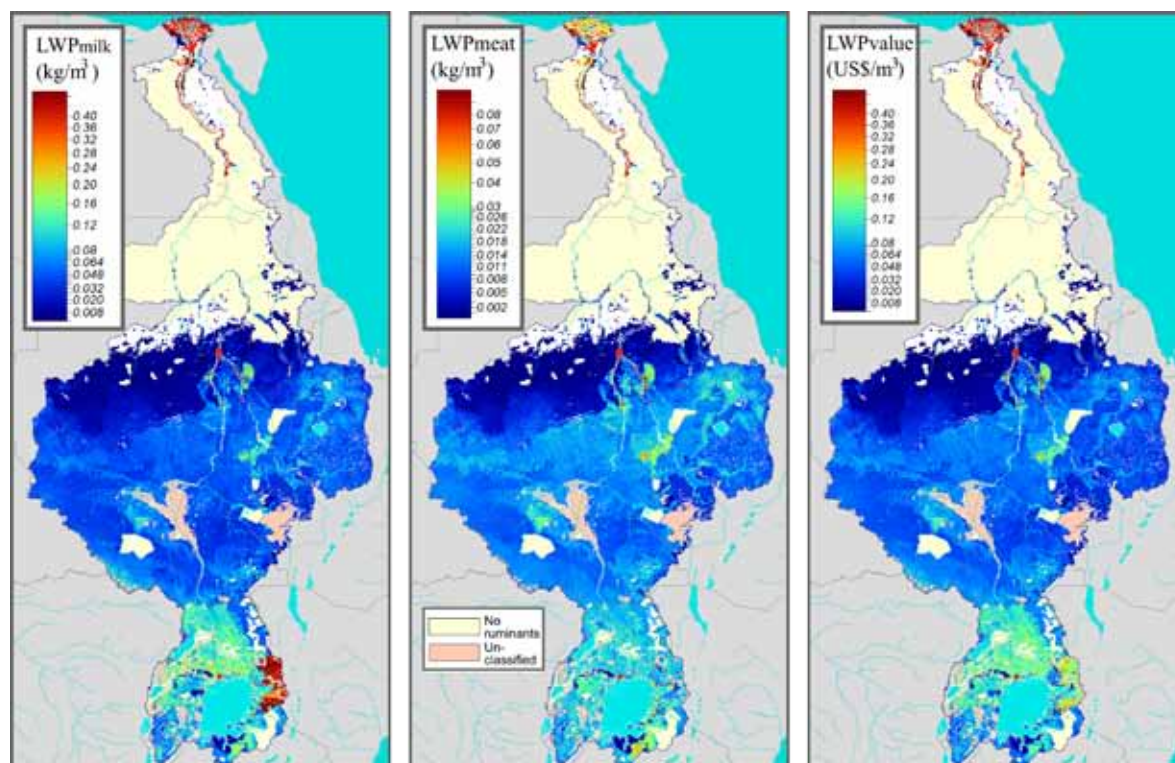


Figure A10. Livestock water productivity expressed as (a) the ratio of milk production and depleted water, (b) ratio of meat production and depleted water, and (c) the ratio of summed value of produced meat and milk and the water depleted to produce the required livestock feed. Water for residues was not included in the calculation of depleted water (van Breugel et al. 2010).

feeding trials LWP ranged from 0.27 to 0.64 USD/m³ (Gebreselassie et al. 2009).

When considering just milk water productivity, smallholder production systems in the Ethiopian highlands are characterized by very low milk water productivity ranging between 0.03 and 0.08 kg/m³ (van Breugel et al. 2010; Descheemaeker et al. 2010b). In other words, the virtual water content of milk (water footprint) in these systems ranges from 12.5 to 33 m³ of water per liter of milk, which is very high considering the global average of 0.77 m³ of water per liter of milk (Chapagain and Hoekstra 2003). However, the difference with the highly specialized and efficient industrial systems, where high milk water productivities are obtained, is that in smallholder systems, milk production is often viewed as a by-product of the livestock. Livestock are kept for multiple purposes and services (Thornton and Herrero 2001; Moll et al. 2007; Cecchi et al. 2010), of which manure production for soil fertility improvement and draft power for land cultivation are usually more important than milk and meat production. The LWP concept and framework developed by IWMI and ILRI (Peden et al. 2007; Descheemaeker et al. 2010a) allows taking into account these multiple livestock products and services in water productivity assessments.

A18.5 Increasing water use efficiency in aquaculture

Water productivity can be defined as 'the ratio of net benefits from crop, forestry, fishery, livestock and mixed agricultural systems to the amount of water required to produce those benefits' (Molden et al. 2007b). Benefits from aquaculture include the production of food, livelihood improvement, nutrition and health (Dugan et al. 2007). Water requirements for aquaculture are both qualitative and quantitative in nature but the definition of the water quantities 'used' presents difficulties (Nguyen-Khoa et al. 2008). Consumptive use of water for the accumulation of aquatic resources biomass is negligible, but water use efficiency varies markedly between different aquaculture production systems (Table A16). Water may be consumed indirectly in the production of aquaculture seed or via percolation, seepage and evaporation from ponds and reservoirs.

There are strong pressures, some resulting from global drivers, to increase water productivity in aquaculture (sub-section 4.3.4. and Table A17). Water productivity of aquaculture can be increased through improving system design, good management, good water quality, good brood stock or using a combination of non-competing species that fill different niches

Table A16. Water use efficiency (in m³ water/kg fresh weight) in aquaculture systems (adapted from Bunting, in press; * based on Verdegem et al. 2006; ** from Bunting 2007).

Aquaculture system	Water use efficiency	Water management characteristics
Traditional extensive fishpond culture	45*	Rainwater and drainage water are routinely channeled into fishponds to compensate for seepage and evaporation losses; excessive water exchange is detrimental as it is desirable to retain nutrients within the pond.
Flow-through ponds	30.1*	Water exchange of 20% of the pond volume per day removes waste and replenishes oxygen levels, production of 30 tons/ha/year is attainable, but seepage and evaporation contribute to water loss in the system.
Semi-intensive fishponds	11.5*	Producing two crops annually with complete drainage to facilitate harvest, fishponds fed with formulated pellet feed can yield 6 tons/ha/year; one-fifth of water consumption is associated with feed inputs.
Wastewater-fed aquaculture	11.4**	Wastewater is routinely fed into fishponds in the East Kolkata Wetlands to make up the water to a desirable level; estimates suggest 550,000 m ³ /day of wastewater is used to produce 18,000 tons/year of fish in 3,900 ha of ponds.
Intensively managed ponds	2.7*	Lined ponds are used to produce 100 tons/ha/year while intensive mixing results in evaporation of 2000 mm/year.
Super-intensive recirculation systems	0.5-1.4*	Process water is re-circulated with pumps and treated with mechanical filters, bio-filters and disinfection technology; stocked animals are entirely dependent on high-protein formulated feed inputs.

Table A17. Management domains and associated pressures for increased water productivity in aquaculture (adapted from Bunting, in press).

