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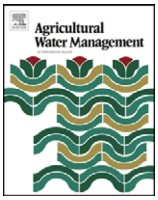

Managing water in agriculture for food production and other ecosystem services

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ABSTRACT

Agricultural systems as well as other ecosystems generate ecosystem services, i.e., societal benefits from ecological processes. These services include, for example, nutrient reduction that leads to water quality improvements in some wetlands and climatic regulation through recycling of precipitation in rain forests. While agriculture has increased ‘provisioning’ ecosystem services, such as food, fiber and timber production, it has, through time, substantially impacted other ecosystem services. Here we review the trade-offs among ecosystem services that have been generated by agriculture-induced changes to water quality and quantity in downstream aquatic systems, wetlands and terrestrial systems. We highlight emerging issues that need urgent attention in research and policy making. We identify three main strategies by which agricultural water management can deal with these large trade-offs: (a) improving water management practices on agricultural lands, (b) better linkage with management of downstream aquatic ecosystems, and (c) paying more attention to how water can be managed to create multifunctional agro-ecosystems. This can only be done if ecological landscape processes are better understood, and the values of ecosystem services other than food production are also recognized.

1. Water for ecosystems—a challenge for agricultural water management

Increases in agriculture over the last century have led to substantial improvements in global food security through higher and stabler food production. They have also contributed to economic growth in many countries. Agriculture, including rangelands, now covers roughly 40% of the world’s terrestrial surface (Foley et al., 2005), with croplands covering more than 50% of the land area in many river basins in Europe and India and more than 30% in the Americas, Europe and Asia (MA, 2005). Through the extent of land use, agriculture has become a main contributor to global environmental change (Foley et al., 2005). One of the major ways in which this takes place is through its interaction with water. Through changes in land use, land cover and irrigation, agriculture has substantially modified the global hydrological cycle in terms of both water quality and water quantity. For example, irrigation now comprises 66% of all water withdrawals (Scanlon et al., 2007) and accounts, by far, for the largest share of consumptive water use (Falkenmark and Lannerstad, 2005). This has caused substantial changes to river flow patterns, downstream coastal ecosystems and wetlands (Finlayson and D’Cruz, 2005; Agardy and Alder, 2005; Vörösmarty et al., 2005) and has led to river depletion affecting several large rivers around the world (Falkenmark and Lannerstad, 2005). Agriculture has also led to a redistribution of the spatial patterns of evapotranspiration globally, decreasing it in areas of large-scale deforestation and increasing it in many irrigated areas (Gordon et al., 2005), with impacts on climate and ecosystems in some regions (Gordon et al., 2008). Agriculture has further contributed to a doubling of nitrogen fixation (Galloway et al., 2004), and a tripling of phosphorus use (Bennett et al., 2001) at the global scale. Increased nutrient loading has caused widespread eutrophication and hypoxic zones (Diaz, 2001).

The ecosystem effects of these impacts can have large societal costs that are increasingly being felt on human well-being (MA, 2005). The effects include decline in downstream fisheries affecting small-scale as well as industrial fisheries; water quality declines with impact on drinking water and recreational values; and reduced water quantity leading to loss of wetlands and coastal ecosystems that can be important, for example, in nutrient retention and local livelihoods (MA, 2005). Some of the changes have negative feedback on the food and fiber production in agricultural systems themselves, for example through reductions in pollinators (Kremen et al., 2002) and degradation of land (Bossio et al., 2007). These adverse changes have varied in intensity, and some are seemingly irreversible, or at least difficult or expensive to reverse, such as the extensive dead zones in the Gulf of Mexico and the Baltic Sea (Dybas, 2005).

