Key Messages

- Agriculture depends on ecosystem functions such as pollination. This means it is closely linked with the health of surrounding ecosystems and should be considered an agro-ecosystem.
- Crop production systems have been managed as though they were disconnected from the landscape in general. Since the complex systems that make up the landscape are interconnected, this approach threatens the processes that make agriculture sustainable.
- Past agricultural management has caused wide scale changes in land cover, streamflow, and groundwater systems. This has undermined the processes that support ecosystems and the services that they provide.
- Agriculture will continue to be a key driver of ecosystem change in the future. In fact, demands for food and for water for food production could double over the next 50 years.
- Taking action now could repair damage and lessen future impacts. It could also help to lessen the damage caused by climate change. But, we have to change the way agriculture and ecosystems are managed. Necessary actions currently not factored into decision making include
  - managing agricultural areas as part of the larger landscape,
  - adaptive management at a variety of levels,
  - managing agro-ecosystems to enhance multiple ecosystem services,
  - valuing agro-ecosystem services for more than just crop production,
  - being aware of trade offs between services.

- Water will be a useful entry point for ecosystem management.
- Long-term sustainability will depend on agro-ecosystem resilience to change through beneficial feedback, the protection of species diversity, and the use of crop-complementary resources and alternative income options, etc.
- Future management of agro-ecosystems has to include innovations, and should deal with uncertainty and facilitate multiscale linkages by striking trade offs and recognising the roles of local actors – particularly state institutions.

SWEDISH WATER HOUSE

The Swedish Water House

The Swedish Water House is an initiative that stimulates co-operation and networking among Swedish-based, internationally oriented academic institutions, consultants, government agencies, NGOs, research institutes and other stakeholders. SWH is funded by the Ministry for Foreign Affairs and the Ministry of the Environment and administered by the Stockholm International Water Institute (SIWI). www.swedishwaterhouse.se

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The Stockholm International Water Institute (SIWI) is a policy institute that contributes to international efforts to find solutions to the world's escalating water crisis. SIWI advocates future-oriented, knowledge-integrated water views in decision making, nationally and internationally, that lead to sustainable use of the world's water resources and sustainable development of societies. www.siwi.org

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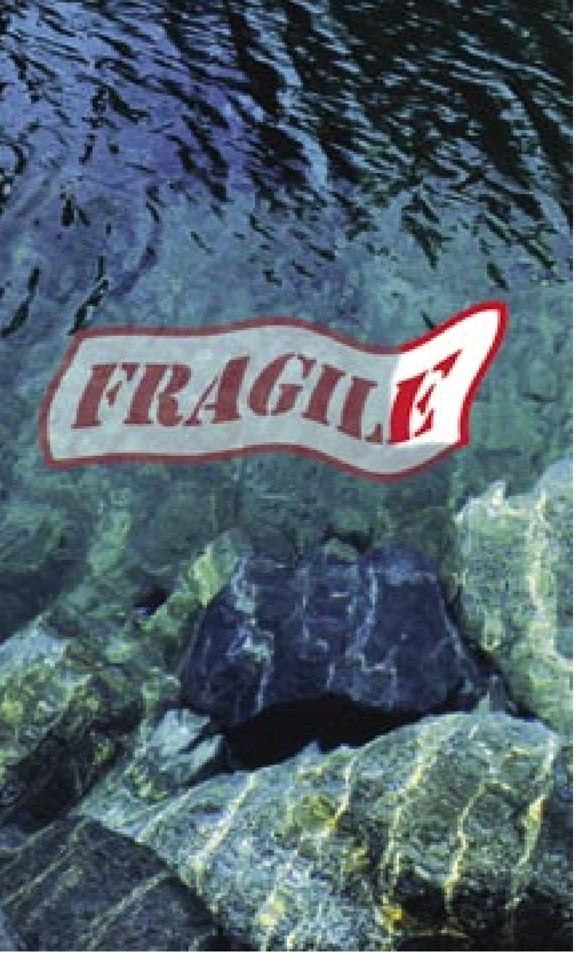

AGRICULTURE, WATER AND ECOSYSTEMS

A policy brief for central governments in developed and developing countries, sub-sovereign national bodies, universities and research institutes, community organisations, banks and private investors, aid donors, multilateral financial institutions, UN agencies and other international organisations.

SWEDISH WATER HOUSE

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Note to the Reader:

Over the next few decades, agricultural production is expected to expand in order to feed a growing global population. Since the amount of food needed is expected to roughly double by 2050, this is a real cause for concern in terms of water use. Increases in populations and incomes, and shifts in markets and people's preferences for particular foods, will mean that more water will be needed for food production. And, almost every increase in water used in agriculture will affect water availability for other uses – including that needed to keep ecosystems healthy and resilient in the face of change and perturbation. Loss of resilience leads to more vulnerable systems, and possible ecosystem shifts to undesired states that provide fewer ecosystem services. So, in the future, agriculture will have to strike a balance between the water required for food and the water needed to keep ecosystems healthy.

An additional factor to be considered for future agricultural production is the impact of climate change. New approaches and coping techniques must be found to prevent vulnerable regions and poor people from even further damage from changed hydrological patterns and decreased quantity and quality of water, a necessity for livelihoods and sustainable development.

This policy brief, Agriculture, Water and Ecosystems, is the result of a joint collaboration between two Swedish Water House cluster groups: The Resilience and Freshwater Initiative and the Swedish Network for the Comprehensive Assessment of Water Management in Agriculture (CAWMA). The main authors are Prof. Malin Falkenmark, Stockholm International Water Institute, and Dr. Victor Galaz, Stockholm University. Contributing authors and reviewers are Dr. David Molden, International Water Management Institute; Dr. Line Gordon, Stockholm University; and Mr. Michael Moore, Mr. Anders Berntell and Dr. Håkan Tropp, Stockholm International Water Institute.

Photo: Rebecca Löfgren, SIWI

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Why We Need to Examine the Agriculture, Water and Ecosystems Nexus

The last 50 years

Over the past 50 years, crop production systems have been managed as though they were separate from the landscapes they sit in, an attitude that neglects the natural ecological processes that ensure that agricultural production is sustainable. Irrigation, drainage, the clearance of natural vegetation, and the construction of water storage facilities have all altered the timing and natural variability of water flows, damaging groundwater recharge and waterscapes like wetlands. Similarly, fertiliser and pesticide use has increased the concentrations of nutrients, trace elements, and agrochemicals in the environment. All of this has altered the key eco-hydrological processes of rivers, lakes, floodplains and groundwater-fed wetlands, damaging their ecosystems and the services that they provide.

Regulation of rivers and the consumptive use of river water for irrigation have greatly lowered the amount of water discharged into the ocean in many cases. In fact, a recent study of 145 major rivers worldwide showed that the amount of water discharged had declined in one-fifth of cases (Falkenmark and Molden 2007). This can cause saline intrusion at river mouths and reduce, and in some cases completely cut off, the flow of water and nutrients to wetlands, lakes and coastal ecosystems.