Domain	Pressures related to water management from global changes
Production efficiency	<p>Production-enhancing inputs such as feed and fertilizer constitute major costs so efficient conversion to marketable products is paramount</p> <p>Nutrients not recovered from the system at harvest constitute potential pollutants</p> <p>Pumping and conditioning water for culture is costly and time consuming so transfer and treatment of excess water must be reduced as much as possible</p>
Management imperatives	<p>Aim at generating higher financial returns from inputs</p> <p>Alternative low-input production strategies can limit costs and associated financial risks</p> <p>Product and livelihoods diversification can generate more regular cash-flows and higher revenue</p>
Risk management	<p>Water abstracted for culture processes may be polluted and affect stock health and production</p> <p>Disease and predator ingress poses a serious threat to aquaculture operations</p> <p>On-farm water movement and wastewater discharge may increase the likelihood of stock escaping, resulting in revenue loss and negative environmental impacts</p>
Conflict avoidance	<p>Abstraction and discharge of water may affect ecological processes and compromise ecosystem services supporting other livelihoods</p> <p>Appropriation of water for aquaculture may lead to competition with other resource users, including aquaculture operators</p> <p>Reduced competition</p> <p>Avoidance of conflict with other resource users</p>
Legislation and controls	<p>Comprehensive assessments concerning values and ecosystem services associated with water resources are likely to make it harder for producers to appropriate desired supply levels and lead to increases in associated costs (licenses, rents and taxes)</p> <p>Stricter controls can be foreseen to protect the ecological status of receiving water bodies, secure water resources for other users and maintain and enhance stocks and flows of ecosystem services</p>
Consumer demand and public perception	<p>Adverse coverage of conflict surrounding groundwater depletion and conflict with local communities over water resources could negatively impact on consumer demand</p> <p>Negative perceptions of aquaculture could give rise to vociferous opposition calling for unreasonable controls or the cessation of aquaculture operations which could threaten livelihoods and reduce the production of food or other aquatic products</p>

in the aquatic ecosystem. Practices and policies including construction, systems design and operation, optimizing production efficiency, water management practices, horizontally integrated aquaculture systems, water rates and pollution taxes and policy and planning have been identified as potential areas where water use efficiency in aquaculture could be improved (Table A18). Integration of aquaculture with

other agricultural and water uses has potential for enhancing the productivity of appropriated freshwater resources as it can be considered complementary to such water uses (Appendix 16). Reservoir storage water, for example, is usually committed to uses other than fish production, but fish can be stocked in these for complementary production, while making non-depletive use of water.

Table A18. Practices and policies for optimizing water use efficiency and increasing sustainability in aquaecosystems (adapted from Bunting, in press).

Practice and policy area	Measures to optimize water use efficiency
Construction	<p>Optimal pond design and surface area to volume ratios can help minimize evaporative losses</p> <p>Employing appropriate pond bottom sealing techniques and liners on free-draining soils can minimize seepage losses</p> <p>Good maintenance of water control structures can reduce leakage</p> <p>Inclusion of simple treatment systems such as sedimentation ponds, constructed wetlands and mechanical filter screens can significantly improve farm discharge water quality</p>
Systems design and operation	<p>Employing aeration and oxygenation can allow higher stocking densities to be maintained and reduce water use per unit biomass production</p> <p>Incorporation of mechanical filters, bio-filters and disinfection technology can permit the recirculation of process water reducing water exchange and use</p> <p>Culturing species with less exacting environmental requirements could help reduce water demand</p>
Optimizing production efficiency	<p>Careful stock or broodstock selection and breeding program management can enhance production efficiency and contribute to optimal water use</p> <p>Optimal feeding strategies, appropriate grading and general good husbandry and animal welfare can enhance food conversion rates, thus reducing waste loadings and water exchange rates required to maintain water quality</p>
Water management practices	<p>Draining fishponds can be avoided where, for example, tea seed cake has been applied to partially anaesthetize tilapia prior to netting</p> <p>Sequential partial draining of fishponds, where 25 cm of water is left in ponds and fish are harvested by netting reduces the discharge of potential pollutants</p> <p>Adopting drop-fill pond water management strategies, where the water level is permitted to fall to a drop point before being made up to a fill level, can potentially reduce groundwater use and effluent release</p>
Horizontally integrated aquaculture systems	<p>Incorporating primary producers to convert waste nutrients discharged from fed culture organisms can improve water quality and make nutrients available to animals in other integrated culture units</p> <p>Integration of different species within a culture system can increase biomass production per unit water appropriated</p>
Water rates and pollution taxes	<p>Statutory limits to the amount of water that may be abstracted or charges per unit volume would help maximize water use efficiency</p> <p>Statutory discharge standards and taxes on the amount of waste discharged from aquaculture would promote more careful husbandry and better considered systems design and operation</p>
Policy and planning	<p>Remove subsidies for fuel that make it easier for producers to abstract and discharge larger water volumes</p> <p>Facilitate joint assessment of water resources management schemes by all stakeholders and include consideration of full range of ecosystem services in decision-making</p> <p>Consider inclusion of water footprints in product labeling and certification schemes to permit buyers and consumers to make educated choices favoring more water efficient products and production strategies</p> <p>Enable good market conditions</p>

Appendix 19

Agroecosystems, Water, and Health

Based on the proposal for CGIAR Research Program 4: Agriculture for Improved Nutrition and Health.

In many parts of the world, diseases associated with agriculture have important health impacts, particularly on poor people. The health of farmers, consumers, and households in agricultural areas can be at risk from a variety of threats related to agricultural water use (Kay 1999; Parent et al. 2002). Health problems associated with water management in agriculture include water-related diseases such as malaria, zoonoses (diseases transmissible between animals and people), misuse of agricultural chemicals and antibiotics, but also food safety issues such as fungal toxins (mycotoxins), plant toxins, and biologically contaminated food. Many of these have a strong relation with the way agricultural production systems are managed and could be positively influenced by an ecological approach.

Parallel to the demand for more sustainable agriculture, the health sector has developed interdisciplinary approaches such as 'One Health', striving to attain optimal health for people, animals, and our environment, and 'Ecohealth', a participatory methodology to understanding and promoting health and wellbeing in the context of social and ecological interactions. These two approaches have much in common and are increasingly aligned; both emphasize multi-disciplinarity and the importance of agriculture and ecosystem-based interventions (Waltner-Toews 2009), which makes them highly suitable for water-related diseases, complementary to the efforts by the health sector. Agricultural practices creating health risks, such as those related to water management, obviously require farm-level interventions, and food-borne diseases require management along the field-to-fork risk pathway. Most zoonoses need veterinary and agroecological interventions in addition to medical ones, as they cannot be controlled while disease remains in the animal reservoir.

Particularly in peri-urban areas, irrigation water may be contaminated with domestic or industrial wastewater, introducing pathogens or chemicals that may affect farmers and enter the food chain, creating a risk of disease where crops are eaten raw (Drechsel et al. 2010). At the same time, the use of polluted irrigation water supports the livelihoods of 20 to 50 million farmers and feeds up to one billion consumers. Water pollutants can also impair the health of livestock and of the consumers of animal products, within a complex system that includes links between waterborne and food-borne.

In rural areas, irrigation and water storage systems provide breeding grounds for, and exposure to, vectors of water-related diseases. These include parasitic infections such as malaria (killing 1.1 million people annually), schistosomiasis, and emerging diseases such as cryptosporidiosis, giardiasis, and buruli ulcer (Erlanger et al. 2005; Keiser et al. 2005a; Steinmann et al. 2006; WHO 2007). Many of these diseases are fostered by poorly designed or managed irrigation or water storage systems or harmful agricultural practices (Boelee and Madsen 2006; Diuk-Wasser et al. 2007). Further risks can derive from toxic algal blooms, associated with agrochemical water pollution (Chorus and Bartram 1999).