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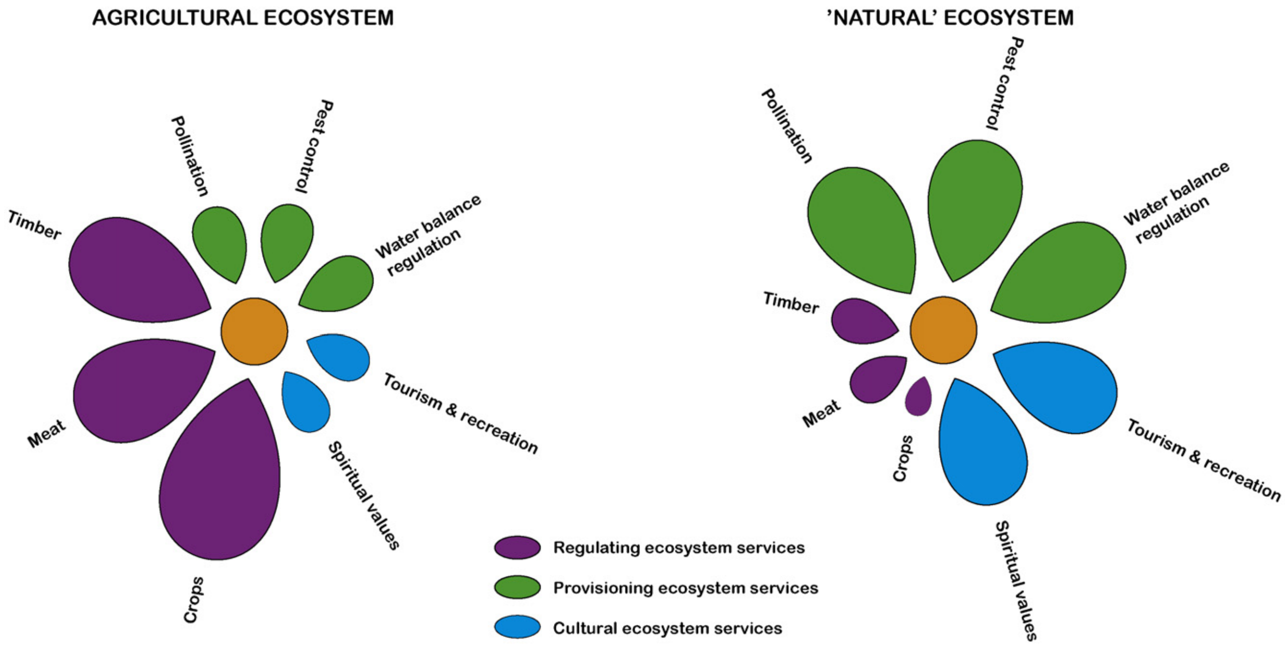


Fig. 1. Agriculture generally increases provisioning ecosystem services at the expense of regulating and cultural ecosystem services that are often higher in less human-dominated ecosystems.

Humanity is thus facing an enormous challenge in managing water quality and quantity to secure adequate food production without undermining the ecological life support systems on which human society also depends. Water management in agriculture is a key component in solving some of the most pressing trade-offs between an increase in agricultural production that can contribute to food security and economic growth on the one hand, and dealing with the losses of important ecosystem benefits that also sustain human well-being and livelihoods on the other.

Here we review the implications of changes of agriculture to the hydrological cycle on ecosystems and the benefits ecosystems generate for human society. We analyze changes across the hydrological cycle, i.e., in both terrestrial and aquatic systems. We particularly highlight emergent thinking on how to improve water management in agriculture to deal with the increasing trade-offs between food and other ecosystem services. Most reviews of these types of trade-offs have dealt with downstream ecosystem services. Therefore, we also include information on the upstream effects across terrestrial landscapes, and the solutions related to management of these landscapes. The analysis thus includes both alterations of the so-called"blue water" flows (surface runoff and groundwater) and "green water" flows (evaporation and transpiration).

2. Agriculture increases provisioning ecosystem services but reduces other ecosystem services

The relation between ecosystems and the well-being of human society was reviewed in the Millennium Ecosystem Assessment (the MA), a large assessment involving around 1400 scientists and researchers (MA, 2005). The benefits that ecosystems generate for society have been called ecosystem goods and services (Daily, 1997). In the Millennium Ecosystem Assessment ecosystem services were classified into four categories: (1) provisioning (which has been previously called ecosystem goods, and includes fuel, food and timber), (2) regulating (including climatic regulation, pest control and pollination), (3) cultural (including providing humans with recreational, spiritual and aesthetic values), and (4) supporting services (basic ecological properties/processes like soil formation) (MA, 2005). The water cycle provides the bloodstream of the biosphere that enables the generation of all these ecosystem services. Agricultural systems comprise one of the ecosystem types reviewed in the assessment; these are primarily managed to produce provisioning ecosystem services such as food, fuel and fiber with far less emphasis on the other categories of services. While agriculture increases provisioning ecosystem services, it unavoidably alters the structure and function of many ecosystem processes and often reduces regulating and cultural ecosystem services (Fig. 1). These changes often include reducing biodiversity and changing the distribution of plants and animals; mitigating climatic variability through water storage and irrigation; smoothing out landscape heterogeneity (e.g., through fertilization and plowing); changing nutrient and biomass cycling (altering harvesting cycles); and altering landscape interactions (like pollination). Understanding and managing these changes are the key to reducing trade-offs and finding synergies among ecosystem services (Kremen, 2005; Foley et al., 2005; MA, 2005).

