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Ecological Processes, Functions and Ecosystem Services: Inextricable Linkages between Wetlands and Agricultural Systems

Onil Banerjee,[1] Neville D. Crossman[1] and Rudolf S. de Groot[2]

[1] CSIRO Ecosystem Sciences, Adelaide, Australia
[2] Environmental Systems Analysis Group, Wageningen University, The Netherlands

Abstract

Ecosystems contribute to human well-being via the provision of goods and services where the benefits are direct, such as in the production of food and raw materials, and indirect as is the case in the regulation of water quality and supply. Underpinning these services is a suite of ecological functions that must be understood in order to manage and enhance ecosystem services provision. For example, a healthy wetland that contains a biologically diverse array of producers and consumers purifies water, making freshwater available for irrigated agricultural production, which in turn provides food for human consumption. Making the link between function and service also enables us to identify threats to ecosystem services from unsustainable management practices. For example, the excessive use of chemicals in agricultural production affects water quality and threatens a wetland's functional capacity to purify water, consequently affecting food production. In this chapter, we identify the relationships between ecosystem function and ecosystem service. This linkage is a precursor to the estimation of ecosystem service values and understanding how changes in land and water management flow through to marginal changes in values. To contextualize this relationship, we consider specifically the services that wetlands provide in support of agricultural systems. We conclude with research challenges on managing complexity, resilience and trade-offs between ecosystem services and agriculture.

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Introduction

A critical challenge in the integration of ecosystem and economic science is the development of an operational classification of ecosystems and their functions which lends itself to the valuation of ecosystem services (de Groot et al., 2002; National Research Council, 2005). In the absence of either a political mandate to protect ecosystem integrity or a method of assigning value to ecosystem services for use in decision making, land use and development decisions will continue to be made without sufficient consideration for the important role ecosystems play in sustaining life (National Research Council, 2005; Daily et al., 2009). Furthermore, assigning monetary value to ecosystem services can aid in making environmental problems visible and thus inform decision processes (Wilson and Howarth, 2002; Spangenberg and Settele, 2010).

The provision of ecosystem services and subsequent benefit to humans is underpinned by a series of biophysical processes and ecological functions which themselves are driven by biological diversity (Balvanera et al., 2006). These linkages are highlighted in Fig. 2.1. Experiments have shown that increasing the amount of biological diversity has in most cases an increasingly positive effect on ecosystem function and service. For example, greater abundance of soil mycorrhiza and a higher rate of soil decomposer activity increases the rate of nutrient cycling, which is a regulating ecosystem service. A faster rate of nutrient cycling can be of direct benefit to humans if harnessed to increase agricultural productivity.

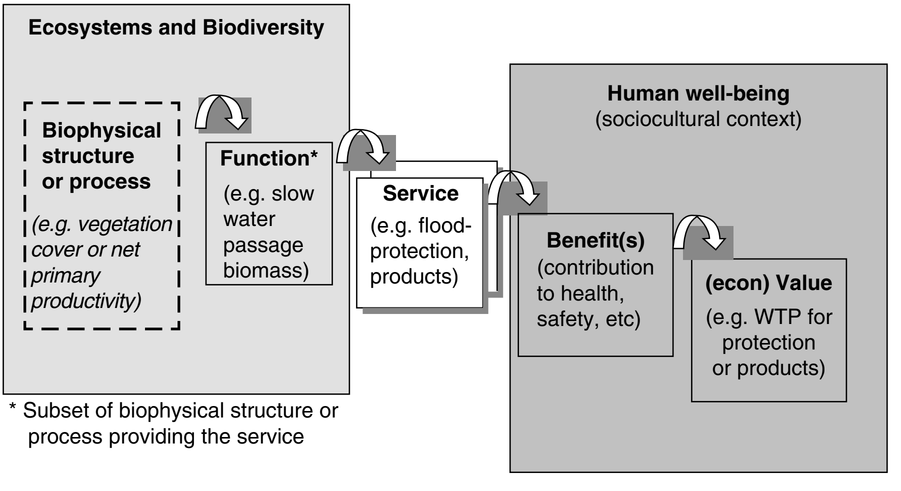

Fig. 2.1 The interdependencies of biological diversity, biophysical process, ecosystem function and service, human well-being, and willingness to pay (WTP). From de Groot, R.S., Alkemade, R., Braat, L., Hein, L. and Willemen, L. (2010). Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. *Ecological Complexity*, **7**, 260–272.