Improved and innovative agricultural and water management practices can help reduce crop contamination, farmer exposure, vector breeding, and vector resistance. The reduction of health risks from using contaminated water, or being exposed to water-associated disease vectors, has to be carefully balanced with the need to support the livelihoods of farmers. Further along the value chain, consumers can be protected while costs for the public health sector will decrease. The role of agroecosystems is particularly important in the case of malaria, that can no longer be handled using existing means only: mosquitoes have become resistant to agricul-

tural insecticides (Diabate et al. 2002), while the parasite itself is increasingly resistant to anti-malarial drugs. Here the health sector has actively sought collaboration with professionals in the areas of water management and plant disease control (Townson et al. 2005). There is vast experience of relevant agroecological interventions that can help mitigate negative health impacts of water management (Keiser et al. 2005c; McCartney et al. 2007).

Similarly, more holistic management of agroecosystems for a wider range of ecosystem services has the potential to enhance pest and disease regulation. In turn this could reduce the need for agrochemicals and limit exposure of farmers to harmful substances, currently an important occupational health hazard in agriculture. People in developing countries bear more than 80 percent of the global burden of occupational disease and

injury, and the agricultural sector is one of the most hazardous (ILO 2000). It is estimated that 2 to 5 million people suffer acute poisonings related to pesticides annually, 40,000 of whom die every year (Cole 2006). Excessive use of pesticides can also lead to resistance in medically important insects, such as malaria mosquitoes (Diabate et al. 2002). Pesticides are used inappropriately due to capacity deficits, inadequate regulation, and perverse incentives, as well as lack of alternatives. Other agricultural inputs, such as nitrates, disinfectants, acaricides, and veterinary drugs, can also have negative health impacts if used incorrectly. With increased biodiversity in agroecosystems, especially when these are managed on a landscape scale, connected by corridors that provide habitat for natural predators, the need for agrochemicals is reduced together with their health risks.

Appendix 20 Role of Technology

A variety of new technologies shows potential for great improvements in food security, water efficiency, and ecosystem sustainability. This includes genetically modified organisms (GMOs) and selective breeding, but also irrigation, water harvesting and soil management techniques. Plant and animal breeding has increased the productivity of many agricultural and livestock species, as well as resistance to pests.

Technology development in other sectors may also be relevant. Renewable energy developments show some promise for reducing both carbon and water footprints of energy production, but may also increase reliance on hydropower with varying consequences. The increasing use of renewable energy has significant water impacts—not only from hydropower dams, but also through the amount of water needed to produce energy through non-renewable sources (UNEP 2007). An increasing demand for hydropower will likely result in the construction of more large dams, mainly in the developing world. In closed basins like the Western US or in much of Europe, hydropower potential has been exhausted (WWA 2009). New dams change the hydrologic cycle where they are implemented, and often have negative environmental effects. On the other hand, renewable technologies such as biogas and solar power may reduce the use of water for power generation. Coal uses about 2 cubic meters of water per megawatt hour of electricity

produced, nuclear power 2.5 cubic meters, and petroleum 4 cubic meters (WWA 2009). Extracting oil also uses lots of water—up to 45 cubic meters per megawatt hour from tar sands, one of the largest ‘new’ sources of oil to be discovered (WWA 2009). The increased applications for biofuel have led to high demand, with all kinds of impacts on water use, food security and agroecosystems (sub-section 2.2.1; Berndes 2002; FAO 2008b, 2009b; Bindraban et al. 2009a, as well as the special 2008 issue 10 S1 of *Water Policy* in 2008).

The primary setback for technology development is its dissemination, and in fact, much of the technology to drastically increase food security, enhance sustainability and improve water efficiency already exists but has not been implemented widely for a variety of reasons. Technological dissemination is one of the largest challenges faced by those seeking to implement new technology. The majority of technological innovations originate in developed countries in response to their needs. This means that much of the new technology is too expensive, utilizes resources that are not available in other countries, or is designed to resolve specific problems that are not as relevant in other places (WWA 2009). In addition, many new technologies aim to make water more accessible or cheaper and have negative results on environmental factors or unintended water consequences (CA 2007).

Appendix 21

Payments for Ecosystem Services (PES)

A21.1 Water services in Sukhomajri, India

Example based on FAO (2007b).

The small village of Sukhomajri in India provides an early and complex example of watershed development that has helped inspire modern watershed development programs. In the 1970s, high rates of sedimentation in Lake Sukhna in the northern Indian state of Haryana created problems for the drinking water supply of the nearby town of Chandigarh (Kerr 2002). Recreational benefits were threatened also. The source of the problem was traced to a small upstream village named Sukhomajri, where villagers were cultivating steep lands and allowing animals to graze freely throughout the watershed. Around 80–90 percent of the sedimentation in Lake Sukhna was found to originate from Sukhomajri (Sengupta et al. 2003). The Sukhomajri farmers' agricultural practices were not only felt downstream; runoff water on one side of the watershed also flooded and destroyed agricultural lands in the village itself.

A central government agency, the Central Soil and Water Conservation Research and Training Institute (CSWCRTI) revegetated the watersheds and installed conservation structures such as check dams and gully plugs to stop the flow of silt. Villagers were asked to refrain from allowing grazing animals into the watersheds. Benefits to the villagers were twofold: not only reduced damage to agricultural lands, but also access to irrigation water stored by the check dams. Although no direct payments were involved, the villagers were thus indirectly compensated for providing the environmental service. At the time of the project implementation, the notion of markets for environmental services was little known, but in effect the project functioned as an environmental services payment scheme.

A drawback was that only a minority of landowners in the village benefited from the scheme; other

villagers, particularly the landless, stood to lose from reduced access to grazing lands. The problem was solved by distributing rights to the water to all villagers and allowing them to trade among themselves – a system that was later abandoned in favor of user fees for water. The project resulted in a 95 percent decrease in siltation into Lake Sukhna, saving the town of Chandigarh about US\$ 200,000 annually (Kerr 2002).

A21.2 China's Grain for Green program

Example based on FAO (2007b).

Pushed into action by a series of devastating floods in 1998, the Government of China launched the Grain for Green program in 1999. One of the largest conservation set-aside programs in the world, its main objective is to increase forest cover on sloped cropland in the upper reaches of the Yangtze and Yellow River Basins to prevent soil erosion. When possible in their community, households set aside all or parts of certain types of land and plant seedlings to grow trees. In return, the government compensated the participants with grain, cash payments and free seedlings. By the end of 2002, officials had expanded the program to some 1.5 million farmers in more than 2000 counties in 25 provinces and municipalities in China (Xu et al. 2004). If the program meets its original goals, by 2010 nearly 1.5 million hectares of cropland will have been set aside, affecting the land of more than 50 million households.

A21.3 Forest reserve water fund in Guatemala

Example based on Spergel and Taieb (2008) and Fundación Defensores de la Naturaleza (2010).

The Sierra de las Minas Biosphere is Guatemala's most important cloud forest reserve. It protects a mountainous region of tropical and coniferous forests home to endangered species such as the quetzal

and the harpy eagle. A total of 63 watercourses originate on this reserve, including the Motagua and the Polochic Rivers, which empty into the Gulf of Honduras and Lake Izabal respectively. These rivers are the main source of water for local irrigation, small industries and household use for communities. Local water users noticed a fall in water quality and quantity, particularly during the dry season.