3. Agricultural water management—past effects on ecosystem services

3.1. Effects on aquatic systems, coastal zones and wetlands

Streamflow reduction and regulation. Around 66% of all water withdrawn for direct human use is being used for agriculture (Scanlon et al., 2007). The better the irrigation efficiency the lesser the amount of this water that returns to the rivers and aquifers and the more the "consumptive use" will be, i.e., it flows to the atmosphere as evaporation or transpiration (Falkenmark and Lannerstad, 2005). Where field application efficiency is low (for example, in flooded paddy in the monsoonal season) most water returns to rivers or aquifers. Interbasin transfers of water between river systems can also further reduce downstream water availability in some basins. These changes have altered water regimes, with substantial declines in discharges (Meybeck and Ragu, 1997; Walling and Fang, 2003; Scanlon et al., 2007) and have transformed several of the world's largest rivers into highly stabilized and, in some cases, seasonally non-discharging channels (Snaddon et al., 1999). Streamflow depletion is a widespread phenomenon, especially in tropical and subtropical rivers and lake ecosystems with large-scale irrigation, including the Yellow (He et al., 2005), Indus, Nile, Ganges, Murray-Darling, Chao Phraya, Incomati and Rio Grande (Falkenmark and Lannerstad, 2005). At times, water management to support agriculture through these alterations has resulted in the loss of other important ecosystem services, including food production through fisheries, both inland and coastal (Kura et al., 2004).

Water regulation in wetlands. Wetlands are particularly challenging ecosystems in terms of agricultural water management. As different wetland types have different water regimes (e.g., flow sequences, depths and residence times) changes to the hydrology both nearby and much further afield can have major effects on at least some wetlands, including those dependent on groundwater as well as surface water and direct rainfall (Bullock and Acreman, 2003). Streamflow reduction and regulation can be a driver for wetland loss when they are dependent on runoff from upstream areas. Water regulation and drainage in wetlands can be a main cause of wetland habitat loss and degradation in groundwater- and rainfall-dependent wetlands (Revenga et al., 2000; Finlayson and D'Cruz, 2005). By 1985, drainage and conversion of wetlands, mainly for agriculture, had affected an estimated 56–65% of inland and coastal marshes in Europe and North America and 27% in Asia (OECD, 1996). Losses are particularly high in countries where extensive agriculture has been developed, exceeding 80–95% for some wetland types in specific regions (Dugan, 2005). Drainage of wetlands can reduce important regulating ecosystem services, with outcomes such as increased vulnerability to storms and flooding and further eutrophication of lakes and coastal waters (Dudgeon et al., 2005; Finlayson and D'Cruz, 2005; Verhoeven et al., 2006).

Water quality. Changes in water quality have occurred with inputs of nutrients, agrochemicals and siltation. The use of fertilizers has brought major benefits to agriculture, but has also led to widespread contamination and eutrophication of surface water and groundwater (Verhoeven et al., 2006). The flux of reactive nitrogen to the oceans has, for example, increased by nearly 80% from 1860 to 1990 (MA, 2005). Eutrophication is usually followed by a loss of ecosystem services, such as loss of recreational values and fish production through the development of algal blooms, anoxia and the decline of aquatic macrophytes and fisheries (Verhoeven et al., 2006). There is a risk that wetlands and lakes could suddenly switch from a state in which they retain nutrients to one in which they release nutrients or emit the greenhouse gas nitrous oxide, which has received increased attention (Gordon et al., 2008; Carpenter et al., 2005). Such shifts are often rapid, but they have likely followed a slower and difficult-to-detect change in ecosystem resilience.