Agricultural commodities, valued in the market place, are just one of the ecosystem services agricultural systems produce. Ecosystem services have use and non-use values, and are valued using various methods. Non-use values include existence, bequest and altruistic values, or simply put – the knowledge that an ecosystem exists for us and for others now and in the future is valuable (National Research Council, 2005; Turner et al., 2008). Use values are categorized as direct and indirect. Direct-use values include timber production; a scenic lake may have recreational value which is captured by a management authority, or a home with a view of a natural and structurally diverse forest may fetch a better market price than a similar house without a scenic view. Ecosystems generate a multitude of indirect use values such as water filtration, nutrient retention and erosion mitigation. These values are less tangible than direct-use values and do not directly involve interaction between a beneficiary and the ecosystem (TEEB, 2010).

In this chapter we document the relationship between biological diversity, ecosystem function and service within agricultural systems. To guide the discussion, we focus on the interdependencies between agricultural production and the ecosystem services provided by freshwater wetlands (hereafter *wetlands*) and the impacts agricultural systems can have on the health and functioning of wetlands. We focus on wetlands because they are biologically complex yet relatively well understood, and critical to the provision of freshwater for agricultural use and human benefit. In the section that follows, ecosystem function and its linkages with ecosystem services are established. The ecological functions and subsequent ecosystem services generated by wetlands are defined and their interactions with agricultural systems are discussed in detail. We conclude the chapter with a discussion of the research challenges involved in managing complexity, resilience and trade-offs between ecosystem services and agriculture.

Linking ecosystem function with ecosystem service

Ecosystems directly contribute to human well-being via the provision of ecosystem services (Costanza et al., 1997; Daily, 1997; Millennium Ecosystem Assessment, 2003; Perrings, 2006; TEEB, 2010). The benefits provided by ecosystem services within agricultural systems are direct, such as food and raw materials, and indirect and include the regulation of water supply and quality and nutrient cycling example. Underpinning these services is a suite of ecological functions that must be understood in a first step to valuing, managing and enhancing ecosystem service provision. Importantly, a healthy and functioning wetland purifies water via biogeochemical and nutrient-retention processes, making freshwater available for irrigated agricultural production, which in turn provides food for human consumption. Making the link between function and service also enables us to identify threats to ecosystem services from unsustainable management practices. For example, agricultural run-off that follows from excessive pesticide or fertilizer use impedes biogeochemical and nutrient retention processes, threatening the ability of wetlands to purify water, which in turn threatens food production.

Ecosystem functions result from the interactions between characteristics, structures and processes (Turner et al., 2000) constituting the physical, chemical and biological exchanges and processes that contribute to the self-maintenance and self-renewal of an ecosystem (e.g. nutrient cycling and food-web interactions). Ecosystem functions involve interactions between biotic and abiotic system components in achieving any and all ecosystem outcomes (National Research Council, 2005). de Groot (1992) illustrates the link between ecosystem function and human benefit by defining function as the capacity of natural processes and components to provide goods and services that generate human utility. Linking ecosystem function to human benefit should encourage ecosystem-based management because of the monetary or non-monetary benefits provided by functionally diverse systems (Turner et al., 2008; Willemen et al., 2010).

