7 Wetlands

Max Finlayson,[1*] Stuart W. Bunting,[2†] Malcolm Beveridge,[3] Rebecca E. Tharme[4] and Sophie Nguyen-Khoa[5]

[1] *Institute for Land, Water and Society (ILWS), Charles Sturt University, Albury, New South Wales, Australia;* [2] *Essex Sustainability Institute, University of Essex, Colchester, UK;* [3] *WorldFish, Lusaka, Zambia;* [4] *The Nature Conservancy (TNC), Buxton, UK;* [5] *World Water Council (WWC), Marseille, France*

Abstract

After commencing with a summary of the current status, importance and productivity of natural wetlands, the chapter reviews the contribution of wetland ecological functions to sustaining vital ecosystem services. Wetlands are vulnerable to a range of anthropogenic pressures, notably land use change, disruption to regional hydrological regimes as a result of abstraction and impoundment, pollution and excessive nutrient loading, the introduction of invasive species and overexploitation of biomass, plants and animals. Natural wetlands have often been modified to accommodate agricultural and aquaculture production, or wetlands may be created in the process of establishing farming systems. Prospects for established practices, such as culturing fish in rice fields, culture-based fisheries and integrating aquaculture with livestock production or into water storage and irrigation schemes are critically reviewed. Apparent conflicts between agricultural development and intensification and wetland conservation are discussed, and opportunities to reconcile competing demands are considered. Wetlands, whether classified as natural or as agroecosystems, sustain a wide range of ecosystem services that contribute to water and food security, but the appropriation of these services should be maintained with adequate provision for sustaining environmental stocks and flows and conserving and protecting aquatic biodiversity.

Background

Globally, wetlands[1] cover at least 6% of the earth's terrestrial surface (Finlayson and D'Cruz, 2005), of which substantively 200–280 million ha occur in Asia, followed by 125–130 million ha in Africa (Table 7.1). Common inland and coastal wetlands comprise lakes, rivers, marshlands, mangroves, estuaries and lagoons, and aquifer systems, through to shallow water coral reefs and seagrass beds. These ecosystems host a wealth of biodiversity and arguably account for about 45% of the total economic value of all global ecosystem

* E-mail: mfinlayson@csu.edu.au
† E-mail: swbunt@essex.ac.uk

Table 7.1. Estimates of global wetland area for the six geopolitical regions used by the Ramsar Convention on Wetlands (Ramsar Convention Secretariat, 2011).

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

services, although estimates vary (Millennium Ecosystem Assessment, 2005; see also the discussion on the valuing of ecosystem services in Chapters 3 and 4). The supply of fresh water to human populations is recognized as one of the foremost natural benefits of wetlands, coupled with the provision of those services that support food security and reduce rural poverty, such as capture fisheries and sustainable aquaculture (Millennium Ecosystem Assessment, 2005; Dugan *et al*., 2007). In many instances, though, the relative contributions of different wetlands types towards food production and food security have not been determined, or are highly variable, as found for wetlands in sub-Saharan Africa (Rebelo *et al*., 2010, 2011; McCartney *et al*., 2011b). Other important benefits associated with wetlands include base-flow releases during dry seasons, the capacity to provide off-season biomass (fish and crops) and their role as biodiversity hotspots – they often provide habitats for nationally or globally threatened species, though once again, the evidence base for all such benefits may not be that strong (e.g. McCartney *et al*., 2011a).

Wetland Ecosystem Services

For this book, the focus on wetlands is their role within the hydrological cycle, where they contribute towards a complex series of hydrological regulatory functions, including water storage (i.e. water holding, groundwater recharge and discharge, and flood prevention or attenuation by flow regulation and mitigation), water purification and the retention of nutrients and sediments (Millennium Ecosystem Assessment, 2005; Finlayson, 2011; Chapter 3). The quantity of water stored globally in wetlands amounts to about 11.5 thousand km^3 (Shiklomanov and Rodda, 2003). It is important to note that most of this is cycled through different wetlands. The elimination of wetlands, and thus the need to maintain hydrological flows to them, may be seen by some as freeing up water for human appropriation but, generally, it reduces the availability of water for direct human use.

Wetlands, notably river floodplains and some upper catchment palustrine wetlands (e.g. in the Andean páramo), are often regarded as functioning as natural sponges; they expand to accommodate excess water in times of heavy rain and contract as they release water slowly throughout the dry season, thereby maintaining streamflow (Millennium Ecosystem Assessment, 2005). In reality, the hydrological functions of most wetlands are more complex and vary considerably among sites (Bullock and Acreman, 2003; McCartney *et al*., 2010, 2011a). Inland wetlands, in particular, play a major role in providing water for agriculture (Falkenmark *et al*., 2007). For example, the Hadejia-Nguru wetlands in northern Nigeria play a major role in recharging aquifers that provide domestic water supplies to approximately a million people (Hollis *et al*., 1993).

The flood mitigation services of wetlands are particularly valuable, especially where they reduce flood risks to housing, industry and infrastructure. Policy and public sentiment in many countries is moving away from artificial flood control approaches (e.g. embankments) towards wetland rehabilitation because it is often cheaper and more sustainable. Male and female farmers are often integral to this process, either because they too have an interest in better flood protection of their assets, or through the receipt of incentives (compensation) from urban areas for reinstating flood protection on their farmlands and reverting to more traditional floodplain pasture cropping or grazing. In New Zealand, formal protection of the Whangamarino Wetland led to reduced costs for flood protection, while conserving water for irrigation during the dry season (Department of Conservation, 2007).

Natural wetlands have often been modified to accommodate agricultural and aquacultural production. Wetlands may also be created in the process of establishing farming systems in the form of storage reservoirs and fish ponds, for example; the resulting array of managed aquatic ecosystems are referred to collectively here as wetland agroecosystems. With agricultural expansion into wetlands, and the growing need to produce more food with less water, it is important that the functions of these agroecosystems are seriously considered and managed in terms of their contributions to ecosystem services (Falkenmark *et al*., 2007; Wood and van Halsema, 2008). Key ecological attributes or functions of wetlands, including sediment and nutrient transport and delivery into estuaries or on to river floodplains, generally enhance food production in downstream agroecosystems. Another important function of wetland agroecosystems is the treatment of wastes. This is facilitated by physical, biological and biochemical processes, but there are intrinsic limits to the waste-processing capabilities of wetlands. Aquatic ecosystems assimilate on average 80% of the global nitrogen load, but this intrinsic self-purification capacity varies widely and is declining as a result of the loss of wetland areas and overloading of the self-purification capacity (Millennium Ecosystem Assessment, 2005; Deegan *et al*., 2012).

The provision of ecosystem services by wetlands is often undervalued and assumed only to comprise fish catches. However, a wide array of other aquatic animals and plants from wetlands are exploited by various groups of people at various times, and often by the poor in times of need (WRI *et al*., 2008). Artificial water bodies and wetland agroecosystems also sustain a range of provisioning ecosystem services and, with the proliferation of water storage reservoirs for irrigation and electricity generation, are emerging as a major source of food and income in remote and highland areas (Welcomme *et al*., 2010).

The most common wetland agroecosystems are rice fields, the total area of which exceeds 125 million ha, and covers some 9% of the earth's arable land (Maclean *et al*., 2002). These continue to provide employment and staple food supplies for a large proportion of the rural poor in Asia. Of the total area planted with rice, just over half (55%) has been estimated to be under irrigation (Frei and Becker, 2005). These vital wetland agro-ecosystems support a wide range of biodiversity, including fish, amphibians and insects, and can play a significant role in the conservation of waterbird populations (Matsuno *et al*., 2002; Bellio *et al*., 2009; Elphick *et al*., 2010). The collection of fish and other aquatic animals by farming households and local communities for food and to sell can often constitute a major benefit of having access to inundated rice fields (Amilhat *et al*., 2009; see subsection below on 'Aquaculture in rice fields').

Such benefits may not be realized in intensively managed rice fields where the natural water regime has been altered and pesticide use is routine. Still, these fields also provide natural drainage systems and help in flood control, although in circumstances where wetlands have been converted to rice fields, there is little information about whether these benefits have been enhanced or have declined. There is also evidence that the construction of rice fields does not substitute for the biodiversity values that were previously obtained from lost or altered wetlands (Bellio *et al*., 2009; Elphick *et al*., 2010). Methane and nitrous oxide emissions from flooded rice fields are a significant source of anthropogenic greenhouse gas (GHG) emissions. In some instances, the value of rice fields as a supply of food has been increased by the addition of fish, particularly in

Asia (Xie *et al*., 2011). Studies indicate, however, that stocking fish in rice plots may promote methane production (Frei and Becker, 2005), thus exacerbating GHG emissions.

Wetlands in Tanzania are extensively used for rice farming in combination with cattle grazing, and in certain parts of the country these agroecosystems contribute up to 98% of household food intake (McCartney and van Koppen, 2004; McCartney *et al*., 2010). Many wetland agroecosystems provide multiple diverse options for meeting food security, especially for the people that are directly dependent upon them. Loss of these agroecosystems can have telling effects, not only on food supply, but also on the hydrological functions maintained by the wetlands.