3.2. Effects on terrestrial systems

Water table. Water can increase the height of the water table if the rate of recharge from rainfall or irrigation exceeds the rate of discharge from the aquifer. This can cause waterlogging and salinization, which have been extensively described for irrigated agriculture (Postel, 1999). Salt-affected soils in irrigation schemes are often related to poor soil and water management in addition to the unsuitability of many soils for irrigation. Less known is that clearing of woody vegetation for pastures and crops can also lead to salinization. Tree-covered landscapes can therefore provide an important regulating ecosystem service by consuming rainfall, limiting groundwater recharge, and keeping the groundwater low enough to prevent salt from being carried upward through the soil. Australia has had major problems with soil salinization since the native woody vegetation was cleared in the 1930s and subsequently for pastures and agricultural expansion (Farrington and Salama, 1996). Consumptive water use has declined, the water table has risen, and salt has moved into the surface soils so that large tracts of land have become less suitable—and even unusable—for agriculture (Anderies, 2005; Briggs and Taws, 2003). In Australia, green water flows (i.e., evapotranspiration) at a continental scale have been estimated to be reduced by 10% (Gordon et al., 2003). However, this phenomenon is largely unassessed outside of Australia and it remains an issue of discussion whether Australia is a special case.

Finlayson and D'Cruz (2005) comment on the issues of groundwater supply, use and quality that have on the whole received far less attention around the world than surface waters. Globally, knowledge of both groundwater resources and interactions with rivers and wetlands is limited as sufficient data, such as those covering groundwater discharge/recharge and aquifer properties, are only beginning to be obtained. While many wetlands overlie impermeable soils or rocks with little or no interaction with groundwater, numerous wetlands are fed largely by groundwater, and recharge of the aquifer occurs during flooding periods. It is well known though that many groundwater resources are vulnerable to a variety of threats, including overuse, whether from declining levels or from contamination. The consequences of groundwater mining on wetlands are often assumed to be severe, but in many places data are missing.

Vapor flow. The ability of changes in land use and land cover, driven to a large extent by agriculture, to influence climate through changes in evapotranspiration (green water flow) has been increasingly recognized. It has been suggested that large-scale deforestation can reduce vapor flows, with impacts on precipitation (Savenije, 1995), and alter the regional climate, with local to global impacts (Kabat et al., 2003; Nemani et al., 1996; Marland et al., 2003; Savenije, 1995). However, models employed to assess climatic implications of land use change seldom deal explicitly with evapotranspiration, but deal with the compounded effects of changes in albedo, surface wind, leaf area index and other indicators. Nevertheless, regional studies in West Africa (Zheng and Eltathir, 1998), the United States (Baron et al., 1998; Pielke et al., 1999) and East Asia (Fu, 2003) have illustrated that changes in land cover affect green water flows, with impacts on local and regional climates. There are indications that increased evapotranspiration through irrigation can alter local and global climates (Pielke et al., 1997; Chase et al., 1999; Boucher et al., 2004). There is increasing concern about the potential consequences of land cover changes for agriculture affecting the African and Asian monsoons, where changes in evapotranspiration constitute one of the driving forces (Fu, 2003; Zheng and Eltathir, 1998). Changes in monsoonal patterns can have dramatic impacts on people's livelihoods that are depending on monsoonal rains.

Water scarcity driving higher rates of land cover change. The need to expand land due to water scarcity on available land for food production might also result in trade-offs between food and other terrestrial ecosystem services. Rockström et al. (1999) estimated that over 5% of the current green water flow from tropical forests and savannas would need to be converted to food production by 2025. Rockstrom et al., 2007 did a similar, but more specific, estimation for the food needs in order to meet the Millennium Development Goals. They estimated that to meet the extra water needs—after considering both plausible improvements in water use efficiency and ecologically driven restrictions in irrigation expansion—a cropland expansion of 0.8% year^{-1}, i.e., a similar rate as over the past 50 years (0.65% year^{-1}), seems unavoidable. The Comprehensive Assessment scenarios included an agricultural expansion by 2050, ranging from 5% in the scenario with the lowest expansion (rain-fed, high yields) to 38% in the scenario with the highest expansion (rain-fed, low yields) (de Fraiture et al., 2007).