There are actually many examples of downstream ecosystems being severely degraded by water diversions, flow control schemes and consumptive water use. Probably the most extreme is the Aral Sea, which has shrunk hugely because the rivers that feed it are being used for large-scale irrigation. But, it isn't the only example. Once the water requirements of ecosystems are factored in, it's clear that too much water is being extracted from many of the world's river basins. Indeed, streamflow depletion in rivers is widespread in tropical and subtropical regions where irrigation is large-scale. Areas affected include the Pangani, Incomati and Nile river basins in Africa; the Aral Sea tributaries, Ganges, Indus, Yellow and Chao Phraya rivers in Asia; the Rio Grande and Colorado in North America; and the Murray–Darling in Australia.

Policy Recommendations

- Policy needs to ensure that ecosystems are healthy enough to cope with change without losing their crucial functions.
- Policy must balance socio-economic activities with action to protect vital ecosystem services.
- Policy makers should work to protect biodiversity to ensure that ecosystems can cope with change without degrading suddenly. Alternative income options in drought and flood prone areas should be promoted to increase livelihood resilience.
- Policy should encourage water users to work together to more efficiently address their needs.
- More effort should be made to manage ecosystems on a catchment scale and recognize the links between them.
- Policy should ensure that sufficient water is allocated to provide for the needs of ecosystems and keep them healthy.
- Care needs to be taken to ensure that appropriate institutions are in place to protect ecosystems and manage water resources equitably.
- Stakeholders should be involved in ecosystem and water resource management and educated to improve their understanding of systems that affect their everyday lives.
- Monitoring efforts should be put in place to help communities and decision makers react to changes that might damage ecosystems and the livelihoods that depend on them.
- Because ecosystems are complex and the changes that can occur are difficult to predict, decision makers should plan for various scenarios and use these to structure their management efforts.
- Adaptive co-management, which involves the public and is based on 'learning by doing', can be a practical way to deal with change.
- Management efforts need to build on the experience and knowledge of actors at all levels. Local stakeholders, for example, are constantly observing their environment and are often best positioned to note changes in the ecosystems around them.

Many other things also degrade water quality, including agrochemicals, siltation and excessive nutrient loads – which have been identified as "one of the most important drivers of ecosystem change in freshwater and coastal ecosystems" (Millennium Ecosystem Assessment 2005). This is because too many nutrients in freshwater and coastal ecosystems lead to algal blooms that use up the oxygen in the water. This process (eutrophication) kills other organisms that depend on oxygen – as has been seen in the Baltic and Adriatic Seas and the Gulf of Mexico.

Wide scale use of agrochemicals also leads to chemical concentrations building up in organisms over time (bioaccumulation). This badly affects many species living in wetlands and lakes, as these systems replace their water slowly and pesticide residues can build up over many years.

Around the world, water tables are also changing, and soils and groundwater are becoming more saline. Though irrigation is often the cause of these kinds of changes, it isn't the only culprit. In dryland areas, clearing deep-rooted woody vegetation to make pastures and grow crops can also lead to soil salinisation and rising water tables.

Modern agriculture has also killed off many pollinators and animals that prey on pest species. In fact, as the Living Planet Index shows, it has had a direct effect on biodiversity in general, and on freshwater biodiversity in particular, which is declining much faster than in other systems (Loh et al. 2005). This is the result of habitat transformation and fragmentation, the modification of water regimes, nutrient loading, and the spread of invasive alien species.


Photo: Freefoto

Box 1. Ways of meeting future demand for water for food

There are three main ways in which food water requirements could be met:

1. increasing the amount of water used on current agricultural lands;
2. increasing water productivity in both irrigated and rainfed agriculture – which means producing more per unit of water with fewer water losses; and
3. expanding the area of cropland available.

In addition, reducing food wastage, including post-harvest losses, and reducing the demand for foods that require a lot of water, like red meat, will also go some way to ensuring sufficient water is available for food in the future.


Photo: Getty Images

Food demand, markets and ecosystems

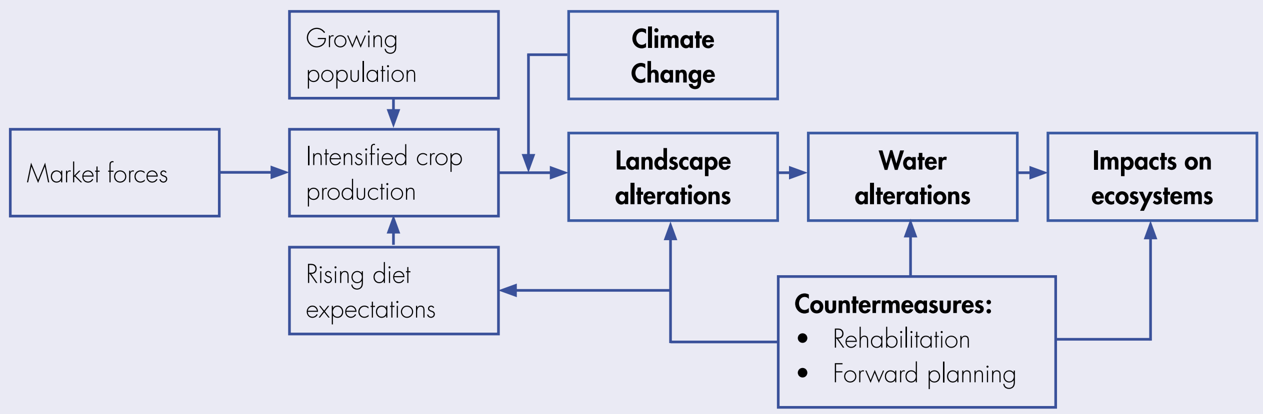


Figure 1. Simplified causal chain linking food demands and market forces to impacts on ecosystems. Further, the resilience of many ecosystems is likely to be exceeded during this century due to an unprecedented combination of climate change and associated disturbances like flooding, drought, wildfire, insects, etc., and other drivers like land use change, pollution and resource exploitation. Catchment scale approaches, improved governance, and other solutions do exist (see page 7).

At the continental scale, in both the Sahel and Amazon regions, vapour flows to the atmosphere have decreased in response to large-scale alterations in land cover, and this has often led to changed rainfall patterns.

The next 50 years

As populations and incomes rise, the demand for food will also grow – probably roughly doubling by 2050 and shifting towards more water-demanding diets (Figure 1). This will increase the amounts of water consumed. The process is already occurring in some countries, as demand is increasing rapidly for meat in China and for dairy products in India.

Considering the damage that agriculture has already done to natural ecosystems, it's clear that the issue of rising food production poses enormous challenges. There are a number of approaches that could be used to meet these needs, some of which will cause more environmental damage than others (see Box 1).