Further, switching from one source of food to another within a wetland can have major implications for biodiversity, livelihoods and the distribution of benefits to people associated with one or the other activity, with both gains and losses, as shown by the case of Kolleru Lake in Andhra Pradesh, India and in the Testa, Brahmaputra and Padma river basins of Bangladesh (Nagabhatla *et al*., 2012a,b; Senaratna Sellamuttu *et al*., 2012). Starting in the early 1990s, the expansion of brackish water pond aquaculture in Thailand and Vietnam – at the expense of rice cultivation – has given rise to competing demands between both types of users, while causing dynamic changes in these wetland ecosystems (Szuster *et al*., 2003; Dung *et al*., 2009). In particular, the establishment of shrimp aquaculture has proven controversial; for example, in the coastal humid regions of South-east Asia and Latin America it has resulted in mangrove destruction on a large scale (Millennium Ecosystem Assessment, 2005). In places, shrimp culture is being developed further inland to counter disease problems; this should reduce conflicts with mangroves, but may result in other negative environmental and social impacts. Elsewhere, integrated land-based marine aquaculture systems have been developed to optimize production, make input use more efficient and minimize waste discharges (Box 7.1).

Wetland Vulnerability and Implications for Food and Water Security

Wetland ecosystems are particularly vulnerable to changes in water quality and quantity (volume, flow pattern and timing), as these may damage their physical, chemical and biological properties (Gregory *et al*., 2002; Alegria *et al*., 2006; UNEP, 2006; Cho, 2007; Tran Huu *et al*., 2009). Negative consequences for these ecosystems include river desiccation and functional fragmentation, groundwater depletion, water pollution and sedimentation, salinization and saltwater intrusion, soil erosion and nutrient depletion (Dugan *et al*., 2007; Atapattu and Kodituwakku, 2009). Consequences such as these induce declines in biodiversity and other undesirable changes in the biota, e.g. trophic imbalance or simplification and loss of genetic populations (Dudgeon *et al*., 2006). Problems relating to water imbalances in agroecosystems have dramatically changed the capacity of wetland ecosystems in the humid tropics to provide ecosystem services (Foley *et al*., 2005).

Despite the importance of agriculture within wetlands, agriculture has been a major driver of wetland loss worldwide, both through water use and direct conversion. By 1985, an estimated 56–65% of inland and coastal marshes (including small lakes and ponds) had

Box 7.1. Horizontally integrated land-based marine wetland agroecosystems.

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

been drained for intensive agriculture in Europe and North America, 27% in Asia, 6% in South America and 2% in Africa (Millennium Ecosystem Assessment, 2005). Where historical records have permitted assessment, the rates of loss were shown to be high, for example, Valiela *et al*. (2001) found that more than one third of mangroves (35%) had been lost in the two decades up to the late 1990s, mainly to aquaculture (13.3% to shrimp farming and 4.9% to fish farming), deforestation (9.1%) and to upstream water diversions (3.9%). Throughout much of Asia, coastal ecosystems were extensively converted to agriculture during the 1960–1970s under the guise of what later became known as the Green Revolution. Operations in south-west Bangladesh and in West Bengal, India, and the associated costal engineering works, established large agricultural areas susceptible to secondary aquaculture development. Destructive practices such as this undermined both the processes that support ecosystems and the provision of associated services essential for human well-being (Millennium Ecosystem Assessment, 2005; Hoanh *et al*., 2006; Molden, 2007; Atapattu and Kodituwakku, 2009).

Sub-Saharan Africa alone contains more than a million km^2 of wetlands, a large part of which are freshwater marshes and floodplains (Rebelo *et al*., 2010). Out of more than 500,000 km^2 of wetlands designated as Ramsar sites, an estimated 93% support fisheries or agriculture, and 71% are facing threats due to these activities (Rebelo *et al*., 2010). Indirectly, irrigation can threaten wetlands, not only by diverting fresh water, but also by reducing the capacity of rivers to transport nutrient-rich sediments that fertilize downstream wetlands and accrete to support the formation of new wetlands.

Excessive nutrient loading from fertilizers causes poor water quality and eutrophication of inland and coastal wetland systems (Lukatelich and McComb, 1986; Falconer, 2001; Molden, 2007; Deegan *et al*., 2012). Chilka Lagoon in Odisha (formerly Orissa), India, for example, is affected by anthropogenic stresses as a result of agricultural practices and drainage in the catchment, which affect the water quality of the lagoon (Panigrahi *et al*., 2007). Globally, in the coastal regions, agrochemical contamination is well documented to result in bioaccumulation and have dire consequences on the numerous and diverse species that reside or feed in wetlands (Atapattu and Kodituwakku, 2009).

While contemplating impacts on wetlands caused by agriculture, we must also acknowledge the importance of wetlands in sustaining agriculture (both crop cultivation and livestock farming) and fisheries in developing countries, and the important role that wetland agriculture fulfills for livelihoods (Wood and van Halsema, 2008; McCartney *et al*., 2010; Rebelo *et al*., 2010). One way of doing this is by emphasizing multiple ecosystem services of agricultural wetlands and their value for livelihoods. In higher income countries, there is increasing realization of the magnitude, extent and importance of wetland services that have been lost; the consequences of which are often felt first among the farmers themselves. For instance, wetlands in the prairies of Canada have undergone a drastic conversion to agricultural land, but many farmers now realize that they suffer from decreased water availability as a result and are moving towards wetland restoration, as mentioned in Canada's fourth national report to the Convention on Biodiversity (CBD).

Urban wastewater is often discharged without adequate treatment and can negatively affect receiving water bodies. The productive use of wastewater to culture fish and irrigate rice and vegetables in the East Kolkata Wetlands of West Bengal, India, serves as an interesting example, however, of how urban wastewater has been turned into an asset (McInnes, 2010; Bunting *et al*., 2011). Deliberate and planned use of wastewater for aquaculture was a feature of several large Asian cities, including Bangkok (Thailand), Hanoi and Ho Chi Minh (Vietnam) and Phnom Penh (Cambodia), but it has generally been phased out or lost owing to urban development (Little and Bunting, 2005; Bunting *et al*., 2006). Contemporary use of wastewater for aquaculture continues widely, but is predominantly informal or unintentional, while responsible authorities may be reluctant to acknowledge that such practices occur. The cultivation of aquatic vegetables continues in peri-urban wetland agroecosystems around many cities in South-east Asia, but inorganic and chemical pollutants affecting wastewater quality constitute a risk to public and environmental health. Health risks can be reduced in a multi-barrier approach, but this would first require recognition of the use of wastewater in aquaculture (WHO, 2006).

Globally, wetlands are further threatened by human-induced climate change and the associated extreme weather events. Findings presented in the third and fourth assessment reports of the Intergovernmental Panel on Climate Change (IPCC) confirm that the changing water cycle is central to most of the climate change-related shifts in ecosystems and human well-being (Pachauri and Reisinger, 2007). By 2050, climate change is anticipated to have had significant impacts on coastal wetlands, both through changes in hydrological regimes and sea level rise. Future use of water and land for agriculture will further constrain the ability of wetland systems to respond and adapt to climate change. Coupled with ever-increasing human pressures, such as high-density populations and their associated needs, wetlands and their ecosystem services are seriously threatened unless the issues are urgently addressed and managed effectively. Hence, when water resource issues are to be addressed in climate change analyses and climate policy formulations, changes in the water cycle have to be considered as important starting points for interventions. Climate change variability will increase the need for improved water storage, and the role of wetlands and other water-based ecosystems in this, and the increased risk to wetlands of this adaptation strategy should be recognized (McCartney and Smakhtin, 2010). In view of the importance of wetlands in delivering ecosystem services, including the achievement of water and food security, the implication of most climate change scenarios is that it is more urgent than ever to achieve better management of wetland ecosystems in order to sustain water supplies and the other ecosystem services that they provide (Le Quesne *et al*., 2010).

Fisheries and Aquaculture in Wetland Agroecosystems

Fisheries and aquaculture are very important sources of food from wetland systems. Fishing techniques and aquaculture practices have been developed to exploit most wetland types (UNEP, 2010). Both fisheries and aquaculture provide synergies with rice cultivation (see above) by increasing water productivity as well as biodiversity. Variability and diversity within and among species and habitats are important for supporting this aquatic ecosystem service, and for increasing resilience (Molden, 2007). Culture-based fisheries, and stocking fish and other aquatic organisms in water bodies to grow for harvest with little further intervention, have been established mainly in seasonal wetlands, lakes and reservoirs, including water bodies in upland and highland areas of South and South-east Asia (Xie *et al*., 2011). Often developed to sustain livelihoods in fishing communities and enhance food security in poor and vulnerable rural communities, culture-based fisheries have also been proposed to increase employment and income from tourism and angling, or to enhance food production to alleviate fishing pressure on wild stocks (Lorenzen *et al*., 2012). Fish stocking and subsequent harvest has been proposed to facilitate the bio-manipulation of water bodies to enhance water quality characteristics, with the notable objectives of reducing invasive macrophyte communities (as well as harmful mosquito populations), increasing water clarity or sequestering nutrients. Stocking juvenile fish, however, constitutes a major cost, and there are ecological, social and economic risks associated with culture-based fisheries (Gurung, 2002).