3.3. Emerging cross-cutting issues

Drawing upon the review of the above-mentioned agriculturally induced hydrological changes, we have picked out three areas that require more attention in research and policy making: (i) increasing risks of threshold effects and ecosystem regime shifts with irreversible losses; (ii) declines in agricultural productivity as a consequence of loss of ecosystem services; and ecosystem effects on (iii) poverty and (iv) health.

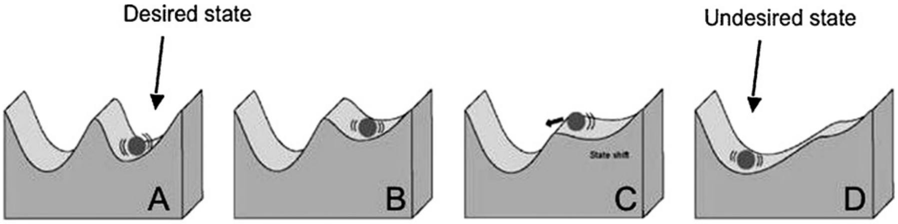
Increasing risks of ecosystem regime shifts. Some of the most catastrophic changes in ecosystem services are due to nonlinear, abrupt shifts between different ecosystem regimes (Scheffer et al., 2001) (Fig. 2). A regime shift in an ecosystem occurs when external forces or gradual internal changes alter the feedback that sustains major processes in an ecosystem so that its organization changes substantially. There will then follow major changes in the ecosystem functions and the services generated from the system. In ecosystems where regime shifts can occur, the system might be able to cope with, and absorb, changes over some time, but a substantial shift occurs once a threshold is passed (Scheffer et al., 2001). Phosphorus inputs to shallow lakes provide an example (Carpenter et al., 2005), where the inputs can have occurred over some time with only smaller changes to the behavior of the lake ecosystem and the fish outputs of the lake. However, phosphorus can be stored in the sediments of the lake, and if the smaller changes that the lake goes through cause oxygen levels at the bottom of the lake to drop this can trigger the sediments to release phosphorus. Suddenly, the phosphorus levels in the lake therefore increase rapidly, accelerating the reduction in oxygen levels and sustaining a higher level of phosphorus in the lake, despite the fact that the input of phosphorus to the lake has not increased. The lake becomes eutrophic, with lower levels of desired fish and reduced value for recreation.

Regime shifts are thus different from gradual changes, since there are thresholds by which bigger changes occur. It is often also difficult to go back once thresholds have been passed. For example, even if farmers decide to dramatically reduce the use of phosphorus in agriculture, the amount of stored phosphorus in the sediments can sustain the eutrophic state for a long time. In Fig. 2, three examples of regime shifts can be observed (adapted from Gordon et al., 2008). The first example illustrates an aquatic ecosystem shift, and the two other examples are terrestrial regime shifts.

Regime shifts, or the crossing of tipping points, are frequently surprising and difficult to reverse, presenting a substantial challenge to ecosystem management and development goals. A rapidly growing body of evidence suggests that agricultural modification of the quality and quantity of hydrological flows can increase the risk of ecological regime shifts (see examples in Fig. 2) in aquatic systems, the soil and land–atmosphere interactions (Gordon et al., 2008). This is important since the shift illustrates increased management costs necessary for restoration. After a regime shift has taken place, it is often more difficult and costlier to restore the system, since the internal feedbacks in the system have been substantially changed.

Loss of ecosystem services hitting back on agriculture. Some ecosystem services, such as pollination, are of importance to agriculture itself. As these decline, as a result of hydrological alterations by agricultural activities, they can have negative effects on agricultural productivity. Several of the impacts discussed above are related to the loss of agricultural production: soil salinization is an example where the regulating ecosystem service (of water table regulation) is compromised in a way that hits back on agriculture.