Conservation International (CI) and Fundación Defensores de la Naturaleza (in collaboration with WWF and TNC) collaborated to protect the biological integrity of the reserve and its hydrological functions, particularly in terms of water delivery. This included the establishment of a water fund for the Motagua-Polochic watershed and the creation of watershed councils that strengthen environmental governance. The water fund receives user fees from individual water consumers and two bottled water companies who benefit from the provisioning ecosystem services of the watershed and then channels these fee revenues to pay the small farmers and landowners who supply these watershed services for conserving the forests that help to maintain water flow and water quality (regulatory and cultural services). The compensation to farmers is in-kind, consisting of training and financial assistance to adopt best management practices. In addition, the Water Fund finances development projects for pollution reduction and watershed conservation. So far six projects have been funded, including watershed management activities such as best management practices in coffee plantations, cleaning campaigns in different communities, construction of ecologic stoves, and prevention of forest fires, thus eventually also enhancing supporting services.

A21.4 Brazil's Water Producer Program

Example based on TNC (2008)

The Parana River is the second longest river in South America running through Brazil, Paraguay and Argentina over a course of 2,570 km. The Parana River provides multiple ecosystem services to the populations living within its watershed, including water for irrigation and the provision of drinking water to South America's largest city, São Paulo. However, the water quality of the Parana River has declined over time due to the intensive deforestation of the Atlantic Forest at

its headwaters. Without forest cover around the river's edge (riparian zone) rainwater washes away soil leading to a build-up of sediment that alters the water quality and may invade irrigation systems.

In an effort to improve the water quality of the Parana River while protecting the biodiversity of the Atlantic Forest, The Nature Conservancy developed the Water Producer Programme implemented by Brazil's National Water Agency (ANA), the Agriculture and Environment Secretaries of São Paulo, the Piracicaba-Capivari-Jundiaí (PCJ) watershed committee and the municipal government of Extrema in the state of Minas Gerais. The program proposes using a portion of water fees collected from major water users such as water supply companies and major industries to plant trees along riparian zones in the river's headwaters. These activities are executed by farmers and ranchers who receive a payment to reforest and maintain key sections of their land that are critical to the health of the Parana River, thus contributing to the regulatory services of the river. Landowners also receive technical assistance on reforestation, soil conservation and erosion prevention from the program's partners.

A cooperation partnership with the PCJ Watershed Committee, the municipal government of Extrema, governmental organizations and local NGOs was formalized through memoranda of understanding (MOUs) in 2006. The definition of the payment structure, as well as the identification and engagement of landowners was also completed that year. The first trees were planted in March of 2007 in three micro-watersheds located within the PCJ watershed: the Posses, Moinho and Cancã. During the inception phase of the program, gaining the PCJ Watershed Committee's approval was a challenge. Several meetings and discussions took place at this stage. To obtain the committee's support it was key to show that the program could help enforcing the Brazilian Forestry Law to support regulatory ecosystem services. With the implementation of the program, local landowners would stop converting areas considered as legal reserves by the Forest Code to agriculture and pastures. When the partnerships were established, defining landowner's payments was also a challenge. The best amount was considered to be one that covers the opportunity cost for farmers and ranchers, thus compensating them for the loss of income from agriculture (provisioning services).

Appendix 22

Integrated Water Resources Management

A22.1 IWRM Process Cycle

In Figure A11 the IWRM process is illustrated as the “Integrated Water Resources Management Cycle”. The cycle starts with the planning processes and continues into implementation of the frameworks and action plans and monitoring of progress.

The various steps in the Integrated Water Resources Management Cycle can be characterized briefly as follows (GWP 2004):

- *Establish status and overall goals.* The starting point of the IWRM process is a critical review of water resources issues in the national context. The expected progress is then translated into a management framework to help address the issues, get agreements and work towards achievement of the overall goals.
- *Build commitment to the reform process.* Political will is a prerequisite, and building or consolidating a multi-stakeholder dialogue comes high on the list of priority actions. The dialogue need to be based on knowledge about the subject matter. This knowledge can be established by raising awareness and arranging for the participation of the broader population.
- *Analyze gaps.* Given the policy and legislation, the institutional situation, the capabilities and the overall goals, gaps in the IWRM framework can now be analyzed in the light of the management functions, prioritizing urgent issues.
- *Prepare strategy and action plan.* The strategy and action plan will map the road towards completion of the framework for water resources management and development and related

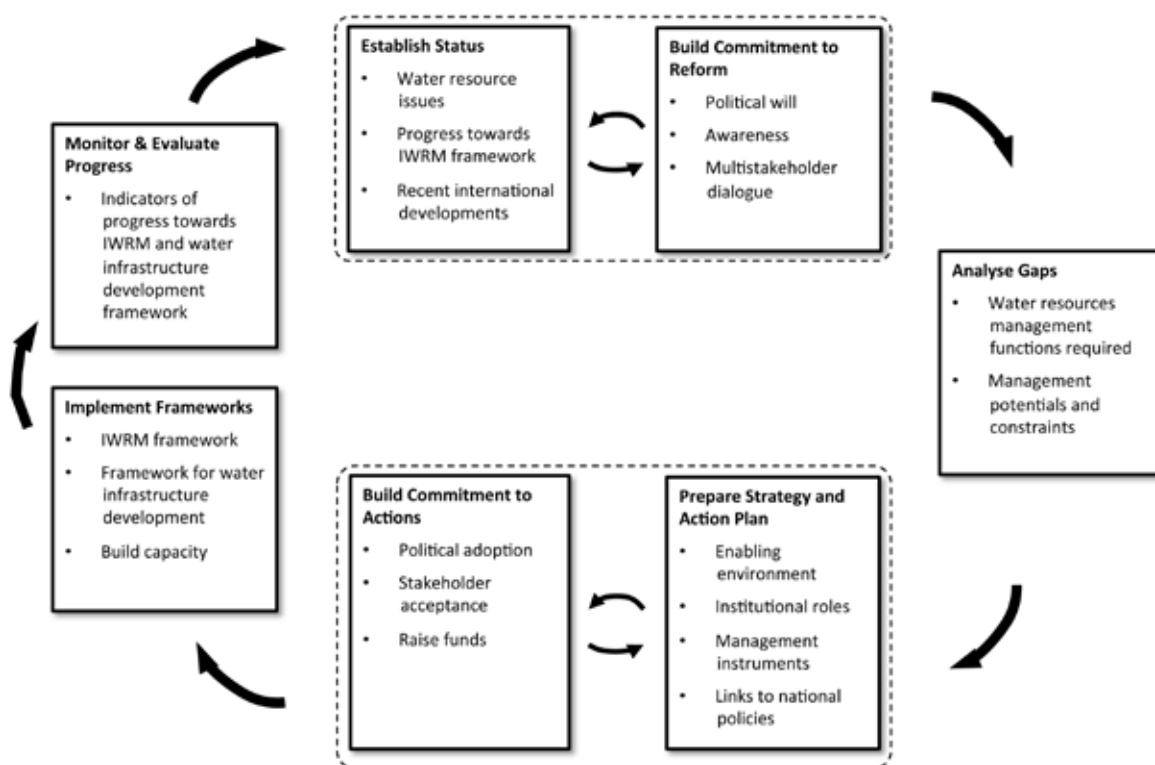


Figure A11. The Integrated Water Resources Management Cycle (after GWP 2004).

infrastructural measures. One of the outputs is a portfolio of actions, which will be set in the perspective of other national and international planning processes.