Interventions such as stocking fish and other aquatic organisms in many wetlands have blurred the difference between capture fisheries, actions constituting fisheries enhancement and aquaculture. A systematic assessment of culture-based fisheries as an emerging aquatic resource management strategy has been undertaken by Lorenzen *et al*. (2012). According to Gurung (2002) carp have been stocked in several lakes in upland areas of Nepal to enhance production and reduce fishing pressure on ‘thinly populated native species’, while safeguarding employment and income for traditional fishing communities ‘until measures for conservation practices of locally vulnerable species are developed’.

Inland capture fisheries landings, including fish, molluscs, crustaceans and other aquatic animals exceeded 11.2 million t in 2010, with the majority in Asia (68.7%), followed by Africa (22.9%), the Americas (4.9%), Europe (3.5%) and Oceania (0.1%) (FAO, 2012). Other assessments of small-scale fisheries in developing countries alone suggest that landings are even more significant in those countries, with an estimated 14 million t caught annually (Mills *et al*., 2010). These catches provide food and livelihoods for 60.4 million people, 33 million of whom are women (UNEP, 2010). A wide range of aquatic ecosystems are important for fisheries, perhaps the most obvious being those where fish and other aquatic animals are caught. Breeding and nursery sites, which may be quite distant from fishing areas, also play a critical role in the life cycles of exploited stocks, and these could be managed better in the wider landscape of agroecosystems (Dugan *et al*., 2007). Similarly, terrestrial ecosystems and catchment land use practices influence the hydrology and quality characteristics of water resources, which, in turn, are critically important in governing the types of species that can survive in certain habitats (Welcomme *et al*., 2010). Stocking aquatic animals in predominantly wetland agroecosystems, with interconnected field and pond systems, may make a significant contribution to food security and nutrition in farming households and local communities (Xie *et al*., 2011). Appropriate management and governance arrangements are required to ensure that costs and benefits are distributed equitably, and that any proposed changes in access arrangements consider the needs of poor and landless groups (FAO, 2010).

Aquaculture development and fisheries depend on the appropriation of various environmental services from aquatic ecosystems; these include clean and oxygenated water for physical support and respiration, inputs of seed, feed and detritus, waste removal, nutrient assimilation and carbon sequestration (Beveridge *et al*., 1997). The failure of many apparently promising aquaculture ventures has occurred when the capacity of ecosystems to meet the cumulative demand for environmental goods and services from rapidly growing numbers of farms and culture units has been exceeded (Bostock *et al*., 2010). An example is the proliferation of cage-based aquaculture in the Saguling Reservoir, Indonesia, where self-pollution was implicated in causing massive fish kills (Hart *et al*., 2002). Early assessments of the appropriation of environmental goods and services by aquaculture systems intimated that the ecological footprints (expressed as m^2 supporting ecosystem/m^2 culture facility),[2] were larger for more intensive production systems (Berg *et al*., 1996; Folke *et al*., 1998). Subsequent reassessment, however, showed that some goods and services were used more efficiently in the intensive production systems than in semi-intensive systems (Bunting, 2001). While expressing ecological footprints per unit area of production system helps to visualize the dependence on the ecosystem support area, assessment per unit of production permits a more rational appraisal of alternative management strategies for the same culture area.

Constructing big dams and the extensive development of small-to-medium sized structures for hydroelectric power has had widespread negative ecological and social impacts. Notable ecological impacts include: immediate devastation wrought on inundated aquatic ecosystems; impacts on downstream wetlands and wetland agroecosystems; and disruption to connectivity and environmental flows between ecosystems. Dam construction may result in fertile land used for cereal crop production being inundated, so threatening food security; even when higher value products can be caught from new water bodies or extracted from forests, the equilibrium of survival may mean that people are unable to buy sufficient staple foods to meet their needs. Added pressure on forest resources affects catchment dynamics, and the lure of valuable harvests may attract migrant fishers with the skills and technology to catch fish in deep lakes, and consequently result in potential benefits not reaching local communities (Nguyen Thi *et al*., 2010).

Water management in humid agroecosystems often involves multiple uses of water and can be further enhanced by considering the whole range of ecosystem services through a gender-sensitive approach. Some good examples are the integration of aquaculture into various agroecosystems, such as livestock–aquaculture integration, rice–fish culture, aquaculture in irrigation reservoirs and water management schemes, and wastewater-fed aquaculture. Evaluation of the full range of provisioning ecosystem services from aquatic ecosystems, not only fish, is vital if the true value of wetlands and wetland agroecosystems in the livelihoods of men and women, and in local and national economies, is to be accounted for and safeguarded.

The current appropriation of aquatic ecosystem services is often not sustainable; this is the case with fishing in most waterways and wetlands, and with the majority of semi-intensive and intensive aquaculture production around the world. As with the assessment of marine capture fisheries, there must be concern over introducing shifting baselines (Pauly, 1995), and setting overly generous limits or inappropriate conservation goals. It is critical to maintain a balance between fisheries – often the most obvious benefit derived from aquatic ecosystems – and the continued provision of stocks and flows of other ecosystem services, as these may actually benefit more people and make a more significant contribution to the well-being and resilience of poor women and men, marginal groups, local communities or regional populations (Welcomme *et al*., 2010). Moreover, assessment and allocation of water resources must also account for environmental water requirements (Gichuki *et al*., 2009).

Integration of Aquaculture in Agroecosystems

Livestock, agriculture, horticulture, aquaculture and fisheries production have been closely integrated in iconic farming systems for hundreds of years. Examples include: dyke pond farming in the Pearl River Delta in Guangdong Province and rice–fish culture in Zhejiang Province, China; canal dyke culture in Thailand and Vietnam; *chinampa* cultivation (growing crops on artificial islands in shallow lake beds) in Mexico; and taro cultivation with fish ponds in Hawaiian *apupua'a* agroecosystems (an *apupua'a* is a designated subdivision of a Hawaiian island) (Beveridge and Little, 2002). Several of these traditional systems have virtually disappeared and most are now under immense pressure to change, owing to greater concentration on high-value, cash crop production supported by external technology (formulated feeds, inorganic fertilizers, agrochemicals, mechanical pumps, aerators and filters, and agricultural machinery). Such intensification of production is often precipitated by the need to increase economic returns from land holdings that have significantly appreciated in value over recent years.

Globalization and the expansion of international trade are major driving forces that are exerting pressure to convert natural wetlands and intensify production in wetland agroecosystems (see Chapter 2). Consequently, trade-based mechanisms such as product certification and ecolabelling might be considered to counter such forces. Fundamental reform may be required, however, to shift aquaculture towards a more sustainable development pathway. Authorities should remove subsidies for unsustainable practices, force producers to account for negative environmental costs and promote the adoption of better management practices. Semi-intensive pond-based fish production that depends on organic and, increasingly, inorganic fertilizer to stimulate the natural production of food to supplement low-cost feeds with modest protein contents remains widespread in China and throughout much of Asia. Prevailing market forces could conceivably compel producers to opt for intensive production that would be totally dependent on high-protein formulated feeds. This would result in the loss of ecosystem services associated with semi-intensive production, notably the managed disposal of large volumes of organic waste, including manure, and agricultural and food processing by-products.

Promising approaches to productive multiple use of water resources that persist include rice–fish farming and the integration of aquaculture and culture-based fisheries in reservoirs, and these are discussed further below. Negative environmental externalities associated with intensive farming become more apparent as the full cost of external feed, fertilizer, fuel and technology inputs are accounted for in cost–benefit or life-cycle assessments (Hall *et al*., 2011). Together, these are likely to influence policy making and consumer attitudes, and may signal a renascence for traditional resource-efficient and conserving farming systems. Therefore, it is important to preserve knowledge and, ideally, examples of such integrated systems to guide and inform emerging ecocultures. Conditions, constraints and water use efficiencies in various aquaculture-based agro-ecosystem combinations are summarized in Table 7.2.

Table 7.2. Integration of aquaculture practices with other activities to optimize efficiency and increase water productivity (adapted from Bunting, 2013).