Analyses by the International Water Management Institute (IWMI) show that, at today's levels of water productivity, some 13,000 km^3 of water per year will be required to feed the world's population by 2050 (Comprehensive Assessment 2007). This is almost 6000 km^3 more than is being consumed by agricultural production today. In addition, cropland will need to expand by some 500 million hectares (Rockström et al. 2007). Increased water use on this scale would have a severe impact on ecosystems.

Aquatic ecosystems, both freshwater and coastal, will suffer as a result of reduced flow, altered flow variability, the increased use of agrochemicals, and the fact that some ecosystems will be cut off from others because of the building of additional water infrastructure for irrigation.

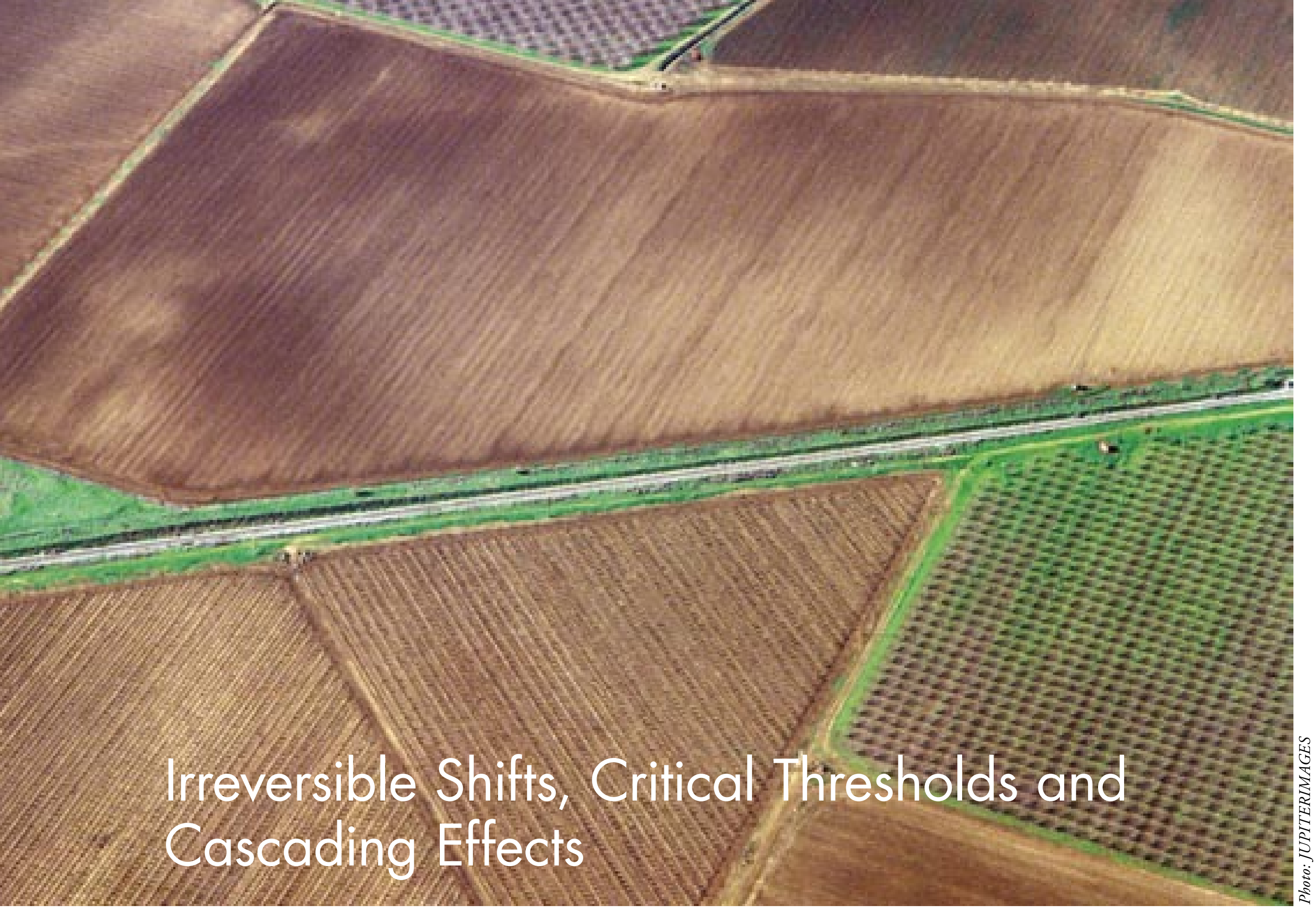
Terrestrial ecosystems will suffer as a result of clearance to open more land for crop production, as well as because of land cover changes and hydroclimatic moisture feedbacks.

However, despite the above estimates, the amount of water used by agriculture does not have to double. The increase can be limited by changing the agricultural practices used today, and by introducing innovative techniques and management methods. This would reduce the effects of future agricultural production on ecosystems.

The need for new irrigation investments could, for example, be substantially reduced by improving crop productivity in rainfed areas. In fact, increasing water productivity (the amount of water used to produce a given amount of crop) could reduce future requirements considerably, by making the most of every drop of water used. Altering our consumption patterns would also go a long way to reducing demand (for instance eating less red meat), as would minimising post-harvest losses, which are quite large in many poor countries (Swedish Environmental Advisory Council, MVB 2007).

The goal ought to be to increase crop production by as much as possible without increasing water consumption. This will require the smarter application of technologies and the development of synergistic links such as those used to meld irrigation and fisheries – an example being the use of irrigation reservoirs to raise fish. Plus, it will have to be recognised that damage to aquatic ecosystems can only be limited by allowing them sufficient amounts of water (so-called environmental flows), limiting water pollution and designing water infrastructure that ensures that ecosystems are not isolated from each other.

A critical aspect not to be forgotten is that increased water demands affect not just ecosystems, but also the important services that they provide. For example, landscape alterations lead to increased eutrophication and potential loss of marine biodiversity and fish stock. Or in another example, drained or altered water bodies or wetlands can greatly affect the cultural, religious, aesthetic, ethical or recreational services provided in different societies around the world.



Irreversible Shifts, Critical Thresholds and Cascading Effects

Irreversible shifts and critical thresholds

Agricultural landscapes provide a range of ecosystem services besides producing crops. These landscapes are made up of a number of poorly understood interlinked biophysical systems – so tinkering with one element can cause vast changes throughout the connected systems. Decision makers have to realize that these systems can undergo damaging and irreversible shifts. What this means, basically, is that once they're broken they can't be fixed. They therefore need to be aware of the critical thresholds which exist in these systems and which, once crossed, can quickly lead to degradation. Several examples of such are dealt with in Box 2.

Ecosystems do not respond to gradual change and disturbances in a linear manner. On the contrary, small changes can have vast negative outcomes. This is one key insight from decades of research on interconnected complex socio-ecological systems. (Reynolds et al. 2007). Practically irreversible shifts to degraded states in ecosystems such as coral reefs, freshwater ecosystems, coastal seas, forest systems, savannas and grasslands, and the climate regime all illustrate the real-world implications of this insight (Folke et al. 2004, Scheffer and Carpenter 2003, Schneider 2004; see also the Resilience Alliance database).