- *Build commitment to actions.* Adoption of the action plan at highest political levels is the key to any progress and full stakeholder acceptance is essential for implementation. Committing finance is another prerequisite for taking planned actions to implementation on the ground.
- *Implement frameworks.* Taking plans into reality poses huge challenges. The enabling environment, the institutional roles and the management instruments have to be implemented. Changes have to be made in present structures and building of capacity and capability, also taking into account infrastructure development, needs to take place. This is a crucial phase that may take long to be fully effective.
- *Monitor and evaluate progress.* Progress monitoring and evaluation of the process inputs and outcomes serve to adjust the course of action and motivate those driving the processes. Choosing proper descriptive indicators is essential to the value of the monitoring.

A22.2 Regulatory instruments in IWRM

In water demand management under IWRM, various policies and measures can be employed, usually grouped in 3 classes:

- *Economic and market-based instruments:* These are signals in the form of incentives and disincentives to motivate desired decision-making. The most common form of economic instrument is unit pricing, which in practice can vary quite substantially both between and within countries, often dependent on the type of the resultant goods and services provided to different sectors. For example, some domestic consumers may receive a form of subsidy, whereas in-

dustrial users may effectively pay for the right to dispose of their pollution in a water body within certain agreed environmental limits. In recent years there has been a growing interest in tradable rights to both use and pollute water, with permit holders being financially compensated for selling or loaning their claims.

- *Regulatory instruments:* This is where government bodies establish a legal framework that is used to guide users and service providers in their duties and obligations, and possibly punish them for non-compliance. The framework consists of laws, rules, and standards that include considerations such as water quality and supply standards, spatial and land use planning, the quantity and timing of water abstractions, and the quality, quantity and timing of the discharge of waste. Hence they include “hard” and “soft” command and control applications, with or without external enforcement, such as rules regarding water quality and abstraction. Establishing a legal framework can be difficult in practice, as determining non-compliance and identifying offenders can be challenging. Experience of enforcing laws and regulations in the water sector in general has not always been very successful as this is not an easy task and governments must be careful in making laws. Stakeholders should be involved in the law making process to ensure that the laws produced are acceptable to all.
- *Awareness and capacity building instruments:* Government or professional bodies, as well as industry, community and interest groups may work together or independently in promoting these instruments. They serve to encourage self-enforcement and social regulation in areas such as water conservation, best practices, and responsible behavior in an effort to promote cultural change, typically through voluntary compliance. Examples of these instruments include guidelines, rules of conduct and public information campaigns aimed at informing the target audience of the possible consequences of their actions or inactions.

A22.3 National basin dialogue in Jordan

Example based on IUCN 2007b, 2008a, 2008b.

The Al Azraq basin is located in Northeastern Jordan and it is one of the most important recharging groundwater basins in the country. The basin consists of three aquifer systems: an upper shallow fresh water basalt aquifer, a middle limestone brackish water aquifer, and a deep sandstone aquifer. Over-extraction of groundwater from the shallow aquifer for agriculture and cities has resulted in a significant reduction of the groundwater reserves and increased salinization of groundwater and soil. This threatened the Azraq oasis and associated wetland. This oasis and associated wetland, surrounded by desert, is a recognized Ramsar site; with high biodiversity and an important habitat for migratory birds.

The World Conservation Union (IUCN) and strategic partners in Jordan have initiated the Al Azraq Basin National Dialogue Initiative to explore solutions and scenarios for the sustainability of Al Azraq Basin, the sustainable future use of its groundwater as well as restoration of a substantial part of the oasis and wetland. This would entail balancing water uses,

maintaining ecosystem services and addressing long term access and rights to water by underprivileged groups in the targeted communities. The inception phase of the project started in 2007. Since then, a large group of government and civil organizations and a group of elected local community representatives have actively participated in the Al Azraq Basin National Dialogue, with technical and logistic support by IUCN and funding from InWEnt. The Ministry of Environment provides the overall political and institutional support as umbrella for the initiative. Other participants include the Al Azraq District Administration, Ministry of Water and Irrigation, Ministry of Agriculture, the Royal Society for the Conservation of Nature, Azraq Farmers Water Management Association, the Arab Women Organization (AWO), as well as a group of local elite residents and resource exploiters representing local stakeholder communities. The stakeholders have decided to formulate a feasible and practical national vision backed up by an implementation strategy. Formal establishment of a National Forum for Azraq basin and local water users associations is underway. During the process, the stakeholders document their experiences and lessons learned for application in the dialogue to achieve its development and sustainability objectives.

Appendix 23

Catering for Climate Change

A23.1 River forest action plan in the United States

Example based on Conservation Fund (2008) and TNC (no date).

The Garcia River is one of the most important rivers of the Californian Redwood Region. For decades, logging has been the predominant land use in the watershed. Increased uncertainty about the timber industry in the California North Coast changed this situation and forced some timber industrial and non-industrial forestland owners to sell their properties. Fragmentation of the Garcia River's forest then started as new rural residential subdivisions and vineyards were established. The preservation of this forestland through public acquisition was not viable, thus, a new protection approach was needed, in particular one that included climate change issues.

In February 2004, The Nature Conservancy and The Conservation Fund (TCF) purchased a 9,623 hectare property along the upper Garcia River Basin in the redwood forest of Mendocino County, California. The goal of this purchase was to protect significant natural, ecological, and aesthetic values, and to develop and implement a model of sustainable forestry practices that would be in accordance with climate change mitigation efforts. Since 2004 various activities are being developed in the Garcia River Forest: restoration and enhancement, watershed management, and silviculture. Additional management activities included public use, monitoring and research, and education and demonstration. These activities are fully described in the Integrated Management Plan for the Garcia River Forest, which was completed in August 2006.

After implementation, results included the following:

- *Silviculture*: in early 2007, the first light-touch logging took place on Garcia River. This meth-

od of timber harvesting selects inferior trees for removal, thus promoting the growth of stronger trees. It is a process that maximizes carbon storage and accelerates the recovery of the forest ecosystem. As a result of light-touch logging, the local mill received 826 cubic meters of timber.

- *Carbon credit certification*: in February 2008, the California Climate Action Registry – the most prescriptive set of standards for forest management carbon projects in the world – certified the Garcia River Forest as a source of carbon credits. It is expected that over its 100 year lifetime, the Garcia River Forest project will absorb and store 4.2 million metric tons of carbon dioxide by ensuring high forest growth rates and the development of larger and denser stands of redwood and Douglas fir.
- *Challenges*: while the first results are encouraging, future challenges include low current timber volumes, a predominance of hardwoods in many stands, the burden of maintaining and improving an extensive road system, as well as the uncertain economic, regulatory, and political environment affecting the timber industry as a whole.

A23.2 Monitoring glaciers in Nepal

Example based on WWF (2010b).

The Nepal Himalayas have 3,252 glaciers, covering 5,323 km² with an estimated ice reserved of 481 km³. Climate change is already affecting the Himalayas glaciers in Nepal with noticeable glacial retreat and changes in freshwater flows. As a result, glacial lakes have been formed, with negative consequences for biodiversity, people, and their livelihoods. In 1985 a glacial lake outburst flood from the Dig Tsho (Langmoche) glacial lake

destroyed 14 bridges and caused about USD 1.5 million of damage to the nearby-completed Namche small hydropower plant. Forests, farms, and people downstream were also affected. While these floods may increase in the coming years, there will be a tipping point as glacial runoff begins a decreasing trend. This situation will also have negative and not well-understood consequences for Nepal and the Himalayan Region.