Management practices	Constraints and conditions	Potential water use efficiency outcomes
	Livestock–aquaculture	
• Ducks and geese foraging on ponds • Wildfowl and poultry housed over fish ponds • Waste from pigs and cattle directed to fish ponds for treatment and nutrient recycling • Plant and fish biomass cultivated using solid and liquid waste fed to livestock	• Possible pathogen and disease transfers within integrated systems • Chemical treatments and dietary supplements for livestock may affect production and accumulate in aquaculture components • Excessive waste loadings or perturbations affecting the ecological balance of the pond can result in low oxygen levels and fish health problems and mortality	• Multiple products from ponds and lakes with lower water footprints • Enhanced environmental protection of receiving water through better on-farm waste management and nutrient recycling • Aquaculture of biomass and fodder crops helps to avoid public health risks and consumer acceptance of aquatic products grown using waste resources
	Aquaculture in irrigation and water management schemes	
• Fish cages in irrigation channels in India and Sri Lanka • Culture-based fisheries in domestic supply and irrigation reservoirs • Aquaculture in traditional irrigation structures within microcatchments in Sri Lanka • Fish culture in irrigated rice fields and farmer-managed systems in Africa and Asia	• Excessive flow rates can have an impact on animal welfare and make food unavailable • Debris can block mesh, reducing flow rates and causing physical damage to fish cages • Management must balance irrigation and aquaculture demands • New structures may be needed to sustain fish populations during low water periods • Agrochemicals in extended irrigation systems and adjacent areas can affect aquaculture productivity and may constitute a public health concern	• Nature of aquaculture means water is conserved, potentially with higher nutrient content, thus enhancing crop production • Aquatic species may predate upon disease vectors, crop pests and weeds • Integration of aquaculture activities may enhance nutrient cycling and uptake by plants under irrigation

Management practices	Constraints and conditions	Potential water use efficiency outcomes
	Aquaculture in water storage reservoirs	
• Fish cages in reservoirs for hydroelectric power generation • Culture-based fisheries in water storage and hydroelectric reservoirs • Polyculture in urban and peri-urban water bodies, primarily for floodwater discharge and amenity	• Inappropriate reservoir bed preparation, presence of submerged structures (including downed trees) and routine drop down may reduce the area suited to aquaculture development • Rapid drop down may damage physical cage structures • Changes in access and use rights associated with aquaculture development may cause social problems	• Multiple use of water in reservoirs could contribute to increased revenue generation and alternative livelihoods for displaced or marginal communities • Appropriate species selection for aquaculture could contribute to weed control and enhance water quality in reservoirs
	Aquaculture in saline drainage and wastewater	
• Aquaculture in saline groundwater evaporation basins in Australia • Fish culture in saline wastewater from industrial processes and desalinization	• Variation in salinity levels and possible extremes may constrain species selection or culture duration • Low production rates as compared with prevailing commercial operations suggest need for further assessment of financial and economic attributes	• Exploitation of saline water resources through integration of aquaculture can contribute to overall farm productivity and generate new income streams • Economic benefits of integrating aquaculture, salt-tolerant crop production and salt harvesting could help offset costs of controlling saline groundwater problems
	Aquaculture in thermal effluents and cooling water	
• Production of juvenile fish in cooling water effluents from nuclear power stations in France • Farming marine worms in thermal effluents in the UK	• Chemicals used to clean power stations and variations in water temperature may affect growth and product quality • Farming species for human consumption may pose unacceptable health risks or not gain consumer acceptance	• Retention of thermal effluents for aquaculture production can facilitate heat dissipation and contribute to meeting statutory discharge standards • Exploitation of thermal effluents can help to avoid greenhouse gas emissions associated with heating water for culturing cold-intolerant species

Continued

Table 7.2. Continued

Management practices	Constraints and conditions	Potential water use efficiency outcomes
Urban and peri-urban aquaculture		
• Fish cages in canals and lakes in Bangladesh and Vietnam • Fish culture in canals, lakes, ponds and borrow pits in peri-urban areas throughout Asia • Macrophyte cultivation in drainage canals and low-lying water bodies, e.g. Bangkok (Thailand), Hanoi (Vietnam), Phnom Penh (Cambodia) • Aquaculture exploiting food and drink production and processing by-products	• Multiple use of urban and peri-urban water bodies may mean hydrology is out of the control of aquaculture producers and associated operational constraints result in suboptimal management • Risks from pollution and poaching may constrain aquaculture development • Insecure land tenure and pressure from urban residential and industrial development may constrain investment in aquaculture systems	• Floodwater storage and groundwater recharge associated with extensive wastewater-fed aquaculture operations can contribute to stabilizing local hydrological conditions • Vigilance of aquaculture producers helps in monitoring pollution and safeguarding water quality for other users
Aquaculture in multi-purpose household ponds		
• Fish culture in small ponds used primarily for domestic and agricultural purposes • Composite fish culture in rainwater harvesting structures	• Introduction of aquaculture can cause conflicts with other agricultural and domestic uses of household ponds • Inclusion of aquaculture in rainwater harvesting ponds may constrain the use of water use for other crops and incur financial risks	• Appropriate integration of aquaculture into household ponds can contribute to food security and livelihood outcomes without reducing water availability for other purposes • Aquaculture in ponds can help reduce pressure on the provisioning ecosystems services of natural water bodies
Wastewater-fed aquaculture		
• Intentional use of wastewater to supply water and nutrients for aquaculture • Lagoon-based sewage treatment systems incorporating fish ponds developed under the Ganges Action Plan initiative, India • Fish culture in 3900 ha of ponds in the East Kolkata Wetlands, West Bengal, India • Duckweed cultivation on wastewater in the UK for processing to biofuel	• Health risks posed by wastewater use for aquaculture demand that appropriate treatment and control measures are adopted • Consumer perceptions, prevailing beliefs and institutional barriers may constrain development • Land area required for combined wastewater treatment and reuse through aquaculture may prohibit development	• Management of wastewater promoted by integration of aquaculture can help operators meet statutory discharge standards and help safeguard public health • Wastewater reuse through aquaculture can help protect the quality of water bodies receiving discharge from the system • Exploitation of wastewater flows for biomass production could help alleviate pressure on freshwater resources

Aquaculture in rice fields

A special case of integrated aquaculture that has a long tradition is fish culture in rice fields. In the discussion of wetlands it is also important to recognize the synergies between fisheries and rice cultivation as practised in South-east Asia and elsewhere. These practices may create agroecosystems that have higher biodiversity and increased water productivity, although there are examples where biodiversity declines (Bellio *et al.*, 2009). For example, the conversion of traditional deep water rice cultivation on floodplains in Asia to irrigated systems planted with high-yielding varieties has been implicated in the loss of both aquatic biodiversity and indigenous rice varieties. Culturing fish in rice fields can help to control pests and weeds, promote nutrient availability to rice plants and increase nutritional benefits and financial returns from what are widely regarded as low input, environmentally friendly and more sustainable farming systems. Integrating fish culture into irrigated and rain-fed rice fields also makes more effective use of appropriated water resources.

The culture of fish in rice fields has been traditionally practised in China, Japan and Java (Indonesia); more recently, rice–fish culture has been introduced by development agencies and extension services to many countries in Asia and to a growing number in Africa. However, integrated culture of rice and fish requires refined farm management approaches to coordinate rice production and fish culture practices, with increased dependency on reliable water supplies. Often, lack of this expertise, combined with poor market linkages (unreliable fish seed production, and poor infrastructure for distribution of harvested fish) has constrained widespread and long-lasting adoption. Where rice–fish culture has been adopted widely, e.g. in north-east Thailand and West Java, it has made an important contribution to incomes and food security in poor and marginal farming communities. Perceived declines in the availability of wild fish and well-developed trading networks for fish seed from private hatcheries have stimulated the adoption of rice–fish culture in north-east Thailand. Paddy fields can also be used as nurseries for fingerlings, and these can be sold to stock ponds; such strategies have great potential in facilitating the decentralization of fish seed supply and promoting aquaculture development.

Low-input rice–fish culture could be a viable alternative, measured in conventional financial terms and based on standard risk assessment criteria, as farmers face increasing bills for fertilizers and pesticides to maintain yields in high-input, irrigated, monoculture rice production. Farmers should be supported in assessing their prospects for adopting rice–fish culture and, where demand exists, action should be taken to ensure a functional enabling institutional environment. The successful development of rice–fish culture has been attributed to: the adaptation of traditional water management approaches to accommodate fish culture; appropriate extension services, training and capacity building; and access to quality fish seed of the appropriate species.

Aquaculture in irrigation systems

New capture fisheries are often cited as a secondary benefit associated with reservoirs developed for irrigation purposes, but the timely colonization by species suited to reservoir conditions and valued by fishermen is not guaranteed. Furthermore, unrestricted and unregulated fishing could limit the establishment of a substantial, self-reproducing stock of desirable species (Munro *et al.*, 1990). Consequently, establishing a culture-based fishery, or fish culture in pens or cages, may be proposed as alternative solutions (Lorenzen *et al.*, 2012). The infrastructure to support culture-based fisheries, including hatcheries, is often commissioned as part of reservoir construction projects, with fishing rights being leased out to local groups. The construction of pens and cages can be used to partition the available water resource, potentially enabling displaced or landless peoples to gain some form of employment and security; then again, the costs of constructing and stocking such structures can be prohibitive, often leading to rich individuals and commercial enterprises dominating the available resources (Beveridge, 2004). Smaller cages can be deployed in irrigation canals, but flow rates and regimes must be suitable and the requirements of cage operators must be considered in the overall planning and management of the irrigation system.

Rapid uncontrollable expansion of aquaculture in larger irrigation reservoirs can result in access to fishing grounds and navigational routes being disrupted and this, in turn, can lead to social tension and an inequitable flow of benefits that tends to be of advantage to the more affluent sections of society (Beveridge and Phillips, 1993). Drawdown and the presence of submerged trees can restrict the area available for the development of cage-based aquaculture (Table 7.2). Rapid drawdown can cause physical damage to cages and lead to upwelling of deoxygenated water from the hypolimnion, which can cause mortalities in overlying fish cages (e.g. Lake Sampaloc, Philippines). Fluctuating water levels can be a serious problem for both fish production and fisheries, as well as for cage aquaculture, in reservoirs used for irrigation and hydroelectric power generation. The uncontrolled development of aquaculture and associated waste discharges can lead to deterioration of water quality, reducing ecosystem services (drinking water, fish) and posing problems for downstream water users (Beveridge and Stewart, 1998). A strong environmental policy and appropriate governance arrangements, including the implementation of adaptive management, are needed to ensure that cage development delivers the anticipated economic, social and food security benefits.