It also needs to be recognized that agricultural systems display an economic threshold level of soil degradation beyond which a conservation investment is simply not worthwhile economically. Once a parcel of land crosses this productivity threshold, soil degradation becomes irreversible in economic terms even though the degradation may be technically reversible. Global surveys suggest that 9% of agricultural land is already so badly degraded that it cannot be reclaimed for productive use by farm-level measures, while 40% of agricultural land is degraded to the point that crop yields are reduced (Wood, Sebastian and Scherr 2000).

Interacting thresholds and cascades

Thresholds in one ecosystem may be affected by a threshold being crossed in another. This may lead to a cascade effect. Projections of the social, economic and ecological state of the Australian wheat-belt, for example, reveal a number of interacting thresholds. Abrupt shifts from sufficient soil humidity to saline soils and from freshwater to saline ecosystems, could make agriculture a non-viable activity at a regional scale and trigger migration, unemployment and the weakening of social capital. These effects illustrate the possibility of one disturbance propagating through spatial scales, and ecological, social and economic systems. Kinzig and others (2006) give a number of examples of the management challenges posed by such cascade effects.

Box 2. Irreversible shifts in different systems: some examples

Shifts in soils and water tables: A good example of an irreversible shift is provided by those areas in which productive non-saline soils have become unproductive salt-drenched and waterlogged. This happened in southwestern Australia, when the native perennial vegetation was replaced with shallow-rooted agricultural plants. These new plants did not take up and consume (evapotranspire) as much water as the native plants. Long term, this caused the water table to rise, bringing stored salt to the surface and badly damaging the area's ability to support ecosystem services (Clarke et al. 2002, Kinzig et al. 2006).

Shifts in lakes: Phosphorus can accumulate in soils and in sediments in lakes. In combination with other factors, like nitrogen levels and fisheries activities, the amount of phosphorous in the water in the lake will determine the degree of eutrophication occurring in the lake. Once a threshold of eutrophication is reached, oxygen levels can decrease and trigger the release of extra phosphorus from sediments – essentially 'trapping' the system in a state of eutrophication (Scheffer and Carpenter 2003, Carpenter et al. 1999).

Shifts in precipitation dynamics: Deforesting areas can reduce the recycling of water which may alter the precipitation pattern elsewhere (Foley et al. 2003, c.f. Steffen et al. 2004, Scheffer and Carpenter 2003, Cramer et al. 2001). A good example of this is the large scale deforestation seen in the Amazon, which has turned areas of rainforest into dry savannah.

Shifts in biodiversity: Modifying a landscape on a large scale also changes the amount of plant and animal biodiversity found in that area. This risks the loss of organisms that perform crucial activities, like recycling nutrients, suppressing undesirable organisms and breaking down poisonous chemicals (Altieri 1999). Loss of biodiversity can also make ecological systems more fragile (Elmqvist et al. 2003), which means that a disturbance that the system could previously have coped with instead sparks off a practically irreversible shift.

Photo: Digital Archive Japan Inc.

Solutions and Recommendations

Recommendations

To ensure that agricultural systems are sustainable, we have to protect crucial ecosystem functions in the natural landscape. These include the provision of safe habitats for birds, insects, and fish, and the production of food, timber and fuelwood. We also have to ensure that ecosystems remain resilient, so that they can cope with unexpected changes without collapsing.

When considering what countermeasures we can take against ecosystem degradation, it is useful to decide whether the manipulations taking place are avoidable or unavoidable. Environmental manipulations which are usually avoidable include incautious land use changes and the use of toxic chemicals that can spread through ecosystems. An example of an unavoidable manipulation of the environment is the consumptive/depletive use of water that occurs as a result of photosynthesis during crop production (Falkenmark & Lannerstad 2005). Unavoidable manipulations will require trade offs to be balanced against vital ecological services.

Such unavoidable manipulations include the following:

- shifting the distribution of plants and animals
- measures to cope with rainfall variability to secure water for crops
- securing enough air for the roots by draining waterlogged land
- the use of manure or chemical fertilisers to replenish the nutrients consumed by earlier harvests
- the disturbance of landscape-scale connectivity – which damages species mobility and subsurface water flows.

What can be done?

In order to ensure that socio-economic activities do not undermine the life support system on which we all depend, new and revised policy must reflect our improved understanding of the interactions that link agricultural activities. Decision makers need to be aware of the very real dangers, as well

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as of the socio-economic costs we face if our ecosystems are seriously undermined by destructive actions. So, we must ask (1) what can be done to protect ecosystems, (2) how can this be achieved and (3) what financial and institutional means need to be used.

The solutions and recommendations dealt with here will be considered by looking at (1) local scale ecosystem-oriented approaches, (2) catchment-scale approaches, and (3) strategic management.

Local ecosystem-oriented approaches

The focus of recent debates has moved away from the need to conserve ecosystem functions and attributes, and towards the need to protect the ecological services that ecosystems provide. Emphasis is also now being placed on the need for trade offs that consider both the beneficiaries of agricultural production and the beneficiaries of other ecological services.

Decision makers also need to be aware that people often mean different things when they refer to an 'ecosystem approach'. The ecosystem concept referred to in international legislation and treaties is fairly diffuse. It is a negotiated, politically based, environmentally oriented concept which is more strongly linked to natural resources and environmental impact issues than to ecosystems in the biophysical sense of the term (Falkenmark and Tropp 2005). In this context, for example, the term has been used in debates over salinity intrusion, overexploitation of groundwater, and ecotourism-based economies.

As a result, decision makers might interpret an ecosystem approach as either a biophysical approach (which focuses on ecological phenomena) or as a broader socio-ecological approach (which focuses on the economic potential of natural resources). In the former, humans are often seen as disturbing agents. In the latter, they are viewed as part of the natural system, dependent on its resources which in turn influence the development potential (Falkenmark and Tropp 2005).

Agro-ecosystem resilience to change

Biophysically, an ecosystem's resilience (its ability to deal with change and continue to function) depends upon species diversity. This is because having many different organisms performing different functions (like predators, pollinators, herbivores and decomposers) means that the ecosystem can reorganise itself after a disturbance such as a dry spell, drought or flood.

Looking at agro-ecosystems from a socio-ecological point of view, however, requires us to see people and their activities as part of the system. So, resilience to change in the face of disturbances in smallholder agriculture can be seen to depend on the resources available to complement cropping and agricultural activities. In dryland agriculture, for example, such crop-complementary resources might include grazing land or emergency food storage in case harvests fail (Enfors and

Photo: Getty Images

Gordon 2007). The required buffering can also be provided using resources for alternative income options, such as fuelwood, wood for charcoal making, and fibre for ropes and handicrafts (Enford and Gordon 2007).