In order to manage the current and anticipated impacts of climate change in the Nepal Himalayas, the WWF-Nepal Program Office started a project to better understand these impacts and begin the process of planning an appropriate community driven management response. Implementation follows a four-module approach:

- *The first module* is focused on developing a model to predict future glaciers behavior under different climatic scenarios. Climatic and hydrological secondary data are collected for five glaciers in Nepal and India, selected after consultations with experts. These data will be combined and validated through primary data collection by the project team on the representative glaciers.
- *The second module* involves the development of a freshwater vulnerability assessment for the selected glaciers. This assessment is conducted in two steps: examination of the effects of glacier retreat on the downstream freshwater regime, and assessment of the implications of these changes for the people, economic sectors, and biodiversity in the downstream areas (for only three glaciers).
- *In the third module*, Community Driven Management Responses (CDMRs) will be developed, based on the results of the model and the freshwater vulnerability assessment. These CDMRs focus on particular community and economic sectors or ecosystems. The involvement of relevant local stakeholders, including policy-makers, will guarantee that the CDMRs are integrated into existing planning frameworks and institutions.
- *The fourth module* involves the dissemination of findings among stakeholders at local, regional

and national levels, this includes, local institutions such as village committees, grass-root civil society organizations, scientific and research organizations, media (at local, regional, national and, where appropriate, international levels), the international community and donors.

A23.3 Freshwater conservation program for Brazil

Example based on WWF (2009b)

To support Brazil's response to the impacts of climate change on inland water ecosystems, WWF- Brazil has developed a freshwater conservation program focused on climate change, supported by Brazilian scientific institutions, governmental organizations at the federal and provincial levels and some representatives of the private sector. The aim is to build river basins' resilience to climate change and tackle the root causes of climate change through basin vulnerability assessments, sustainable river flow assessments, a project to strengthen Brazil's basin governance, planning and policy, and projects to influence the activities on the hydropower and forestry sectors. An information campaign directed to the general public is also part of the program. By combining water management with reforestation, a wide range of ecosystem services can be provided: first and foremost supporting services, notably climate change mitigation, but also provisioning services such as wood, cultural services such as tourism, and regulatory services such as water regulation.

The basin vulnerability assessment evaluates the impacts of climate change, including weather extreme events, as related to water availability within priority river basins and big cities. It also provides decision makers and authorities with information on risks and alternatives. Currently, this assessment is being conducted in the Alto Paraguay Basin, where baseline data are collated and collected in the field in partnership with the Centro de Pesquisas do Pantanal (CPP). Partnership agreements with federal agencies (Environment Ministry's Water Secretariat, National Water Agency) and other strategic water users (hydropower companies) are under negotiation. While mechanisms to assure the functioning of the aquatic ecosystems on priority

basins would be the main result of this project, in addition it contributes to capacity building as knowledge and expertise on sustainable river flows will be acquired by local researchers. The results of the vulnerability and river flow assessments will support further activities in basin governance, planning and policy, such as adaptation of public policies to freshwater and its vulnerability to climate change, creation of an institutional basis for water management in the Amazon, and development and implementation of financing mechanisms that harmonize good productive practices with conservation of natural resources (e.g. payment for environmental services). In Brazil, the main source of energy is hydropower. The WWF-Brazil freshwater program expects to influence the National Energy Plan and increase financial resources and goals for energy efficiency electric sector to incorporate the World Dams Council's

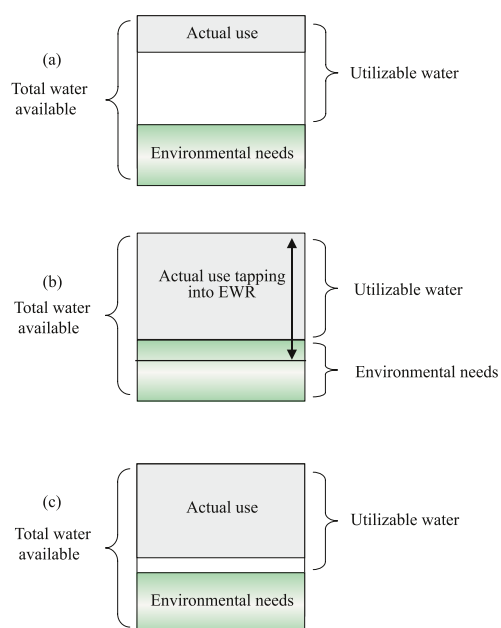
recommendations for building dams and Ministries of Environment, Energy, National Water Resources Council and National Water Agency to enforce the use of river basin protection when constructing new hydroelectric plants.

Mechanisms will be developed to reduce deforestation and GHG emissions in the Amazon by encouraging sustainable business with forest resources. Work will also be done with financial institutions to encourage the adoption of sustainable credit lines and the Environmental Licensing System for Rural Properties as a pre-condition for loans. To raise awareness on how climate change will affect water resources and Brazilians' lives, a communication campaign is currently under development, this is intended to inform 11 million Brazilians about the threats of climate change and the related impacts on water by 2011.

Appendix 24 Environmental Flows

A24.1 Calculation of environmental water requirements (EWR)

The concept of Environmental Water Requirements (EWR) can be illustrated in the schematic diagram below (Figure A12).



Note: EWR = Environmental water requirement

Figure A12. A schematic representation of the relationships between total water resources, total present water withdrawals, and EWR in environmentally safe (a) and environmentally water scarce (b) river basins (Smakhtin et al. 2004).

The traditional expression for Water Stress Index (WSI) is:

$$WSI = \frac{\text{Withdrawals}}{MAR}$$

WSI by taking into account EWR is:

$$WSI = \frac{\text{Withdrawals}}{MAR - EWR}$$

Where

MAR = Mean Annual Runoff

EWR = Environmental Water Requirement

A24.2 Pangani River Basin Management Project in Kenya and Tanzania

Example based on Pangani River Basin Management Project (2010), IUCN (2010a), King et al. (2010)

The Pangani River Basin covers an area of about 43,650 km², mostly in Tanzania with approximately 5% in Kenya. Generally, the basin comprises a low elevation slope that drops gently south and southeastwards towards the Indian Ocean. Flows in the basin have been reduced from several hundred m³/s to less than 40 m³/s, due to uncontrolled irrigation and urban water demand. The remaining water is seriously over-allocated. The shortage of water is affecting all water users, from the irrigation fields in the center of the basin and the electricity producers further downstream, to the coastal communities that notice saltwater moves inland and fish stocks decline. Large and smaller conflicts are on the rise between water users from various sectors. The IUCN, through its Water And Nature Initiative (WANI), started the Pangani River Basin Management Project in 2001 to improve management of the basin's water resources and reduce the conflicts that exist between the users. The project aims to 1) assess environmental flow requirements to effectively conserve the basin's natural resources, 2) establish forums for community participation in water management, and 3) raise awareness about climate change impacts and adaptation strategies. After a workshop with key stakeholders in May 2002, a Situation Analysis Report was commissioned. This report was based on interviews with a wide variety of stakeholders and the various existing sources of information about the Pangani Basin and discussed at a second workshop with stakeholders in May 2003.

The flow assessment component of the project started in 2004 and ended in 2008. Field and deskwork was completed by a multidisciplinary group of scientists, including experts in hydrology,

water quality, riverine and estuary ecology, socio-economic and geographic information systems. Fifteen development scenarios and thus 15 flow scenarios related to each development scenario were tested. A team of Tanzanian specialists were mentored by the project's team throughout the process as a means to create capacity building on environmental flows in the country. Eight technical reports were prepared as a result, including a State of the Basin Report, a Pangani Flows assessment-scenario evaluation decision support system (DSS) Report, and a Water Allocation Scenarios Report. The various scenarios and technical information obtained during the flow assessment are currently being presented to stakeholders at all levels, with particular emphasis on the Basin Water Board, the governmental organization responsible for allocating water in the basin. Consultations with stakeholders are intended to raise awareness of the water issues in the basin, help select the best development path for the river and eventually facilitate the integration of the selected environmental flow scenario (out of the 11 tested) into an Integrated Water Resource Management (IWRM) Plan for the Pangani Basin.