Poverty reduction. Ecosystem services play an extra important role in poverty reduction (Silvius et al., 2000; WRI et al., 2005). The Millennium Ecosystem Assessment concluded that a failure to tackle the decline in ecosystem services could seriously erode efforts to reduce rural poverty and social inequity and eradicate hunger; this is a critical issue in many regions, particularly in sub-Saharan Africa (WRI et al., 2005). Continued and increasing poverty can intensify pressure on ecosystems as many of the rural poor and other vulnerable people are left with no options but to overexploit the remaining natural resource base. The result is often a vicious circle in which environmental degradation and increased poverty are mutually enhancing forces (Silvius et al., 2003). Many rural poor rely on a variety of sources of income and subsistence



Clear water lake	phosporous leakage from agriculture, accumulate in soil/mud	flooding event, increased hypoxia	turbid lake
Australian farming on deforested woodlands	water table rise, mobilisation of salts	capillary rise and reduced production	salinised state - highly reduced productivity
Amazon rainforest	clearing of vegetation, reduced moisture recycling	prolonged dry seasons	savannization of the rainforest

Fig. 2. Three examples of ecological regime shifts. Many ecosystems can exhibit alternative stable regimes. In (A) the ecosystem is in one regime. As stresses to the system increases (B) the stability landscape can change and make the regime less stable. In (C) the stress increases further and/or is accompanied by external disturbances pushing the system across a threshold. In (D) the system has settled in a new stable regime, where it is very difficult, if at all possible, to go back to the previous regime even if the different stresses are removed (adapted from Gordon et al., 2008).

activities that are based on ecosystems and are thus most directly vulnerable to the loss of ecosystem services. These sources of income include small-scale farming and livestock rearing, fishing, hunting, and collecting fuelwood and other ecosystem products that may be sold for cash or used directly by households. Ecosystem services other than crop production can also be particularly important in times of crop failure. For example, it was found that after two seasons of consecutive droughts smallholder farmers in the Pare Mountains in Tanzania derived 18% of their direct food intake from other ecosystems than their harvest, and that 42% of the income they used to buy food came from activities based on other ecosystem services (such as charcoal making, handicrafts and selling of livestock) (Enfors and Gordon, 2008). Thus, using water management to improve the capacity to deal with drought should also consider these other ecosystem services, since they might be undermined by water-using activities if not explicitly dealt with.

Ecosystems and health. Many water-related diseases have been successfully controlled through water management whether specifically or by thoughtful approaches when supplying water for agriculture, but others have been exacerbated by the degradation of inland water through water pollution and changes in flow regimes mediated by increased agriculture (Coravalan et al., 2005). There are many instances where water management practices in agriculture have contributed to a decline in the human well-being and health (Finlayson and D'Cruz, 2005). The connection with agriculture may be indirect or indeed overridden by nonagricultural water management practices, but in many cases agricultural water management is part of the wider water management regime that predominates with interrelated activities and effects. In addition to disease from inland waters, waterborne pollutants from agriculture have a major effect on human health, often through their accumulation in the food chain. Many countries now experience problems with elevated levels of nitrates in groundwater from the large-scale use of organic and inorganic fertilizers. Excess nitrate in drinking water has been linked to methemoglobin anemia in infants. There is also increasing evidence that humans are at risk from a number of chemicals that mimic or block the natural functioning of hormones, interfering with natural bodily processes, including normal sexual development. More recently, attention has been directed to the health effects from the draining and burning of forested peat swamps in Southeast Asia that have had devastating health effects that extend across many countries and that may be long-lasting (Page et al., 2002).

4. Dealing with trade-offs and finding synergies between water for food and other ecosystem services

The need to produce more food globally and the vast negative effects of agriculture and altered hydrology on ecosystem services provide a major challenge for agricultural water management (Molden et al., 2007). The challenge is, in many circumstances, taken seriously at the international level, and in some cases steps are taken even to reverse the effects that have already occurred. The partial rehabilitation of some iconic symbols of past follies, such as the Aral Sea (Pala, 2006) and Mesopotamia marshes (Richardson et al., 2005), are examples of such efforts. However, despite much attention to the issue and the severity of the situation there is still a huge gap between what agronomists and hydrologists think is possible and what ecologists deem is necessary. Here we outline a few of the policy options and management approaches aimed at these problems in order to deal with potential trade-offs between food and other ecosystem services when necessary, and find synergies among these when possible.