Considering the scale of an ecosystem

An ecosystem approach can focus either on ensuring the functioning of individual local ecosystems within a landscape, or on addressing the whole catchment as a composite ecosystem (Falkenmark 2003).

Local-scale ecosystems have to be protected by addressing their key water determinants. Protection of catchment-scale ecosystems, on the other hand, has to focus on protecting catchment-specific interactions like groundwater recharge. This type of management can benefit from the fact that the need for water can drive people to work together. This allows governments and communities to manipulate the catchment in ways that lead to activities within the system being compatible.

Catchment-scale approaches

Water as an entry point

Currently ecosystems are rarely managed on a catchment scale. As water plays an extremely important role in ecosystem functioning (see Figure 2), water management can be used to introduce integrated and holistic approaches for managing a whole range of other natural resources as well (Falkenmark 2003). One way to do this is to incorporate the protection of vital ecosystems into integrated water resource management (IWRM) efforts.

A catchment can be seen as a grouping of interconnected nested ecosystems. Because of this, changes in one part of a basin will affect both water availability and ecosystem health in other parts of the basin (see Figure 3). So, paying adequate attention to hydrological–ecological linkages and dependencies is one way to approach water management. Examples would include the links between a forest and groundwater recharge, or between a grazed floodplain and the periodic flooding and grass production that occurs there.

Striking trade offs and stakeholder participation

Catchment-scale approaches involve work to strike trade offs and balance different interests. They demand both well-organised stakeholder participation, and the definition of bottom lines and resilience criteria to protect key ecosystems (Falkenmark 2007). A good example of this is the establishment of environmental flows. This involves defining the quantity, timing and quality of the water flows considered necessary to protect the structure and function of an aquatic ecosystem and the services and species that depend on it.

Environmental flows can be assessed and applied in both open and closed basins. In open basins, where development is planned, an environmental flow assessment should be undertaken as part of IWRM. This will ensure that the ecosystem services dependent on the flow regime are maintained and can continue to support the livelihoods and incomes of the people who rely on them. In closed basins, allocating water to ecosystems will help to restore them, but will require existing water allocations to be renegotiated.

Environmental flow assessments have been undertaken in many systems around the world, and can take many different forms depending on the resources available and how comprehensive the assessment should be. One example can be found in the Huong River Basin in Vietnam, where a rapid environmental flows assessment was undertaken. This was used to guide planning processes in the basin and ensure that both existing and planned dams would continue to meet the needs of the stakeholders and the ecosystems in the basin.

When incorporating environmental flows into water allocation frameworks, it is critical to recognize that water availability varies between areas and years. This means clearly defining how water will be allocated during times of shortage and agreeing how to share scarcity – for example, by planning mechanisms to compensate farmers so that irrigation water can be released for other uses during times of drought.

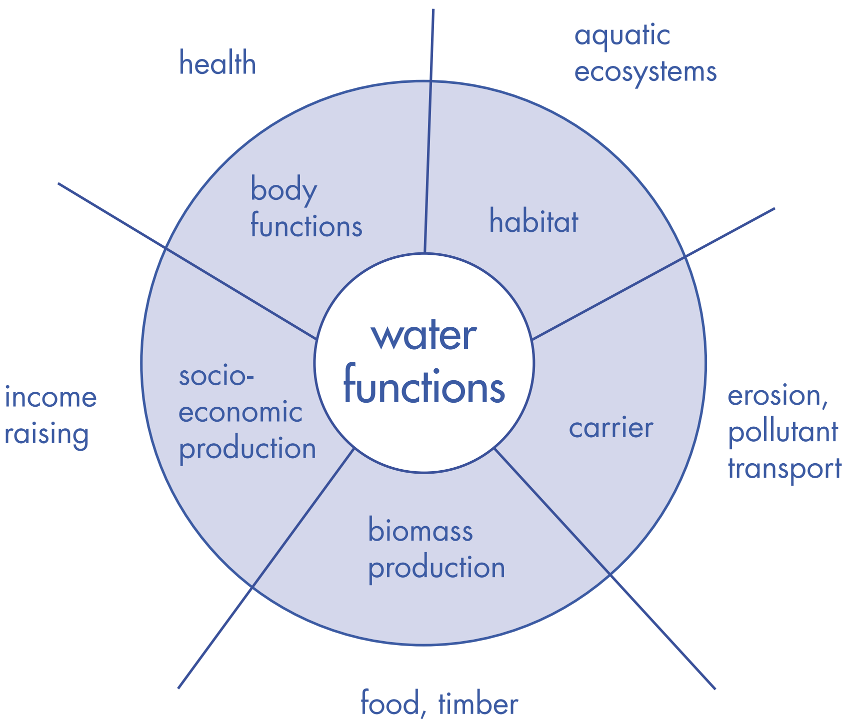

Figure 2. Water's many parallel functions.