A24.3 Assessing environmental flows in Honduras

Example based on TNC (2007) and Cárcamo et al. (no date).

The Patuca River is the second largest river in Central America, flowing from the mountains of central Honduras eastward to the Caribbean Sea near the Nicaragua border. The area through which the river flows is part of the largest uninterrupted rainforest north of the Amazon and it functions as a biological corridor for Central American wildlife. Three indigenous communities live in this area: Tawahka, Pech and Miskito, who all rely on the river and its surrounding landscape to maintain their traditional ways of life. The government plans for the construction of a hydropower dam to address the increasing energy demands of the country threaten the intricate link between these indigenous communities and the Patuca River. The Nature Conservancy (TNC) entered into a unique agreement with Honduras' National Utility Company (ENEE) to design flow recommendations that would maintain the rivers' health and the ecosystems services it provides

to indigenous communities. TNC developed a collaborative process with scientific experts, water managers and indigenous communities to formulate these recommendations, while ENEE showed willingness to include these recommendations in the design and management plan of the dam.

The first step in the process was to learn more about the river system – the linkages between its ecology and hydrology – and the people who depend on it. In August 2006, a group of 12 researchers visited local communities during 11 days, and interviewed local individuals and small groups of fishermen. These interviews helped identify locations for cross-sectional surveys, such as location of highest flow from past wet seasons; creating a species list and fish ecology descriptions; and elaborating maps with locations of communities, river features and resources for agriculture, fisheries etc. These findings and hydrological analyses were discussed among scientists and developed into preliminary environmental flow and made recommendations. Indigenous community members then discussed the effects of the flow recommendations on fish, agriculture and transportation, contributing their site-specific expertise. Subsequently, maps were prepared, depicting seasonal flow levels and critical sites where low flow hinder boat traffic, as well as graphics showing the specific months when flows are preferred for crops. These outputs helped to make visible what the agreed environmental flow will do and were integrated into the draft flow recommendations for dam engineers and operators.

A24.4 Sustainable Rivers Project USA – Savannah River

Example based on TNC (2010).

Originating in the Blue Ridge Mountains of North Georgia, the 480 kilometers Savannah River flows eventually into the Atlantic Ocean. The lower Savannah River watershed encompasses more than 27,000 square kilometers and supports extremely high species diversity, including the greatest number of native fish species (108) of any river draining into the Atlantic. Despite its scenic beauty and natural diversity, the ecological health of the river system – from the headwaters to the estuary – is declining. The construction of three dams and reservoir systems

just 50 years ago has negatively altered the natural flow patterns that support the wildlife and natural communities of the Savannah River, its floodplain and its estuary.

In 2002, the US Army Corps of Engineers (Corps) and The Nature Conservancy (TNC) launched the Sustainable Rivers Project to restore rivers below the Corps' dams. One of these rivers was the Savannah River. The main restoration strategy was to define flow regimes that restore downstream ecosystem processes and services, while continuing to meet other human uses of water such as power generation (provisioning service), recreation (cultural), and flood control (regulatory). The project began in April 2003 with an orientation meeting with more than 50 leading scientists from the Georgia and South Carolina state governments, federal agencies, academic institutions and other non-governmental organizations to define the process. Using historical data, the seasonal water flows needed to support the freshwater, floodplain and estuary were defined. It was quite difficult to get the participants in the flow recommendations workshops to suggest any quantitative flow targets. However, by reminding them that their recommendations were a first approximation that would be refined over time through an adaptive management process, the targets could be established. Working with many scientists and agencies can be onerous and time-consuming, but most of these constraints were avoided by giving the most time-consuming activities to one research team. This report became the accepted basic knowledge for the other scientists in the project, making it easier to reach consensus during the flow recommendations workshop. Costs were reduced because researchers contributed their time as part of their regular job duties and because a considerable volume of relevant information already existed for the Savannah River.

Eventually a flow prescription plan for executing a series of seasonal controlled releases was designed and tested. For five days, the Corps released the first controlled flood of 450 cubic meters per second (cms) of water from the Thurmond Dam, a sizable increase from the existing daily release of 130 cms. Several controlled floods have been conducted since March 2004 to present time. These controlled releases mimic flow conditions

prior to the construction of dams. The ecological effects of the water flow restoration efforts have also been evaluated through a number of projects. These included monitoring the potential regenerative benefits to floodplain forest, tracking the movement of shortnose sturgeon, monitoring floodplain invertebrates and fish, and measuring the effects of the controlled floods on the salinity of the estuary. Through this process, TNC and its partners have gained valuable insight to the water flow patterns necessary to support native wildlife. The Savannah River project is today a model for sustainable dam operations and management worldwide.

A24.5 Environmental flow assessment in Vietnam

Example based on IUCN Vietnam (2005), IUCN (2007a, 2008c, 2010b).

The Huong (Perfume) River Basin is situated in the Hue Province in central Viet Nam. Before reaching the sea, the river opens into a lagoon system that extends about 70 km along the coastline. This system supports a number of livelihood activities and a lucrative aquaculture industry. The river is characterized by a steep gradient of 28.5%. Rainfall is very abundant, with an annual rainfall of 2,500 mm in coastal areas to 3,500 mm in the upper part of the basin. Due to these two physical characteristics, frequent downstream flooding occurs in the rainy season (September – November) resulting in large losses to crops, regional infrastructure and life. During the dry season (February till May) reduced flows and salinity intrusion threatens irrigation and domestic water intake of Hue city. Responses to the various challenges in the Huong River Basin included structural interventions such as flood protection dams and a salinity barrage to prevent salinity intrusion. Yet, the devastating floods of 1999, and the less severe floods of 2000, indicate shortcomings of this approach to flood management and mitigation. IUCN proposed preparing an integrated river basin management plan (IRBM) to address water issues in the basin instead.

The first step in the IRBM process was the elaboration of an Environmental Flow Assessment (EFA). Between 2003 and 2004, IUCN and partners organized three workshops in Hue city to assess

possible models for a river basin organization and to discuss the implementation of the Environmental Flow Assessment (EFA) process in Huong River. After selecting the EFA methodology and discussing the institutional and legal framework, a multidisciplinary team of experts was composed to develop a detailed EFA plan. The workshop participants identified the sites in the basin where field work should be conducted and what disciplines (such as hydrology, aquatic ecology, salinity, fisheries, and socio-economics) should be involved. After field work, data collection and analysis, the results were discussed in a workshop and preliminary EFA assessments were discussed, e.g.:

- A 50% increase in dry season flows in April would enhance the growth of aquatic plants and decrease phytoplankton density, leading to desired impacts on fish and shrimps. This would improve water quality, increase seasonal groundwater levels and have positive social impacts, such as more depth for floating villages.
- A 50% decrease in wet season flows in October would increase aquatic micro- and macrophytes, a negative impact as it would reduce the habitat for freshwater fish and hinder migration of eels. Most other indicators were expected to be negatively affected too.
- A 50% reduction in intra-annual floods would impede the flushing and refreshing of the river, with possible negative implications on all kinds of indicators.
- A removal of small flow peaks in May and June would have a negative impact on water quality because of increased salt intrusion, in-stream of aquatic organisms. However, if the dry season flows could be increased, the impact of removing these peaks would be low.