Wetlands Assessment and Management

Wetlands contain biodiversity of exceptional conservation significance and support many unique ecosystems and a wide array of globally threatened species. At the same time, they typically form an essential component of local, national and even regional economies, as well as underpinning the livelihoods of many rural communities. Yet, despite their importance, they are under increasing pressure. Often, wetlands and wetland agroecosystems have been managed in isolation – disconnected physically and in policy making and planning from the associated river basin system. Weak consideration of wetlands in decision making remains one of the major factors leading to their degradation (Horwitz and Finlayson, 2011). Management decisions affecting wetlands rarely consider the wider biological, ecological, developmental or economic values of wetlands, as they are challenging and costly to assess.

Various agricultural practices can be advocated that promote the wise use of wetland ecosystems while ensuring sustainable development. Ecosystem analysis must be integrated with assessments of associated livelihood strategies if resulting management plans are to gain broad-based support and address the underlying pressures and unsustainable use practices. Knowledge of the interconnectedness of wetlands and fisheries provides valuable examples in this regard (e.g. Smith *et al*., 2005).

The adoption of strategies (i.e. of the relevant provisions of the CBD and Ramsar Convention) that work towards the environmental management of these ecosystems would link environmental stewardship directly to poverty alleviation, food security and the quality of water in wetlands (Millennium Ecosystem Assessment, 2005). Food production practices and wetland management plans should be jointly assessed by concerned stakeholder groups, and measures taken to ensure that the demands placed on the environment are within acceptable limits (see Box 7.2). Such assessments should be conducted with groups that have been disaggregated on the basis of wealth, gender and generation to account for differences in needs and priorities, otherwise the outcomes risk further disadvantaging poor and vulnerable groups and, ultimately, undermining conservation and management initiatives (see Box 7.3). Alternative approaches include a combination of limited data collection and modelling – instead of full-scale assessments – to develop options for wetland management (Cools *et al*., 2012, 2013; Johnston *et al*., 2013).

If better management is sought, the development, assessment and diffusion of applicable technologies that increase the production of food per unit of water, without

Box 7.2. Integrated wetland assessment in Cambodia and Tanzania.

The International Union for Conservation of Nature (IUCN) has developed a toolkit of methodologies for assessing the value of wetland biodiversity to livelihoods, particularly those of the poorest, and finding ways to clearly present this information to decision makers (Springate-Baginski *et al.*, 2009). The methodologies are integrated and incorporate biodiversity, economics and livelihoods approaches. The toolkit was put into practice in two demonstration sites: the Stung Treng Ramsar site in Cambodia and Mtanza-Msona village in Tanzania (Allen and Springate-Baginski, 2008). Following initial preparation and orientation activities, notably clarifying the management objectives of stakeholders, the integrated wetland assessment fieldwork was completed, and integrated reports on the livelihood, biodiversity and economic values of the areas were prepared.

These assessments yielded detailed scientific and management information, including GIS (geographical information system) maps and databases, which document key values and overlaps between threatened species and areas of high human dependence. Information obtained in the Stung Treng Ramsar site was included in the management and zoning plan for this site, towards supporting pro-poor wetland conservation and sustainable use to the benefit of local livelihoods and biodiversity. Data obtained from the second demonstration site helped local communities to understand the importance of wetland resources in their livelihoods.

The main output of the project was *An Integrated Wetland Assessment Toolkit: A Guide to Good Practice* (Springate-Baginski *et al.*, 2009). This guide provides a set of integrated assessment methods that combine and investigate the links between biodiversity, economics and livelihoods, with a particular focus on strengthening pro-poor approaches to wetland management. It aims to assist in overcoming the current methodological and information gaps in wetland planning, to factor wetland values into conservation and development decision making and management planning, and to assist in identifying areas of potential conflicting priorities. The toolkit is expected to be of use to wetland site managers, conservation and development planners, and researchers from both natural and social science disciplines.

The studies in Cambodia and Tanzania brought experts from social, ecological and economic backgrounds to work together. It was not easy to convince them of the value of the work in each of the other two disciplines. For example, it was challenging, but ultimately successful, to convince the social scientists of the value of biodiversity assessment; vice versa, it was challenging to find good models and tools as examples of integrated work (Allen and Springate-Baginski, 2008).

harmful trade-offs, is both feasible and essential (see Chapter 8). Though such technologies have already been identified and are available, the majority of countries have failed to promote them and to penalize more damaging practices, and less developed countries lack the financial resources to improve their capacity to adopt such approaches (Millennium Ecosystem Assessment, 2005). However, certain strategies can be adopted in order to realign policies on agriculture and wetlands (Peden *et al.*, 2005; Molden, 2007; Wood and van Halsema, 2008; McCartney *et al.*, 2010):

- Improve the agricultural practices of farmers in ways that positively influence wetlands, while at the same time not compromising livelihoods. This can be done by: increasing agricultural productivity (intensification) without expanding land area or water use, thereby not compromising the water regulatory functions of wetlands; shifting from irrigation to rainfed agriculture; and improving soil management.
- Adopt supporting strategies that maintain and improve wetland ecosystem services so that a broader range of stakeholders, including the rural poor, receive the benefits.
- Assess water use by the surrounding agro-ecosystems and adapt its use to be in harmony with a sustainable supply, using trade-off analyses.
- Improve land and water management techniques after a comprehensive evaluation of the social and ecological products and services supported by the wetlands for women and men.
- Provide alternate livestock drinking sites away from sensitive wetland areas, not only for the benefit of the wetlands, but also as a means to reduce animal health risks.

Box 7.3. Wetlands and livelihoods in South Africa (WWF, 2009)

The Sand River's upper catchment wetlands in South Africa's Limpopo Province are within densely populated communal lands. The wetland farmers, 90% of whom are women, are among the poorest of the country and depend on these freshwater ecosystems as their only source of food. However, their farming practices, passed from generation to generation, are causing increased erosion, increased desiccation, poor soil fertility and low productivity. In partnership with the Association for Water and Rural Development (AWARD), the World Wildlife Fund for Nature (WWF) South Africa Programme Office started a project to recover the ecological functions of the Sand River's wetlands while improving the livelihoods of the communities living in this area. The project aims to promote awareness of the value of goods and services of the Sand River wetlands in providing livelihood security to poor rural communities, and to develop good agricultural practices among wetland farmers and harvesters in the Sand River Basin.

The project started by evaluating the nature and intensity of farming practices in the wetlands; detailed and rapid appraisals on 60 plots were completed using interviews, field assessments and documentary photographs. The appraisals confirmed erosion, desiccation and poor soil fertility as the main negative outcomes from farming practices. Because wetland farmers relied very much on the wetlands for their livelihoods, it was assumed that they understood their value, but this was shown not to be true, and getting farmers to change their practices and think about long-term management of the wetlands was a challenge. Based on this information, all 60 farmers were grouped according to shared issues, and were engaged in a series of workshops and field visits, whereby they were introduced to basic wetland concepts, conservation tillage methods and good wetland practices. During these workshops, discussions about the need for change were carried out so that farmers could understand the connection between their livelihoods and long-term wetland security and functioning. Farmers then designed their own action plans as well as impact indicators.

These actions were implemented and their impact upon agricultural practices and the state of the wetlands was determined using the indicators that had been defined. An obstacle to this was the inadequate communication and lack of self-organization among farmers. Poor trust hampered exchange of knowledge about the actions implemented, although with the support of the project team, in time the farmers understood the importance of working together to find ways to use the wetlands more sustainably. They also became aware that a number of the problems they faced had their origins at the microcatchment level, and that working with other stakeholders was needed. Hence, they started working on reducing livestock, avoiding damaging crops, preventing gully erosion and managing the large quantities of water entering the wetland from the surrounding villages.

- Improve awareness among all stakeholders who are involved in agricultural water management, and improve their understanding of ecosystem services.
- Improve the inventories, assessment and monitoring of interactions with agroecosystem changes, and of changes to the surrounding wetland. Apply environmental monitoring and decision support systems that involve the affected local communities.
- For each water use activity, identify who are the winners and losers among men and women and affected social groups, and determine the costs and benefits incurred by each and look for ways to transfer costs into incentives to farm more sustainably.
- Adopt an integrated approach to water management that considers the whole catchment, its land use and the water and wetland ecosystems within it, in a way that balances the multiple water requirements for livelihoods along with the needs of the different ecological processes of wetland ecosystem services.

When planning and implementing stocking strategies, appropriate risk assessments and control measures should be employed to protect native fish populations and ensure that other species are not negatively affected (Lorenzen *et al*., 2012). The potential social, cultural and environmental impacts of such interventions demand careful assessment prior to their implementation. It is important to adopt a gendered approach in developing such strategies, as there are gender-related differences both in resource access and use, and in the accrual of productive benefits and their distribution among family members (e.g. World Bank *et al*., 2009).