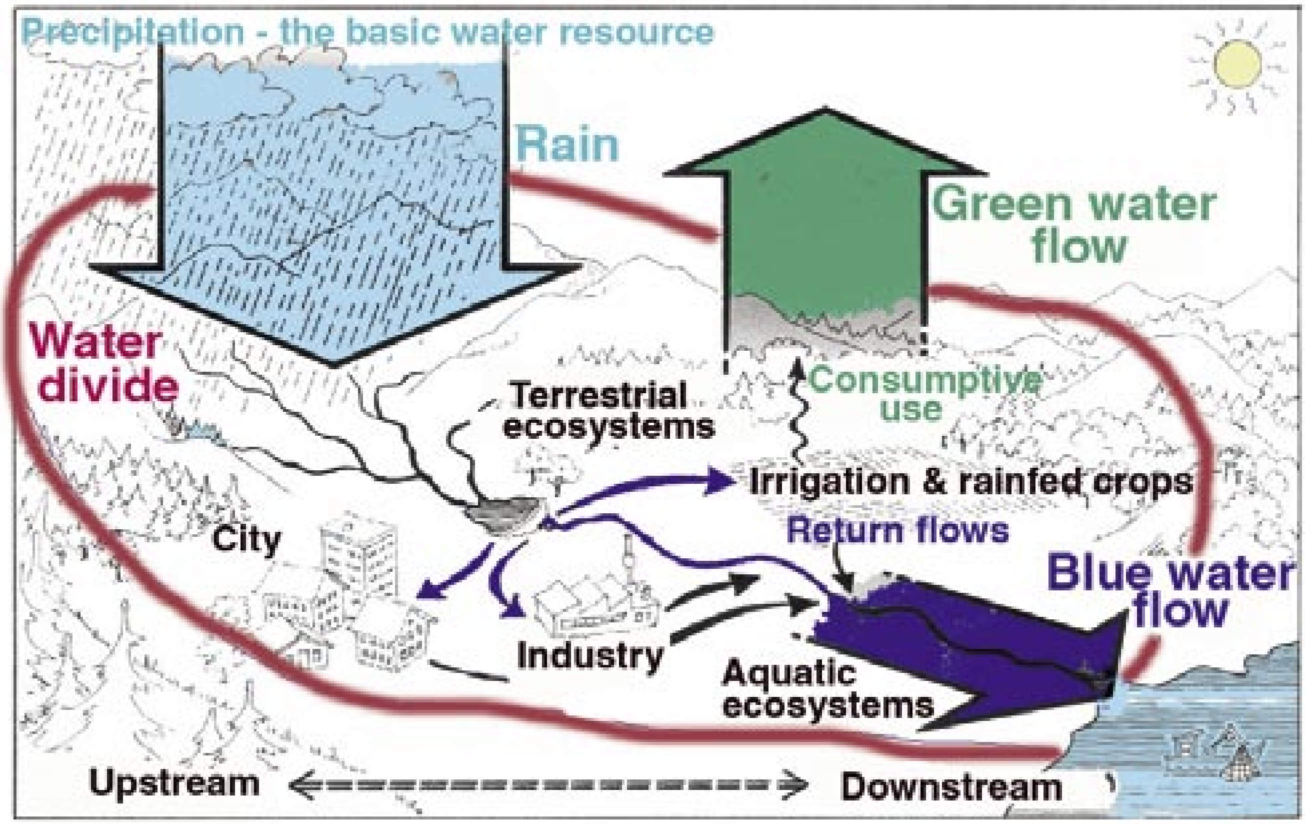

Figure 3. Links between direct water use and ecosystems in a catchment.

Strategic management

As well as identifying what to govern (for example, people's agricultural activities), decision makers must also identify the best way to govern. This involves an array of consecutive steps: fact finding and problem analysis; production of a strategic plan of action; the use of tools to put that plan into action (legislation, financing, competent institutions, stakeholder participation, etc.); and the use of tools to secure its implementation (incentives/sanctions, capacity building, media campaigns, etc.).

When working to protect ecosystems, decision makers need to consider (1) what issues should be included in water management, and (2) what institutions are needed to make protection possible. The first question can be clarified by using diagnostic analysis to identify the major ecological issues in a catchment, the root causes of ecosystem degradation, and the causal chains involved (Duda 2003). Such an analysis has to identify the key water determinants that will have to be secured using integrated water management and work to protect water quality and land cover. The strategic action plans developed should incorporate standards for minimum residual streamflows (environmental flows), maximum contaminant concentrations, protected areas of forest in the recharge areas of key aquifers, flood-flow mimicking through dam-based flow-regulation, etc.

Addressing problems that have already manifested themselves will involve efforts to minimise whatever is perceived to be the cause of the degradation. One example would be work to manage demand or to buy back water from irrigators in order to reduce streamflow depletion. Another would be finding better ways to manage agricultural fertilisers in order to reduce the eutrophication of lakes and coastal waters, etc.

Managing uncertainty

In agro-ecosystem management, it is necessary to be prepared to cope with uncertainty and surprises. The vast uncertainties associated with global climate change, and the possibilities of threshold behaviour and surprises linked to agricultural landscapes, all call for innovative approaches in ecosystem-oriented water management. So, a very important part of any strategic approach to agro-ecosystem planning and management is to promote ecosystems resilience (Walker et al. 2002), the capacity of a system, like a society or an ecosystem, to deal with change and continue to develop.

At the same time, it should also be remembered that agro-ecosystems are dynamic socio-ecological systems. So good management also needs to promote social learning, in order to improve users' understanding of the dynamics of the system. Decision makers also need to ensure that links exist between users and managers at different levels, to ensure prompt and effective responses to socio-economic or ecological changes.

Ensuring that ecosystems show resilience to change

A good example of such management for resilience can be found in the Kruger Park – a protected area in South Africa. There, management is built around monitoring activities which are used to identify social, economic or biophysical changes that might push freshwater systems beyond critical thresholds. Monitoring of these thresholds of potential concern, enhances the ability of communities and water and land managers to respond quickly to changing circumstances (Rogers and Biggs 1999).

So, in this protected area managers do not only monitor for changes in the factors determining water quantity and quality and ecosystem-relevant parameters linked to soil characteristics. They also assess the major social, ecological and economic drivers that might cause "surprises" – work which involves roughly estimating potential thresholds.

In fact, looking for thresholds and surprises is an important activity when trying to grasp the dynamics of any ecosystem. Without a thorough understanding of these dynamics, monitoring activities could simply miss the possibility that a system is becoming more vulnerable to the impacts of intensified agricultural production, and climate variability and change.

One way to increase the resilience of agro-ecological systems is to introduce a multifunctional agro-ecosystem. As well as increasing the diversity of organisms in the system (which can help in times of disturbance) such a system also provides alternative income options for local people (Figure 4).

Four management options

The main management approaches that should be used differ according to whether one is dealing with controllable situations or situations involving uncertain information, an inadequate understanding and outcomes that vary in terms of their controllability (Figure 5). In controllable situations, decision making is more straightforward than in uncontrollable situations, where the use of scenarios is one way to build a structured approach.

Scenario planning involves using a few contrasting scenarios to explore the uncertainty and thresholds associated with the future consequences of a certain decision. Combining scenario planning with repeated stakeholder dialogues can improve decision makers' understanding and management of ecological and social processes. It also increases the likelihood that it will be possible to enhance the resilience of an agro-ecosystem in the face of global environmental change.

Flexibility through adaptive co-management

In controllable but uncertain situations, good ecosystem management needs to be flexible. Those involved should experiment with different management strategies, while being aware of, and respecting, existing uncertainties in the functioning of particular agro-ecosystems. Management according to this perspective can be seen as a continuous learning-by-doing process, benefiting from public participation and joint learning (Schluster et al. 2003, Folke et al. 2005). Examples of

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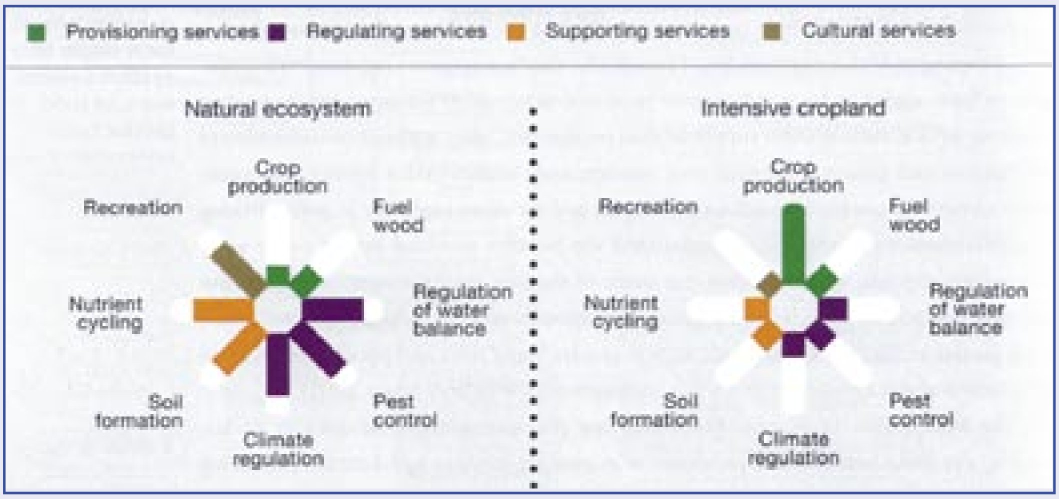

Figure 4. Comparison of intensive agricultural systems managed for the generation of one ecosystem and multi-functionality in agri-ecosystems (Comprehensive Assessment 2007).