Following the Millennium Ecosystem Assessment (Millennium Ecosystems Assessment, 2005), ecosystem functions may be conveniently grouped into four categories, namely: production, regulation, habitat and informational functions. Regulatory functions include gas and nutrient exchange, disturbance prevention, water regulation, soil retention and formation, waste treatment, pollination and biological control. Critical habitat functions are the provision of habitat and maintenance of biological diversity, while the production function includes the production of food and other raw materials such as medicinal, genetic and ornamental resources. Informational functions include aesthetic, recreational, cultural and spiritual functions.

Ecosystem function and their resulting services have an inherently spatial nature. Services may be created and the benefits enjoyed in situ. An example of this is the provision of habitat which may be used by animals that are subsequently hunted for recreation. Benefits may be omnidirectional where services are created in one location, though the benefits are spatially extensive, which is the case of the role of wetlands in sequestering carbon (Zedler and Kercher, 2005) and thus mitigating climate change – a benefit enjoyed globally. Finally, services may be directional, where a function occurs in one location, while the benefits are perceived directionally from that location due to the direction of flow. An example of this is the function riparian ecosystems serve in downstream flood control (Zedler and Kercher, 2005; Turner et al., 2008).

Wetlands

Wetlands are particularly diverse and productive ecosystems (Woodward and Wui, 2001; Zedler and Kercher, 2005) providing direct and indirect benefits at local, landscape and global scales (Acharya, 2000). Wetlands may be defined as areas exhibiting a temporary or permanent presence of water above or close to the soil surface and are maintained by waterlogging. Water is the primary factor affecting plant and animal life in these systems. Wetlands, although occupying less than 9% of the earth's terrestrial surface, contribute significantly in the provision of ecosystem services (Zedler and Kercher, 2005).

There are three major types of freshwater wetlands (Barbier et al., 1997): riverine, palustrine and lacustrine wetlands. Riverine wetlands are areas that are periodically flooded by a river rising above its banks and include water meadows, flooded forests and oxbow lakes. Palustrine wetlands are characterized by a mostly permanent presence of water and include ponds and kettle and volcanic crater lakes. Lacustrine wetlands are permanently inundated areas with minimal water flow. The following sections provide an overview of key wetland functions, linkages to ecosystem services and their relationship with agricultural systems.

Wetland functions

Wetlands provide regulation (hydrological and biogeochemical), production, habitat and informational functions. The hydrological aspects of a wetland are critical in defining their characteristics and processes (Maltby, 2009). Three principal hydrological functions of wetlands are floodwater detention, groundwater recharge/discharge and sediment retention (Turner et al., 2008). Table 2.1 describes the linkages between wetland function and ecosystem service, and presents metrics to assess the presence and level of service provision.

A wetland's hydrological function contributes to its high productivity through the capture and cycling of nutrients from upstream (Barbier et al., 1997). Wetlands reduce overbank flooding and slope run-off (Zedler and Kercher, 2005). By storing water, wetlands delay and reduce peak flows which could otherwise cause downstream flood damage. Wetlands may have significant interactions with groundwater where the substrate between the two is permeable. In these cases, wetlands may be involved in groundwater recharge and/or discharge of aquifers (Maltby, 2009). Finally, wetlands serve to retain sediments thereby alleviating downstream navigational problems, water treatment costs and damage to pumping infrastructure and spawning habitat.

The interaction of a wetland's biogeochemical function with hydrological functions enables interactions with surrounding wetlands (Mander et al., 2005). Specifically, biogeochemical functions of wetlands influence water quality, pollution control and biodiversity (Mander et al., 2005; Zedler and Kercher, 2005; Maltby, 2009). Oxidization and reduction processes in the soil are responsible for significant biogeochemical reactions. Wetland flooding results in oxygen depletion where, through time, organic substrates are consumed and oxygen, nitrates and other compounds are reduced. The inundation of floodplains facilitates nutrient exchange; these sites are also often important spawning grounds for fish.