The Environmental Flows Assessment (EFA) process in Huong River made clear how changes in river flow affect both economic returns and ecosystem health. Basin authorities were able to determine which flow options accommodate economic goals while protecting downstream ecosystems and their services. As a result of the increasing awareness and capacity created by the flow assessment, environmental flows have been incorporated into planning for the Huong Basin by the provincial People's Committee and, at national level, the government has included environmental flows in the natural resources strategy and in water sharing plans.

Appendix 25

Ecosystem Restoration

Many of the examples in the appendices, particularly those relating to action in wetlands or changing agricultural practice, are actually about ecosystem restoration. In most cases, this means restoring or enhancing the services provided by the ecosystem. This also holds true for the transformation of conventionally managed agroecosystems into multifunctional agroecological landscapes that provide the widest range of ecosystem services.

A25.1 River restoration in Jordan

Example based on IdRC (2006) and IUCN (2009).

The Zarqa River is the second tributary to the Jordan River. It rises in springs near Amman and flows through a deep and broad valley into the Jordan River. Around 65% of the Jordanian total population and more than 90% of the small-medium industries of Jordan are concentrated in the Zarqa River Basin. The demands for water are very high. This has led to over-pumping of groundwater for agriculture, drinking and industrial uses that together have reduced the natural base flow of the river. The flow characteristics have been further modified by the discharge to the river of treated domestic and industrial wastewater that compose nearly all of summer flow and substantially degrade the water quality.

In a heavily populated and industrialized region, it is a challenge to establish a solid waste management strategy to stop the contamination of the river. However, in 2006, IUCN helped the Jordan Ministry of Environment to develop a long-term strategy for the restoration of the Zarqa River with the support of strategic partners. The Ministry of Environment placed the rehabilitation and integrated environmental management of the Zarqa River Basin at the top of its priorities in 2006. With support of IUCN, the Ministry formed a Committee with representatives of governmental institutions, research organizations, universities and local NGOs to develop a national strategy for the

restoration of the Zarqa River. The strategy builds on the principles of integrated water resources management (IWRM) combining development of effective governance, application of economic tools, knowledge management and capacity building, civil society engagement and implementation of restoration and sustainable management.

The restoration strategy has three phases. In the first three year phase, urgent pilot restoration activities show people how progress can be achieved and what the benefits of a healthy river are. At the same time, planning takes place for cleaning up the rubbish in the river, re-establishing riverside vegetation and managing water resources sustainably. This is backed by participation of river users and communities in decision making and action. Economic benefits from restoration will grow over time, together with regulatory, provisioning (agriculture), and cultural (recreation and tourism) ecosystem services. In the second and third phases, the whole river ecosystem will be restored to health over a period of 10–15 years.

A25.2 Managing community resources in the Peruvian Amazon

Example based on WWF (2009c).

The Peruvian Amazon is home to many indigenous communities that rely on the forest and its ecosystems services for their livelihoods. These services include food supply (e.g. bush meat), wood and non-wood products (e.g. fodder, medicinal plants), as well as spiritual and recreational services. Forested areas along riversides also prevent erosion and maintain water quality in the rivers (regulatory services), which are used by local communities as sources of water and food. Indigenous communities living in Peru's Amazon are among the poorest of the world, a situation that could be changed through the

sustainable management of the natural resources of the forest in which they live.

To reduce poverty levels of indigenous communities in the Peruvian Amazon, WWF-Peru developed the Managing Community Resources Project, building on the unique mechanisms that indigenous communities have to manage their environment. Awajun and Wampis native communities of the Condorcanqui Province received technical assistance on productive activities, such as cacao production, fish-farm management, and rubber production. The indigenous federations that represent these communities also benefited from capacity building activities, which focused on land use planning and property rights. Through the project, 20 communities and their representative organizations learned how to better manage their forests, freshwater ecosystems and agricultural units. In addition, 600 families within the project area improved their income through family-based productive systems, in particular family-owned fishfarms and agroforestry systems. Landscape and conservation plans were also prepared for the Tunta Nain Conservation Area and 16 communities around it.

A25.3 Restoration of the Chilika Lagoon, India

Example based on Hirji and Davis (2009)

Chilika Lagoon, located on the east coast of India in the state of Orissa, is the largest brackish lagoon in Asia. It runs parallel to the coast of the Bay of Bengal, separated by a 60 km barrier spit that varies from 0.5 to 2.0 km wide. The lagoon is a biodiversity hotspot, especially for water birds and other aquatic species and is home to the Irrawaddy dolphin, which is listed as an endangered species by IUCN. The lagoon ecosystem and surrounding catchment provides income to about 200,000 people who are dependent upon the fish, crab, and prawn catch, and also to the cashew and rice farmers. The surroundings also support grazing for over 50,000 cattle and provide fuelwood. In addition, Chilika has a growing ecotourism industry and numerous temples that draw large local populations. The lagoon's ecosystem depends on the water, sediment, and salt balances of the water

body. The Chilika lagoon lies within the Mahanadi Basin (the Mahanadi River reaches the ocean to the northeast of the lagoon). The Daya, Nuna, and Bhargavi branches of the river delta, along with smaller rivers and streams from the catchments along the western side of the lagoon, provide freshwater and sediment inflows to the lagoon. The lagoon is primarily connected to the Bay of Bengal through a channel in the north. Water exchange through this channel, freshwater inflows and evaporation, control the salinity of the lagoon.

The productivity of the lagoon declined significantly during the 1990s, primarily due to declining salinity as a result of reduced interchange between the lagoon and the ocean because of the northward littoral drift of the channel. There was an increase in sediment load from the western catchments and irrigation areas of the Mahanadi Delta. These sediments are believed to have been deposited within the lagoon itself, as well as near and along the mouth of the lagoon resulting in the closure of the lagoon mouth. The salinity level of the lagoon dropped dramatically from 20–30g/l to 2–3 g/l during May as the freshwater buildup continued. Due to the hydrologic and water quality changes fish catches declined from 6,000 tons in 1980 to 1,641 tons in 1997/98 (a reduction of nearly 73 percent); crab and shrimp catches also declined while several sponge species became extinct; other species became endangered, including the Irrawaddy dolphin. During the 1999 super cyclone blockage of the lagoon outlet led to flooding and waterlogging of large areas of paddy crop in lakeside villages, with consequent sanitation problems and outbreaks of disease.

In 1992, the state government of Orissa formed the Chilika Development Authority (CDA) to manage conservation efforts for the lagoon and develop a management plan. Following concerns on declining fish catches and biodiversity, the lagoon has been rehabilitated through combining immediate and long-term restoration actions. The most important immediate actions included the cutting of a new exit to the ocean and the dredging of a new channel between the Mahanadi Delta and the new mouth to facilitate tidal influx and freshwater outflows (after extensive stakeholder consultations and scientific studies). The new exit was completed in September

2000. This helped to restore the balance of freshwater, salt and sediment in the lagoon. As predicted by studies, oceanic exchange through the new channel has led to a remarkable recovery of the lagoon and the lagoon's productivity improved. The World Bank provided assistance for determining the environmental flow needed to sustain the lagoon in

the longer run through the Orissa Water Resources Consolidation Project (OWRCP) 1995–2004. While the increased exchange with the ocean has clearly led to immediate and widespread benefits, they will not be sustainable unless the natural flow regime from the Mahanadi River is at least partially restored and siltation of the entrance is arrested.

ISBN: 978-92-807-3170-5

Job Number: DEPI/1392/NA