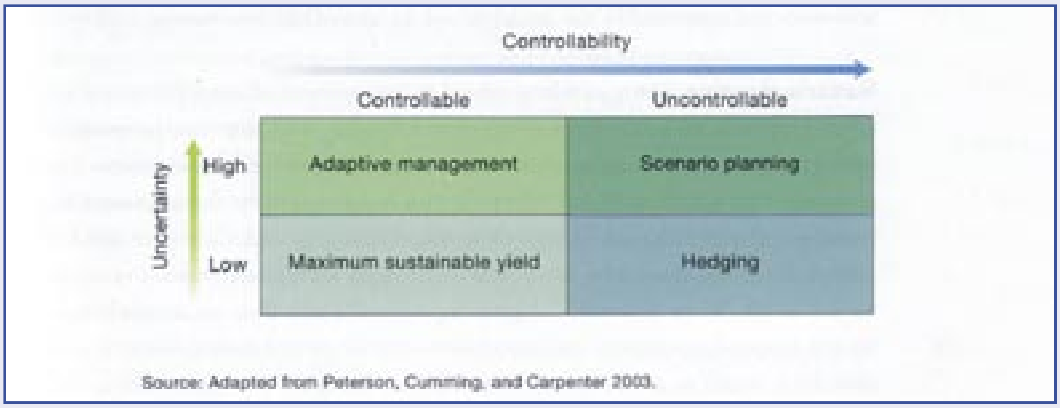

Figure 5. Different management approaches for dealing with uncertainty in information and the controllability of outcomes (Comprehensive Assessment 2007).

its use can be found in the Northern Highlands Lake District, Wisconsin (USA) (Peterson et al. 2003), and the Gariep River Basin (South Africa) (Bohensky et al. 2006).

Successful adaptive co-management depends on the use of organisational rules that are flexible and fairly easy to adapt as our understanding increases with time. Fixed organizational rules that are difficult to change over time will act as obstacles.

Multilevel interaction

The social, economic and ecological effects of events like flash floods, droughts, influxes of invasive species and large-scale abrupt shifts in landscapes, surpass the scale of even catchment-based management. Organisational rules therefore have to allow for the development of strong multilevel cooperation between local actors and central administration and policy makers. These linkages are important in two ways.

First, the involvement of local actors is crucial, as they can detect environmental change and surprises in agro-ecosystems. While conventional water monitoring certainly is important, local communities' observations about changes in their local environment can provide an important complement in the face of surprising changes.

Second, decision-making by central actors remains crucial in securing a fast response to large-scale shocks and disturbances in agro-ecosystems. While community participation is important, central government must also be able to detect large-scale patterns of change, and coordinate mitigation measures before critical thresholds are crossed. For example, the option to migrate in times of drought or flooding, and strategies to diversify incomes are all risk-reducing policy initiatives that require multilevel collaboration between local communities, non-state actors and central agencies (Moench and Dixit 2004, Downing et al. 2005).

Photo: Digital Archive Japan Inc.

References

Altieri, M.A. 1999. The Ecological Role of Biodiversity in Agroecosystems. *Agriculture, Ecosystems and Environment*, Vol. 74, pp. 19–31.

Bohensky, E.L., Reyers, B. and Van Jaarsveld, S. 2006. Future Ecosystems Services in a Southern African River Basin: A Scenario Planning Approach to Uncertainty. *Conservation Biology*, Vol. 20(4), pp. 1051–1061.

Carpenter, S.R., Ludwig, D. and Brock, W.A. 1999. Management of Eutrophication for Lakes Subject to Potentially Irreversible Change. *Ecological Applications*, Vol. 9(3), pp. 751–771.

Clarke, C. J., George, R.J., Bell, R.W. and Hutton, T.J. 2002. Dryland Salinity in South-western Australia: Its Origins, Remedies, and Future Research Directions. *Australian Journal of Soil Research*, Vol. 40, pp. 93–113.

Comprehensive Assessment of Water Management in Agriculture. 2007. *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. London: Earthscan, and Colombo: International Water Management Institute.

Cramer, W., Bondeau, A, Woodward, F.I., Prentice, I.C., Betts, R., Brovkin, V.,; Cox, P., Fisher, V., Foley, J.A., Friend, A.D., Kucharik, C., Lomas, M.R., Ramankutty, N., Sitch, S., Smith, B., White, A. and Young-Molling, C. (2001). Global Response of Terrestrial Ecosystem Structure and Function to CO2 and Climate Change: Results from Six Dynamic Global Vegetation Models. *Global Change Biology*, Vol. 7, pp. 357-373.

Duda, A.M. 2003. Integrated Management of Land and Water Resources Based on a Collective Approach to Fragmented International Conventions. Biological Sciences, *Philos Trans R Soc Lond B Biol Sci.* 2003 December 29; 358(1440): pp. 2051–2062.

Elmqvist, T., Folke, C., Nystroem, M., Peterson, G., Bengtsson, J., Walker, B. and Norberg, J. 2003. Response Diversity, Ecosystem Change, and Resilience. *Frontiers in Ecology and the Environment*, Vol. 1(9), pp. 488–494.

Enfors, E. and Gordon, L. 2007. Analysing Resilience in Dryland Agro-ecosystems: A Case Study of the Makanya Catchment in Tanzania Over the Past 50 years. *Land Degradation & Development*, Vol.18, pp. 1-16.

Falkenmark, M. 2003. Water Management and Ecosystems: Living with Change. *GWP/TEC Background Paper No. 9.* Global Water Partnership, Stockholm.

Falkenmark, M. 2007. Good Ecosystem Governance: Balancing Ecosystems and Social Needs. In: Governance as a Trialogue: Government-Society-Science in Transition. (Eds.) Turton, et al. Springer Verlag, Berlin.

Falkenmark, M. and Lannerstad, M. 2005. Consumptive Water Use to Feed Humanity - Curing a Blindspot. *Hydrology and Earth Sciences,* Vol. 9, pp. 15-28.

Falkenmark, M and Folke, C. 2003. Freshwater and Welfare Fragility – Introduction. Biological Sciences, P*hilos Trans R Soc Lond B Biol Sci*. December 29; 358(1440): pp. 1917–1920.