The nutrient retention function of wetlands can affect water quality considerably, especially through the mitigation of incoming pollution. Nutrients and trace elements may be retained in plant structures or soil and organic matter (Mander et al., 2005), while nutrient export contributes to water quality maintenance and occurs through gaseous emission (Zedler, 2003), biomass harvest or erosion. Carbon is also retained in wetlands and is dependent on waterlogging, pH, nutrients and temperature. The level of pH and aerobic conditions in a wetland affects biodiversity in terms of the species and community assemblages possible. Organic carbon concentrations affect water turbidity and pH (Maltby, 2009).

With regards to habitat function, wetlands often support a disproportionately large amount of biodiversity, including a significant number of rare or endangered species. Efforts aimed at protecting wetlands are often driven by concern for their biodiversity (Zedler and Kercher, 2005). A higher level of species diversity is promoted by ecological disturbance that occurs as a consequence of wetting

Table 2.1 Wetland ecosystem function, service and indicator.

Ecosystem function	*Ecosystem service*	*Establishing presence*	*State indicator; sustainable yield*
Provisioning			
	Food	Fish, game, fruits and grains	Total or average stock (kg ha^{-1}) Net productivity (Kcal year^{-1})
	Water	Water storage for domestic/ industrial/ agricultural use	Total water (cubic m ha^{-1}) Net water inflow (m^{3} year^{-1})
	Fibre, fuel and other raw material	Biotic/ abiotic resources, e.g. peat, fodder, fuel wood	Total biomass (kg ha^{-1}) Net productivity (kg year^{-1})
	Genetic resources	Genes for pathogen resistance, ornamental species	Number of species Maximum sustainable harvest (kg ha^{-1})
	Biochemical and medicinal resources	Potential medicines and other biotic materials	Amount of useful substances (kg ha^{-1}) Maximum sustainable harvest (kg ha^{-1})
Regulating			
	Air quality	Capacity to extract atmospheric aerosols and chemicals	Leaf Area Index or NOx-fixation Quantity of aerosols/ chemicals extracted
	Climate	Influence on global and local climate	Greenhouse gas balance, carbon sequestration, land cover Quantity of GHGs fixed
	Water regulation	Groundwater recharge/ discharge	Surface or soil water retention capacity Quantity of water stored and influence of hydrological regime
	Waste treatment	Biotic and abiotic processes to remove excess nutrients/ pollutants	Denitrification (kg N ha^{-1} year^{-1}) Immobilization in plants and soil Maximum amount of waste recycled and influence on water and soil parameters
	Erosion protection	Soil and sediment retention	Root matrix Amount of soil/ sediment captured/ retained
	Soil formation and regeneration	Natural processes in soil formation and regeneration	Bioturbation
	Pollination	Habitat for pollinators	Number and impact of pollinating species

(*continued*)

Table 2.1 (*Cont'd*)

Ecosystem function	*Ecosystem service*	*Establishing presence*	*State indicator; sustainable yield*
	Biological regulation	Control of pests through trophic relations	Number and impact of pest-control species Reduction of disease and pests, and crop pollination dependence
	Natural hazard	Forests and dampening extreme events	Water storage in cubic meters Reduction of flood danger and prevention of infrastructure damage
Habitat			
	Nursery	Breeding, feeding and resting habitat	Number of species and individuals Ecological value
	Gene pool	Maintenance of ecological balance	Natural biodiversity; endemic species Habitat integrity
Information			
	Aesthetic	Structural diversity and other factors	Number/area of landscape features Number of sustainable users
	Recreational and inspirational	Landscape features	Number/area of landscape features Number of sustainable users
	Cultural	Culturally significant features	Number/area or presence of landscape features Number of users
	Spiritual	Spiritually significant features	Number/area or presence of landscape features Number of users

Sources: de Groot et al. (2002); de Groot et al. (2006); Food and Agriculture Organization (2008).

and drying cycles of wetlands. The production function of wetlands involves the conversion of energy, nutrients, water and gases into living biomass. This is a form of food-web support – the efficient primary production of biomass (Maltby, 2009). This function generates significant human utility through its production and provision of raw materials. Wetlands also serve an important function in maintaining habitat connectivity (Zedler, 2003; Mander et al., 2005; Tscharntke et al., 2005). Finally, information functions contribute to human cognitive, emotional and spiritual health, among other things.

