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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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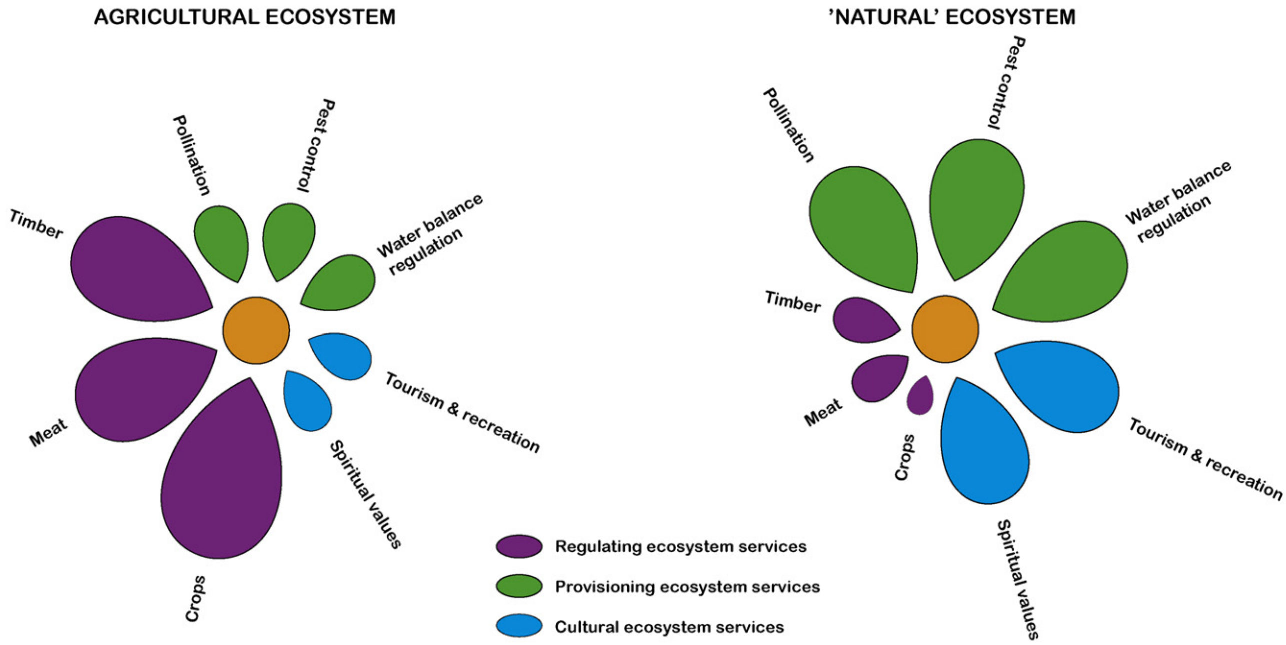

Fig. 1. Agriculture generally increases provisioning ecosystem services at the expense of regulating and cultural ecosystem services that are often higher in less human-dominated ecosystems.

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.,