Falkenmark, M. and Tropp, H. Ecosystem Approach and Governance: Contrasting Interpretations. *Water Front 2005*, No. 4. SIWI

Foley, J.A., Costa, M.H., Delire, C., Ramankutty, N. and Snyder, P. 2003. Green Surprise? How Terrestrial Ecosystems Could Affect Earth's Climate. *Frontiers in Ecology and the Environment,* Vol. 1(1), pp. 38-44.

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L. and Holling, C.S. 2004. Regime Shifts, Resilience and Biodiversity in Ecosystem Management. *Annual Reviews of Ecological Systems*, Vol. 35, pp. 557–581.

Folke C., Hahn T., Olsson P., and Norberg J. 2005. Adaptive Governance of Social-ecological Systems. *Annual Review of Environmental Resources*, Vol. 30, pp. 441–473.

Kinzig, A. P., Ryan, P., Etienne, M., Allison, H., Elmqvist, T. and Walker, B.H. 2006. Resilience and regime shifts: assessing cascading effects. *Ecology and Society* 11(1): 20. [online] URL: http://www.ecologyandsociety.org/vol11/iss1/art20/

Loh, J., Green, R.E., Ricketts, T., Lamoreux, J., Jenkins, M., Kapos, V., and Randers, J. 2005. The Living Planet Index: Using Species Population Time Series to Track Trends in Biodiversity. Biological Sciences, *Philos Trans R Soc Lond B Biol Sci.* February 28; 360(1454): pp. 289–295.

Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-Being: Wetlands and Water Synthesis*. World Resources Institute, Washington, DC.

Peterson, G.D., Cumming, G.S. and Carpenter, S.R. 2003. Scenario Planning: A Tool for Conservation in an Uncertain World. *Conservation Biology*, Vol. 17 (2), pp. 358–366.

Reynolds, J., Smith, D., Lambin, E., Turner, B.L., Mortimore, M., Batterbury, S., Downing, T., Dowlatabadi, H., Fernandez, R., Herrick, J., Huber-Sannwald, E., Jiang, H., Leemans, R., Lynman, T., Maestre, F., Ayarza M. and Walker, B. 2007. Global Desertification: Building a Science for Dryland Development. *Science*, Vol. 316, pp. 847.

Rockström J., Lannerstad M. and Falkenmark, M. 2007. Assessing the Water Challenge of a New Green Revolution in Developing Countries. *Proc Natl Acad Sci USA*. 2007 Apr 10; 104(15): pp. 6253-60. Epub 2007 Apr 2.

Rogers, K. and Biggs, H. 1999. Integrating Indicators, Endpoints and Value Systems in Strategic Management of the Rivers of the Kruger National Park. *Freshwater Biology*, Vol. 41, pp. 439–51.

Scheffer, M. and Carpenter, S.R. 2003. Catastrophic Regime Shifts in Ecosystems: Linking Theory with Observation. *Trends in Ecology and Evolution*, Vol. 18(12), pp. 648–656.

Schneider, S.H. 2004. *Abrupt Non-Linear Climate Change, Irreversibility and Surprise*. Working Party on Global and Structural Policies, OECD.

Schusler, T.M., Decker, D.J. and Pfeffer, M. 2003. Social Learning for Collaborative Natural Resource Management. *Society and Natural Resources*, Vol. 15, pp. 309-326.

Steffen, W., Sanderson, A., Jäger, J., Tyson, P., Moore III, D., Matson, B., Richardson, P.A., Oldfield, K., Schellnhuber, H.J., Turner II, B.L. and Wasson, R.J. (Eds.) 2004. *Global Change and the Earth System: A Planet Under Pressure*. Springer-Verlag, Heidelberg, IGBP Book Series

Walker, B., Carpenter, S., Anderies, J., Abel, N., Cumming, G.S., Janssen, M., Lebel, L., Norberg, J., Peterson, G.D. and Pritchard, R. 2002. Resilience Management in Social-ecological Systems: A Working Hypothesis for a Participatory Approach. *Conservation Ecology*, Vol. 6(1), pp. 14. [online] URL: http://www.consecol.org/vol6/iss1/art14.

Wood, S., Sebastian, K. and Scherr, S.J. 2000. Soil Resource Condition. In Wood, S., Sebastian, K., and Scherr, S. J., (eds.) *Pilot Analysis of Global Ecosystems: Agroecosystems. Washington*, D.C., IFPRI and World Resources Institute.

Secondary References

Antle, J.M., Stoorvogel, J.J. and Valdivia, R. O. 2006. Multiple Equilibria, Soil Conservation Investments, and the Resilience of Agricultural Systems, *Environment and Development Economics*, Vol. 11, pp. 477–492.

Beresford, Q., Bekle, H., Phillips, H. and Mulcock, J. 2001. *The Salinity Crisis: Landscapes, Communities and Politics*. University of Western Australia Press.

Berkes, F. and Folke, C. (Eds.). 1998. *Linking Social and Ecological Systems*. Management *Practices and Social Mechanisms for Building Resilience*. Cambridge: Cambridge University Press.

Downing, T.E., Aerts, J., Soussan, J., Barthelemy, O., Bharwani, S., Ionescu, C., Hinkel, J., Klein, R.J.T., Mata, L.J., Martin, N., Moss, S., Purkey, D. and Ziervogel, G. 2006. Integrating Social Vulnerability into Water Management. *SEI Working Paper and Newater Working Paper* No. 4. Oxford: Stockholm Environment Institute.

Folke, C. 2006. Resilience: The Emergence of a Perspective for Social–ecological System Analyses. *Global Environmental Change*, Vol. 16(3), pp. 253–267.

George R.J., McFarlane, D.J. and Nulsen, R.A. 1997. Salinity Threatens the Viability of Agriculture and Ecosystems in Western Australia. *Hydrogeology Journal*, Vol. 5 (1), pp. 6–21.

Moench, M. and Dixit A. (Eds.). 2004. *Adaptive Capacity and Livelihood Resilience – Adaptive Strategies for Responding to Floods and Droughts in South Asia*. Boulder, Colorado, The Institute for Social and Environmental Transition (ISET).

Noble, A.D., Pretty, J., Peening de Vries, F. and Bossio, D. 2004. D*evelopment of Bright Spots in Africa: Cause for Cautious Optimism?* New Partnership for Africa's Development (NEPAD), Conference Paper No. 18.

Olsson, P. and Folke C. 2001. Local Ecological Knowledge and Institutional Dynamics for Ecosystem Management: A Study of Lake Racken Watershed, Sweden. *Ecosystems*, Vol. 4(2), pp. 85-104.

Penning de Vries, F.W.T. (Ed.). 2005. *Bright Spots Demonstrate Community Successes in African Agriculture*. Colombo, Sri Lanka: International Water Management Institute, (Working Paper 102).

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