Wetland–agricultural systems interactions

Agricultural systems rely on ecosystem services to enable the production of food, fibre, bioenergy and pharmaceuticals, and other important commodities. This present volume as well as recent research discuss in detail the ecosystem services on which agriculture depends (Porter et al., 2009; Power, 2010; Ribaudo et al., 2010; Sandhu et al., 2010a, 2010b, 2012). Approximately 20% of global agriculture depends on blue water (i.e. freshwater) extracted from surface water and groundwater resources and close to 70% of global water withdrawal is used for agricultural purposes (Comprehensive Assessment of Water Management in Agriculture, 2007). The water filtration service undertaken by wetlands is therefore critical to agricultural productivity.

In addition to ensuring adequate water quality and supply, wetlands provide agriculture with services related to pollination, biological pest control, maintenance of soil structure and fertility, and erosion mitigation. Wetlands mitigate floods and reduce floodwater peaks; they replenish stream flow through subsurface flow, contribute to water table recharge and, depending on their position in the landscape, wetlands may retain water from aquifer discharge (Food and Agriculture Organization, 2008). Wetlands and riparian areas influence microclimates of adjacent fields by regulating humidity and evapotranspiration, and serve in filtering often contaminated overland flow from intensively managed agricultural areas (Mander et al., 2005).

Various crops such as rice, corn, some vegetables and fruits are grown in, or in proximity to, wetlands. Activities such as fishing, livestock grazing and hay production are also conducted in or supported by these ecosystems. Soils in these areas are typically quite fertile with high clay content, particularly in seasonally inundated floodplains (Food and Agriculture Organization, 2008). Agricultural systems themselves produce ecosystem services (Tscharntke et al., 2005): they sequester carbon, regulate soil fertility, retain and cycle nutrients, and provide landscapes with aesthetic, cultural and spiritual values (Antle and Stoorvogel, 2006; Porter et al., 2009; Ribaudo et al., 2010). Wetlands support not only agriculture in these ways, but also agricultural communities, by providing potable water and adequate supply for hydroelectric power generation. Wetlands and agricultural systems are therefore inextricably linked as they provide agriculture with critical and valuable services.

Negative feedbacks, otherwise known as disservices (Power, 2010), created by agricultural systems have adverse impacts on wetlands through habitat deterioration, contamination of fisheries and spawning areas, biodiversity loss, run-off, sedimentation, greenhouse gas emissions and the release of toxins into the environment. The primary pathway by which agricultural systems affect wetlands is through the diversion of water for irrigation and nutrient loading of nitrogen and phosphorous (Millennium Ecosystems Assessment, 2005; Comprehensive Assessment of Water Management in Agriculture, 2007).

Irrigated agriculture in some regions has resulted in soil salinization, equating to a global loss of 1.5 million hectares of arable land per year. Furthermore, large quantities of salt from land salinization are transported into wetlands by irrigation run-off, having substantial impacts on biodiversity, productivity and biogeochemical composition in wetlands (Williams, 2001). Changes to water regimes can have devastating effects on wetlands and their regulating functions including those dependent on groundwater, surface water and direct rainfall. Wetland degradation may expose agricultural systems to increased vulnerability to storm, flood and eutrophication events.

The interactions between wetlands and agricultural systems may be characterized as in situ or external where the former constitutes an agricultural intervention within a wetland and the latter is an intervention that is upstream, downstream or peripheral to a wetland. In situ interactions may involve a substantial transformation of the wetland ecosystem or a more benign interaction. Significantly altering the ecosystem could involve drainage, grazing, ploughing or the application of pesticides and fertilizers. Fishing or the managed gathering of plants and animals is considered non-transformative, while enhancement can include manipulation of wetlands for agricultural or aquacultural purposes, including the creation of rice paddies, fish ponds and water storage areas (Food and Agriculture Organization, 2008).