4.1. Managing water at the field scale: increasing water productivity

An obvious way to reduce stresses that come from overuse of water in agriculture is to increase water productivity (Molden et al., 2007). The Comprehensive Assessment scenarios have shown that future water needs could be cut by more than 50% with increasing water productivity (de Fraiture et al., 2007). It has been suggested that the highest gains in water productivity can come from improvements in low-yielding agriculture when supplemental irrigation is combined with improved tillage and nutrient management (Rockstrom and Barron, 2007). Paying attention to trade-offs between water quantity (from improved productivity) and water quality (from, e.g., increased use of fertilizer and pesticides) is in these circumstances important. However, these are likely to be small in regions of low soil fertility and low fertilizer use, if fertilizer application is managed well.

4.2. Managing water between upstream and downstream water use

There has been much attention in the literature on how to deal with the consequences of upstream production of food on downstream aquatic ecosystems and wetlands. Determining how much water can be allocated to consumptive human uses without the loss of downstream ecosystem services is becoming a more common component of efforts to maintain and rehabilitate rivers and wetlands, including estuaries and other coastal ecosystems. One of the key concepts in this discussion is *environmental water flows* that refer to the quantity, seasonality and quality of water needed for protecting the structure and function of an aquatic ecosystem and its dependent species and services. Estimation of environmental flows should take into account the temporal differences in water requirements as well as the spatial variability. The allocation of an environmental flow is thus defined by the long-term availability of water, including the extent of temporal and spatial variability and identified ecosystem responses (Dyson et al., 2003). Such flows are often established through environmental, social and economic assessments (King et al., 2003; Dyson et al., 2003). This is often not a simple exercise, but requires in depth site-specific ecological and hydrological knowledge as well as increasing recognition that environmental and social impacts need to be integrated into the planning of environmental flows (Brown and Watson, 2007).

4.3. Managing water in landscapes for increased multifunctionality and resilience

Conventional commercial agriculture has tended to favor conversion of ecosystems into monocropping (or low diversity of crops) with management focusing on a single or a few provisioning ecosystem services, such as food, timber or fish. One reason is that many ecosystem services do not have a market price, are often neglected in decision making and not included in landscape management planning. Increased attention to ecosystem services supports efforts to emphasize multifunctionality (see Fig. 3). For agricultural systems this would imply that the system is managed for a larger set of ecosystem services, including provisioning, regulating and cultural services, of which regulating and cultural services seldom have a price on the market. It is thus important to map using economic, or other, terms, the values of all ecosystem benefits from these systems. For example, a review of investment in resource-conserving agriculture with attention to multiple goals across over 150 projects in developing countries showed that increasing yields could go hand-in-hand with reduced environmental impacts through increased water use efficiency, improved water quality and increased carbon sequestration (Pretty et al., 2006). This example showed that ecosystem-based

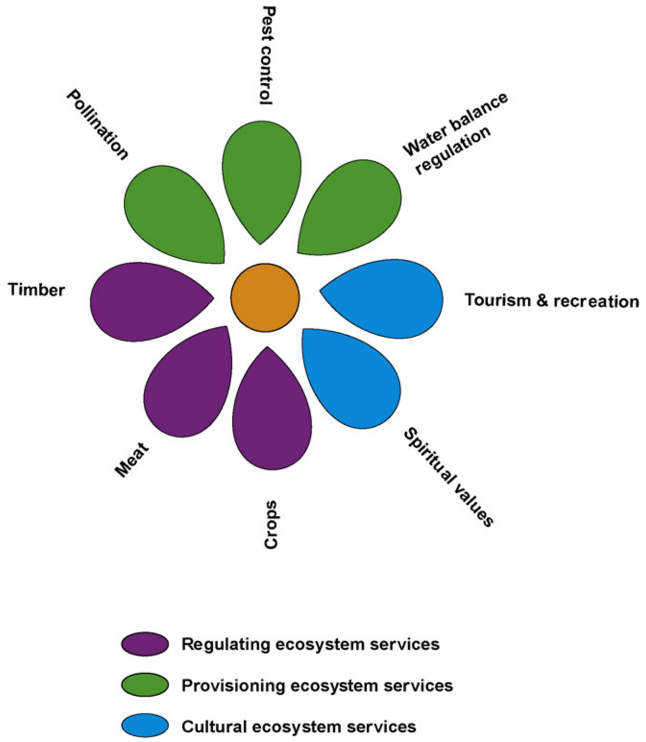


Fig. 3. Agricultural systems designed to produce multiple ecosystem services can increase synergies among these and therefore reduce the amount of trade-offs. Attention should be paid to provisioning, regulating and cultural services in this design.

approaches to water management need not constrain agricultural development, but can be points of convergence for policies that simultaneously address concerns for global food security, biodiversity conservation, and carbon sequestration.