Greater understanding is required of the continuum of practices from capture fisheries via stock enhancement to fully-fledged aquaculture, if natural resource managers and responsible authorities are to account for such activities in planning and policy making. Notably, it needs to be understood that management regimes may shift as a result of perceived production risks, environmental change, emerging market opportunities, and evolving governance structures and organizational arrangements.

As an alternative to stocking natural water bodies and in response to environmental concerns over intensive, monoculture-based aquaculture, horizontally integrated or land-based integrated multi-trophic aquaculture (IMTA) systems have been developed (see Box 7.1). Within such systems, farmers use formulated feeds for some species, e.g. fish, shrimp or abalone, but these are cultured together with other organisms, notably microalgae, shellfish and seaweed, that convert nutrients released from the fed component to harvestable biomass. This can be used as a supplementary food source, hence reducing the demand for formulated feed, or generating additional revenue, thereby increasing the efficiency and productivity of the system. Also, the integration of aquaculture with other activities can enhance water use efficiency and productivity, though the opportunities and constraints associated with different strategies vary (Table 7.2), and the attendant risks and potential benefits may be difficult to quantify (Bunting and Shpigel, 2009; Troell *et al*., 2009).

Integrated systems permit the generation of higher revenues and more regular cash flows from water pumped ashore or from underground, or available via tidal exchange. A pond-based system combining fish, microalgae and shellfish developed on the Atlantic coast of France received water from a tidally filled reservoir. The disadvantage of the system was that reservoir capacity limited the biomass of fish cultured and, consequently, the amount of integrated production that could be maintained in the system. In tropical coastal areas, integrated farming systems combining pond-based fish and shrimp production with shellfish and seaweed production have been developed, although high concentrations of suspended solids can constrain shellfish growth, and high turbidity and grazing can limit algal production. In such systems, mangrove stands have been used to condition incoming water and treat aquaculture wastewater.

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

Conclusions

Wetlands across the world play a critical role in the provision of freshwater for human consumption and agriculture, while both fresh and saline waters provide food security by supporting fisheries, aquaculture and other related activities. Many wetland agroecosystems represent multiple and diverse options for meeting food security, as well as for meeting basic human needs for water, especially for populations that are directly dependent upon them. Where wetlands themselves are used for agricultural production, as in many parts of Africa and Asia, they help to safeguard the livelihoods of the rural poor; but the increasing deterioration in the condition and, thus, the resilience to future shocks of these natural systems is increasingly putting in jeopardy such safeguards for people.

Urgent steps are needed to protect biodiversity-rich wetland ecosystems, with their multitude of functions and services, as well as the livelihoods and well-being of the dependent communities. Once these areas are identified as wetland agroecosystems with their own set of ecosystem services, effective water management can be put in place with the minimum of trade-offs against other services. The monitoring of wetland functions and services is crucial to ensure the continuation of wetland ecosystems and safeguard their role in secure, high-quality food and water provision, as well as in many other critical and related ecosystem services, including flood protection and climate regulation. A number of priorities can be identified for action, investment and policy to conserve wetlands and promote sustainable development:

- An ecosystem-based approach to wetland management should be adopted that takes into account the contribution of such areas to the livelihoods of primary stakeholders, notably poor and marginal groups, resource users and local communities.
- Investment is needed to identify and promote approaches to food production supported by wetlands that are sustainable and appropriate, given the local social–ecological conditions and food security needs.
- Formulation of wetland management plans should be based on principles of integrated wetland assessment that enable combined biodiversity, economic and livelihoods analysis across different disciplines and sectors.
- Wetlands sustain an array of ecosystem services contributing to human well-being and food security, but polices and management plans are needed to ensure that environmental stocks and flows are protected so as to safeguard aquatic biodiversity.

Notes

[1] Wetlands were defined under the Ramsar Convention as 'areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres' (Ramsar Convention Secretariat, 2011).

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

References

Alegria, H., Bidleman, T.F. and Figueroa, M.S. (2006) Organochlorine pesticides in the ambient air of Chiapas, Mexico. *Environmental Pollution* 140, 483–491. doi:10.1016/j.envpol.2005.08.007

Allen, D. and Springate-Baginski, O. (2008) Good practice toolkit for integrated wetland assessment integrating species assessment, livelihoods assessment and ecosystem service valuation for improved wetland planning and management. Presentation from the Water Pavilion at the: *IUCN World Conservation Congress, Barcelona 5–14 October 2008*.

Amilhat, E., Lorenzen, K., Morales, E.J., Yakupitiyage, A. and Little, D.C. (2009) Fisheries production in Southeast Asian farmer managed aquatic system (FMAS) I. Characterisation of systems. *Aquaculture* 296, 219–226.

Atapattu, S.S. and Kodituwakku, D.C. (2009) Agriculture in South Asia and its implications on downstream health and sustainability: a review. *Agricultural Water Management* 96, 361–373. doi:10.1016/j.agwat.2008.09.028

Bellio, M.G., Kingsford, R.T. and Kotogama, S.W. (2009) Natural versus artificial – wetlands and their waterbirds in Sri Lanka. *Biological Conservation* 142, 3076–3085.

Berg, H., Michelsen, P., Troell, M., Folke, C. and Kautsky, N. (1996) Managing aquaculture for sustainability in tropical Lake Kariba, Zimbabwe. *Ecological Economics* 18, 141–159. doi:10.1016/0921-8009(96)00018–3

Beveridge, M.C.M. (2004) *Cage Aquaculture*, 3rd edn. Blackwell, Oxford, UK.

Beveridge, M.C.M. and Little, D.C. (2002) The history of aquaculture in traditional societies. In: Costa-Pierce, B.A. (ed.) *Ecological Aquaculture. The Evolution of the Blue Revolution*. Blackwell, Oxford, UK, pp. 3–29.

Beveridge, M.C.M. and Phillips, M.J. (1993) Environmental impact of tropical inland aquaculture. In: Pullin, R.S.V, Rosenthal, H. and Maclean, J.L. (eds) *Environment and Aquaculture in Developing Countries, Bellagio, Italy, 17–22 September 1990*. ICLARM Conference Proceedings 31, International Center for Living Aquatic Resources Management [now WorldFish], Manila and Deutsche Gesellschaft für Technische Zusammenarbeit Frankfurt/Main, [now Deutsche Gesellschaft für Internationale Zusammenarbeit, Bonn], Germany, pp. 213–236.

Beveridge M.C.M. and Stewart J.A. (1998) Cage culture: limitations in lakes and reservoirs. In: Petr, T. (ed.) *Inland Fishery Enhancements*. FAO Technical Paper 374, Food and Agriculture Organization of the United Nations (FAO), Rome, pp. 263–279.

Beveridge, M.C.M., Phillips, M.J. and Macintosh, D.J. (1997) Aquaculture and the environment: the supply and demand for environmental goods and services by Asian aquaculture and the implications for sustainability. *Aquaculture Research* 28, 797–807. doi:10.1046/j.1365-2109.1997.00944.x

Bostock, J., McAndrew, B., Richards, R., Jauncey, K., Telfer, T., Lorenzen, K., Little, D., Ross, L., Handisyde, N., Gatward, I. and Corner R. (2010) Aquaculture: global status and trends. *Philosophical Transactions of the Royal Society B* 365, 2897–2912. doi:10.1098/rstb.2010.0170

Bullock, A. and Acreman, M. (2003) The role of wetlands in the hydrological cycle. *Hydrology and Earth System Sciences* 7, 358–389.

Bunting, S.W. (2001) Appropriation of environmental goods and services by aquaculture: a re-assessment employing the ecological footprint methodology and implications for horizontal integration. *Aquaculture Research* 32, 605–609. doi:10.1046/j.1365-2109.2001.00563.x

Bunting, S.W. (2013) *Principles of Sustainable Aquaculture: Promoting Social, Economic and Environmental Resilience*. Earthscan, London, from Routledge, Oxford, UK.

Bunting, S.W. and Shpigel, M. (2009) Evaluating the economic potential of horizontally integrated land-based marine aquaculture. *Aquaculture* 294, 43–51. doi:10.1016/j.aquaculture.2009.04.017

Bunting, S., Little, D. and Leschen, W. (2006) Urban aquatic production. In: van Veenhuizen, R. (ed.) *Cities Farming for the Future: Urban Agriculture for Green and Productive Cities*. Published for RUAF Foundation (Resource Centres on Urban Agriculture and Food Security), International Institute of Rural Reconstruction (IIRR) and International Development Research Centre (IDRC) by IIRR, Silang, Cavite, Philippines and ETC Urban Agriculture, Leusden, the Netherlands, pp. 379–410 (unnumbered). Available at: http://www.ruaf.org/sites/default/files/Chapter%2013.pdf (accessed February 2013).

Bunting, S.W., Edwards, P. and Kundu, N. (2011) *Environmental Management Manual: East Kolkata Wetlands*. MANAK Publications, New Delhi.