External interactions are more common than direct wetland interventions. Upstream interactions can involve diversion of water to agriculture which may have water quantity, quality and flow effects to wetlands situated downstream. Return flows of diverted water will be lower in quantity and may contain substantial amounts of nutrients and toxins. Hydraulic gradients may also be created resulting in more rapid release of upland water and a lower watertable. Upstream agricultural practices that create erosion, sedimentation and runoff are detrimental to wetland ecosystems (Zedler and Kercher, 2005). Less common is the case where wetlands affect agricultural activity upstream through their capacity for water storage and sediment retention; should their capacity in this regard be compromised, upstream waterlogging of agricultural areas may result (Food and Agriculture Organization, 2008). Furthermore, these types of interactions are seldom confined to one agricultural production unit and wetland, rather these interactions typically occur and are compounded at the catchment scale.

Some research challenges

Understanding complexity and resilience

Ecosystems provide numerous goods and services, many of which have indirect value and are not traded in the market place. Our understanding of the ecosystem functions underpinning these services is limited, complicated by the spatial and temporal scales over which ecosystem services operate, and the interdependencies between ecosystem components and functions. Ecosystem functions are dynamic, exhibiting thresholds, complementary relationships to keystone processes, and system integrity and irreversibility (Turner et al., 2008). A threshold occurs where an ecosystem may cease to function or may function in an alternative undesirable state because one or more of its attributes are degraded beyond a specific level. Complementary relationships describe the interactions and interdependence of ecosystem components where the survival of one species depends on the existence of other species. These relationships have contributory value, which is a reflection of limited substitution possibilities. The notion of keystone processes describes system dependence on a limited number of ecosystem functions. A reduction in ecosystem diversity (e.g. structural or species diversity) can affect system resilience and adaptability to shocks. Ecosystem structure and function reflects the notion that the health of an ecosystem depends on system integrity and the whole functioning of the system.

Trade-offs

Management and planning for wetlands and agriculture should focus on enhancing multifunctionality where multiple ecosystem services are provided for human well-being and economic development. There is great potential to achieve synergies and win–win outcomes from effective planning and the development of economic incentives (DeFries and Rosenzweig, 2010; Gordon et al., 2010; Raudsepp-Hearne et al., 2010). However, the less desirable lose–lose or lose–win outcomes are commonplace due to trade-offs between services and agriculture production (Tallis et al., 2008; Gordon et al., 2010; Crossman et al., 2011). Trade-offs arise when provisioning services, especially agricultural production, seem to conflict with regulating, habitat and information services. Globally, most wetland ecosystems have been heavily modified to make way for food provisioning at the expense of other ecosystem services (Comprehensive Assessment of Water Management in Agriculture, 2007). The principle cause for the decline of ecosystem services other than provisioning services, and a major barrier to the evolution of multifunctional landscapes, is the lack of economic valuation of these services. Where the value of these services is not accounted for in decision-making frameworks, such as cost–benefit analysis, the importance of these services in support of agricultural production are overlooked and trade-offs may be made using poor information.

Management of wetlands and surrounding agricultural landscapes needs to account for the values of multiple ecosystem services (Carpenter et al., 2009). While there are an increasing number of examples of the creation of markets for ecosystem goods and services, including the provision of freshwater (Carroll et al., 2008; Bayon et al., 2009; Garrick et al., 2009), markets for most services are either absent or immature, leading to a lack of appropriate price signals for enhancing multifunctionality. Major challenges that lie ahead are the design of efficient markets for ecosystem service provision, and the development of strong institutions and regulatory instruments that underpin these markets. The goal is the sustainable growth of agricultural provisioning services without increasing the production of ecosystem disservices as these markets and institutions evolve.

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