The concept of multifunctional agriculture has long been practiced in many forms and requires approaches based on an ecological understanding of fragmentation and landscape heterogeneity (Cumming and Spiesman, 2006). Hydrological understanding is important. For example, it is possible to control insect outbreaks by timing irrigation events (Lansing, 1991) if the interactions between pest dynamics and hydrology are understood. Similarly, to optimize food production and avoid salinization in Australia, an understanding of hydrological heterogeneity across landscapes is important in order to understand in what particular parts of the landscape to plant trees that reduce vulnerability to waterlogging and salinization in other parts of the landscape (Anderies, 2005).

Biodiversity is important for securing multifunctionality as well as resilience. Whether an ecosystem is managed primarily for food production, water regulation, or for other services it is possible to secure these for the long term only if basic ecosystem functioning is maintained. Biodiversity is the variability and diversity within and among species, habitats and ecosystem services, and can be important in its own right and the ethical argument for conserving biodiversity for its own intrinsic value is often highlighted in projects aimed at conservation of endangered species (establishment of protected areas, changed land use practices) (Adams et al., 2004). However, it can act as an insurance mechanism by increasing ecosystem resilience (Holling et al., 1995; Tilman et al., 1997). Species that may seem redundant during some stages of ecosystem development may be critical for ecosystem reorganization after disturbance (Folke et al., 2004). Of all ecosystems, biodiversity decline is most severe in freshwater systems (MA, 2005).

Efforts to manage resilience have led to a shift from policies that aspire to control change in systems assumed to be stable to policies to manage the capacity of social-ecological systems to cope with, adapt to, and shape change (Berkes et al., 2003). Variability, disturbance and change are important components of an ecosystem. For example, when variability in river flows is altered, marked changes in ecosystem functions can be expected (Richter et al., 2003). Wetting and drying of soils can be important for the resilience of ecosystem functions, such as pest control and nutrient retention in wetlands. Exactly what level of variability to maintain and when variability is site-specific are areas of intense research (Richter et al., 2003).

5. Concluding discussion and policy lessons

While agriculture has generated many so-called “provisioning ecosystem services” such as food, fiber and timber, it has substantially altered water quality and water quantity in many places. These alterations have had large impacts on ecosystems and the other ecosystem services they generate and on which human society depends. We have highlighted that these impacts take place not only in downstream aquatic systems and wetlands. They also occur across the terrestrial landscape where vapor flows, changes in water table, and land cover change are important mechanisms. Some emerging issues that need more attention include how hydrological changes (driven by agriculture) can increase the risk of regime shifts in ecosystems, their impacts on agricultural production itself, and how they relate to poverty and health of the people.

Agricultural water management is a central entry point for minimizing trade-offs and finding synergies between food production and other ecosystem services. It is important to reduce negative impacts by improving management practices on already existing agricultural lands. We have identified three main strategies:

(1) The opportunity to improve management practices on agricultural lands to increase the efficiency with which water is used to produce food (i.e., water productivity), and to reduce water pollution including nutrient leakages. This can relieve some of the pressure from upstream water use on other ecosystems.
(2) The need to link agricultural water management and management of downstream aquatic systems in order to strike trade-offs, where necessary. Involving stakeholders who can negotiate unavoidable trade-offs between upstream food production and downstream ecosystem services is important in this process. There might be scope to reduce these trade-offs by paying more attention to how agriculture alters the dynamics (e.g., timing and variability) of water flows and how this can be better adapted to downstream ecosystem dynamics.
(3) Paying more attention to how water can be managed to create multifunctional agro-ecosystems can increase synergies among ecosystem services. This can only be done if ecological landscape processes are better understood, and the values of ecosystem services other than food production are recognized. Since most ecosystem services do not have a price on the market and are seldom part of current agricultural decision making, this requires a considerable shift in thinking.

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