Cho, D.-O. (2007) The evolution and resolution of conflicts on Saemangeum Reclamation Project. *Ocean and Coastal Management* 50, 930–944. doi:10.1016/j.ocecoaman.2007.02.005

Cools, J., Diallo, M., Boelee, E., Liersch, S., Coertjens, D., Vandenberghe, V. and Kone, B. (2012) Integrating human health into wetland management for the Inner Niger Delta, Mali. *Environmental Science and Policy* (in press). doi:10.1016/j.envsci.2012.09.011

Cools, J., Johnston, R., Hattermann, F.F., Douven, W. and Zsuffa, I. (2013) Tools for wetland management: lessons learnt from a comparative assessment. *Environmental Science & Policy* (in press). doi:10.1016/j.envsci.2013.01.013

Deegan, L., Johnson, D.S., Warren, R.S., Peterson, B.J., Fleeger, J.W., Fagherazzi, S. and Wollheim, W.M. (2012) Coastal eutrophication as a driver of salt marsh loss. *Nature* 490, 388–392.

Department of Conservation (2007) The economic values of Whangamarino Wetland. Document No. DOCDM-141075, Department of Conservation New Zealand. Available at: http://www.doc.govt.nz/Documents/conservation/threats-and-impacts/benefits-of-conservation/economic-values-whangamarino-wetland.pdf (accessed February 2013).

Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z., Knowler, D.J., Lévêque, C., Naiman, R.J., Prieur-Richard, A., Soto, D., Stiassny, M.L.J. and Sullivan, C.A. (2006) Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological Reviews* 81, 163–182. doi:10.1017/S1464793105006950

Dugan, P., Sugunan, V.V., Welcomme, R.L., Béné, C., Brummett, R.E., Beveridge, M.C.M. *et al.* (2007) Inland fisheries and aquaculture. In: Molden, D. (ed.) *Water for Food, Water for Life: Comprehensive Assessment of Water Management in Agriculture*. Earthscan, London, in association with International Water Management Institute (IWMI), Colombo, pp. 459–483.

Dung, L.C., Hoanh, C.T., Le Page, C., Bousquet, F. and Gajeseni, N. (2009) Facilitating dialogue between aquaculture and agriculture; lessons from role playing games with farmers in the Mekong Delta, Vietnam. *Water Policy* 11(Supplement 11), 80–93. doi:10.2166/wp.2009.105

Elphick, C.S., Parsons, K.C., Fasola, M. and Mugica, L. (2010) Ecology and conservation of birds in rice fields: a global review. *Waterbirds* 33, Special Publication 1.

Falconer, I.R. (2001) Toxic cyanobacterial bloom problems in Australian waters: risks and impacts on human health. *Phycologia* 40 (3), 228–233. doi:10.2216/i0031-8884-40-3-228.1

Falkenmark, M., Finlayson, C.M., Gordon, L.J. *et al.* (2007) Agriculture, water, and ecosystems: avoiding the costs of going too far. In: Molden, D. (ed.) *Water for Food, Water for Life: Comprehensive Assessment of Water Management in Agriculture*. Earthscan, London, in association with International Water Management Institute (IWMI), Colombo, pp. 233–277.

FAO (2010) *The State of Food Insecurity in the World. Addressing Food Insecurity in Protracted Crises.* Food and Agriculture Organization of the United Nations, Rome.

FAO (2012) *The State of World Fisheries and Aquaculture 2012*. FAO Fisheries and Aquaculture Department, Food and Agriculture Organization of the United Nations, Rome. Available at: www.fao.org/docrep/016/i2727e/i2727e00.htm (accessed February 2013).

Finlayson, C.M. (2011) Managing aquatic ecosystems. In: Wilderer, P. (ed.) *Treatise on Water Science, Volume 1*. Academic Press, Oxford, pp. 35–59.

Finlayson, C.M. and D'Cruz, R. (2005) Inland water systems. In: Hassan, R., Scholes, R. and Ash, N. (eds) (2005) *Ecosystems and Human Well-being: Current State and Trends, Volume 1. Findings of the Condition and Trends Working Group of the Millennium Ecosystem Assessment*. World Resources Institute and Island Press, Washington, DC, pp. 551–584.

Finlayson, C.M., Davidson, N.C., Spiers A.G. and Stevenson, N.J. (1999) Global wetland inventory – current status and future priorities. *Marine and Freshwater Research* 50, 717–727. doi:10.1071/MF99098

Foley, J.A. *et al.* (2005) Global consequences of land use. *Science* 309, 570–574. doi:10.1126/science.1111772

Folke, C., Kautsky, N., Berg, H., Jansson, A. and Troell, M. (1998) The ecological footprint concept for sustainable seafood production: a review. *Ecological Applications* 8, S63–S71. doi:10.1890/1051-0761(1998)8[S63:TEFCFS]2.0.CO;2

Frei, M. and Becker, K. (2005) Integrated rice–fish production and methane emission under greenhouse conditions. *Agriculture, Ecosystems and Environment* 107, 51–56.

Gichuki, F.N., Kodituwakku, D.C., Nguyen-Khoa, S. and Hoanh, C.T. (2009) Cross-scale trade-offs and synergies in aquaculture, water quality and environment: research issues and policy implications. *Water Policy* 11(Supplement 1), 1–12. doi:10.2166/wp.2009.100

Gregory, P.J. *et al.* (2002) Environmental consequences of alternative practices for intensifying crop production. *Agriculture, Ecosystems and Environment* 88, 279–290.

Gurung, T.B. (2002) Fisheries and aquaculture activities in Nepal. *Aquaculture Asia* 7, 39–44.

Hall, S.J., Delaporte, A., Phillips, M.J., Beveridge, M.C.M. and O'Keefe, M. (2011) *Blue Frontiers: Managing the Environmental Costs of Aquaculture*. WorldFish, Penang.

Hart, B.T., van Dok, W. and Djuangsih, N. (2002) Nutrient budget for Saguling Reservoir, West Java, Indonesia. *Water Research* 36, 2152–2160.

Hoanh, C.T., Tuong, T.P. and Hardy, B. (eds) (2006) *Environment and Livelihoods in Tropical Coastal Zones: Managing Agriculture–Fishery–Aquaculture Conflicts*. Comprehensive Assessment of Water Management in Agriculture Series 2. CAB International, Wallingford, UK in association with International Rice Research Institute (IRRI), Los Banos, Philippines and International Water Management Institute (IWMI), Colombo.

Hollis, G.E., Adams, W.M. and Kano, M.A. (eds) (1993) *The Hadejia-Nguru Wetlands: Environment, Economy and Sustainable Development of a Sahelian Floodplain Wetland*. IUCN, Gland, Switzerland.

Horwitz, P. and Finlayson, C.M. (2011) Wetlands as settings: ecosystem services and health impact assessment for wetland and water resource management. *BioScience* 61, 678–688.

Johnston, R., Cools, J., Liersch, S., Morardet, S., Murgue, C., Mahieu, M., Zsuffa, I. and Uyttendaele, G.P. (2013) WETwin: A structured approach to evaluating wetland management options in data-poor contexts. *Environmental Science & Policy* (in press). doi:10.1016/j.envsci.2012.12.006

Le Quesne, T. *et al*. (2010) *Flowing Forward: Freshwater Ecosystem Adaptation to Climate Change in Water Resources Management and Biodiversity Conservation*. Water Working Notes No. 28, The World Bank, Washington, DC.

Lehner, B. and Döll, P. (2004) Development and validation of a global database of lakes, reservoirs and wetlands. *Journal of Hydrology* 296, 1–22. doi:10.1016/j.jhydrol.2004.03.028

Little, D.C. and Bunting, S.W. (2005) Opportunities and constraints to urban aquaculture, with a focus on south and southeast Asia. In: Costa-Pierce, B.A., Edwards, P., Baker, D. and Desbonnet, A. (eds) *Urban Aquaculture*. CAB International, Wallingford, UK, pp. 25–44.

Lorenzen, K., Beveridge, M.C.M. and Mangel, M. (2012) Cultured fish: integrative biology and management of domestication and interactions with wild fish. *Biological Reviews* 87, 639–660.

Lukatelich, R.J. and McComb, A.J. (1986) Nutrient levels and the development of diatoms and blue–green algal blooms in shallow Australian estuary. *Journal of Plankton Research* 8, 597–618. doi:10.1093/plankt/8.4.597

Maclean, J.J., Dawe, D.C., Hardy, B. and Hettel, G.P. (eds) (2002) *Rice Almanac*, 3rd edn. International Rice Research Institute (IRRI), Los Baños, Philippines, West Africa Rice Development Association (WARDA), Bouaké, *Côte d'Ivoire* [now AfricaRice, presently at Cotonou, Benin], International Center for Tropical Agriculture (ICTA), Cali, Colombia and Food and Agriculture Organization, Rome.

Matsuno, Y., Ko, H.S., Tan, C.H., Barker, R. and Levine, G. (2002) *Accounting of Agricultural and Nonagricultural Impacts of Irrigation and Drainage Systems: A Study of Multifunctionality in Rice.* IWMI Working Paper 43, International Water Management Institute (IWMI), Colombo.

McCartney, M. and Smakhtin, V. (2010) *Water Storage in an Era of Climate Change: Addressing the Challenge of Increasing Rainfall Variability*. IWMI Blue Paper, International Water Management Institute, Colombo.

McCartney, M.P. and van Koppen, B. (2004) *Wetland Contributions to Livelihoods in United Republic of Tanzania.* FAO–Netherlands Partnership Programme: Sustainable Development and Management of Wetlands, Food and Agriculture Organization of the United Nations, Rome.

McCartney, M., Rebelo, L.-M., Senaratna Sellamuttu, S. and de Silva, S. (2010) *Wetlands, Agriculture and Poverty Alleviation: Appropriate Management to Safeguard and Enhance Wetland Productivity.* IWMI Research Report 137, International Water Management Institute, Colombo. doi:10.5337/2010.230

McCartney, M., Morardet, S., Rebelo, L-M. and Finlayson, C.M. (2011a) A study of wetland hydrology and ecosystem service provision: GaMampa Wetland, South Africa. *Hydrological Sciences Journal* 56, 1452–1466.

McCartney, M., Rebelo, L.-M., Mapedza, E., de Silva, S. and Finlayson, C.M. (2011b) The Lukanga Swamps: use, conflicts and management. *Journal of International Wildlife Law and Policy* 14, 293–310.

McInnes, R. (2010) Urban Development, Biodiversity and Wetland Management: Expert Workshop Report. UN Habitat and Ramsar Convention on Wetlands Expert Workshop, 16 to 17 November 2009, Kenya Wildlife Service Training Institute, Naivasha, Kenya. Bioscan UK), Oxford, UK. Available at: http://www.unhabitat.org/downloads/docs/ExpertWorkshopWetlands.pdf (accessed February 2013).

Millennium Ecosystem Assessment (2005) *Ecosystems and Human Well-being: Wetlands and Water – Synthesis. A Report of the Millennium Ecosystem Assessment.* World Resources Institute, Washington, DC. Available at: www.maweb.org/documents/document.358.aspx.pdf (accessed February 2013).

Mills, D.J., Westlund, L., de Graaf, G., Kura, Y., Willman, R. and Kelleher, K. (2010) Underreported and undervalued: small-scale fisheries in the developing world. In: Pomeroy, R.S. and Andrew, N. (eds) *Small-scale Fisheries: Management Frameworks and Approaches for the Developing World.* CAB International, Wallingford, UK, pp. 1–15.

Molden, D. (ed.) (2007) *Water for Food, Water for Life: Comprehensive Assessment of Water Management in Agriculture.* Earthscan, London, in association with International Water Management Institute (IWMI), Colombo.

Munro, J.L., Iskandar and Costa-Pierce B.A. (1990) Fisheries of the Saguling reservoir and a preliminary appraisal of management options. In: Costa-Pierce, B.A. and Soemarawoto, O. (eds) *Reservoir Fisheries and Aquaculture Development for Resettlement in Indonesia.* ICLARM Technical Report 23, Perusahaan Umum Listrik Negara, Jakarta, Indonesia, Institute of Ecology, Padjadjaran University, Bandung, Indonesia and International Center [Centre] for Living Aquatic Resources Management, Metro Manila, Philippines (ICLARM) [now WorldFish, Penang], pp. 285–328.

Nagabhatla, N., Beveridge, M.C.M., Nguyen-Khoa, S., Haque, A.B.M. and Van Brakel, M. (2012a) Multiple water use as an approach for increased basin productivity and improved adaptation: A case study from Bangladesh. *International Journal of River Basin Management*, 10, 121–136.

Nagabhatla, N., Dhyani, S., Finlayson, C.M., Senareratna Sellamuttu, S., Van Brakel, M., Wickramasuriya, R., Pattanaik, C. and Narendra Prasad, S. (2012b) A case study approach to demonstrate the use of assessment and monitoring tools for participatory environmental governance. *Ecologia* 2, 60–75.

Nguyen Thi, H.T., Nguyen Thi, T., Nguyen Hai, D., Do Van, T. and Nguyen Thi, D.P. (2010) *Situation Analysis Report on Highland Aquatic Resources Conservation and Sustainable Development in Northern and Central Vietnam*. HighARCS (Highland Aquatic Resources Conservation and Sustainable Development) Project Report, Research Institute for Aquaculture No. 1, Bac Ninh, Vietnam.

Pachauri, R.K. and Reisinger, A. (2007) *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*. IPCC, Geneva, Switzerland.

Panigrahi, S., Acharya, B.C., Rama Chandra, P., Bijaya Ketan, N., Banarjee, K. and Sarkar, S.K. (2007) Anthropogenic impact on water quality of Chilika Lagoon RAMSAR site: a statistical approach. *Wetlands Ecology and Management* 15, 113–126.

Pauly, D. (1995) Anecdotes and the shifting baseline syndrome of fisheries. *Trends in Ecology and Evolution* 10, 430.

Peden, D., Ayalneh, W., El Wakeel, A., Fadlalla, B., Elzaki, R., Faki, H., Mati, B., Sonder, K. and Workalemahu, A. (2005) *Investment Options for Integrated Water-Livestock-Crop Production in Sub-Saharan Africa.* International Livestock Research Institute (ILRI), Addis Ababa.

Ramsar Convention Secretariat (2011) *The Ramsar Convention Manual: A Guide to the Convention on Wetlands (Ramsar, Iran, 1971)*, 5th edn. Ramsar Convention Secretariat, Gland, Switzerland.

Rebelo, L.-M., McCartney, M.P. and Finlayson, C.M. (2010) Wetlands of sub-Saharan Africa: distribution and contribution of agriculture to livelihoods. *Wetlands Ecology and Management* 18, 557–572. doi:10.1007/s11273-009-9142-x

Rebelo, L.-M., McCartney, M.P. and Finlayson, C.M. (2011) The application of geospatial analyses to support an integrated study into the ecological character and sustainable use of Lake Chilwa. *Journal of Great Lakes Research* 37, 83–92.

Senaratna Sellamuttu, S., de Silva, S., Nagabhatla, N., Finlayson, C.M., Pattanaik, C. and Prasad, N. (2012) The Ramsar Convention's wise use concept in theory and practice: an inter-disciplinary investigation of practice in Kolleru Lake, India. *Journal of International Wildlife Law and Policy* 15, 228–250.

Shiklomanov, I.A. and Rodda, J. (2003) *World Water Resources at the Beginning of the 21st Century*. United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris.

Smith, L.E.D., Nguyen-Khoa, S. and Lorenzen, K. (2005) Livelihood functions of inland fisheries: policy implications in developing countries. *Water Policy* 7, 359–384.

Springate-Baginski, O., Allen, D. and Darwall, W.R.T. (eds) (2009) *An Integrated Wetland Assessment Toolkit: A Guide to Good Practice.* International Union for Conservation of Nature (IUCN), Gland, Switzerland and IUCN Species Programme, Cambridge, UK.

Szuster, B., Molle, F., Flaherty, M. and Srijantr, T. (2003) Socioeconomic and environmental implications of inland shrimp farming in the Chao Phraya Delta. In: Molle, F. and Srijantr, T. (eds) *Perspective on Social and Agricultural Change in the Chao Phraya Delta.* White Lotus Press, Bangkok, Thailand.

Tran Huu, T., Mai Van, X., Do Nam and Navrud, S. (2009) Valuing direct use values of wetlands: A case study of Tam Giang–Cau Hai lagoon wetland in Vietnam. *Ocean and Coastal Management* 52, 102–112. doi:10.1016/j.ocecoaman.2008.10.011

Troell, M., Joyce, A. and Chopin, T. (2009) Ecological engineering in aquaculture – potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. *Aquaculture* 297, 1–9.

UNEP (2006) *Marine and Coastal Ecosystems and Human Well-being: A Synthesis Report Based on the Findings of the Millennium Ecosystem Assessment.* United Nations Environment Programme, Nairobi.

UNEP (2010) *Blue Harvest: Inland Fisheries as an Ecosystem Service*. WorldFish, Penang, Malaysia and United Nations Environment Programme, Nairobi.

Valiela, I., Bowen, J.L. and York, J.K. (2001) Mangrove forests: one of the world's threatened major tropical environments. *BioScience* 51, 807–815.

Welcomme, R.L., Cowx, I.G., Coates, D., Béné, C., Funge-Smith, S., Halls, A. and Lorenzen, K. (2010) Inland capture fisheries. *Philosophical Transactions of the Royal Society B* 365, 2881–2896. doi:10.1098/rstb.2010.0168

WHO (2006) *Guidelines for the Safe Use of Wastewater, Excreta and Greywater in Agriculture.* World Health Organization, Geneva, Switzerland.

Wood, A. and van Halsema, G.E. (2008) *Scoping Agriculture-Wetland Interactions. Towards a Sustainable Multiple Response Strategy.* FAO Water Reports 33, Food and Agriculture Organization of the United Nations, Rome.

World Bank, FAO and IFAD (2009) *Gender in Agriculture Sourcebook*. World Bank, Washington, DC with Food and Agriculture Organization of the United Nations, Rome and International Fund for Agricultural Development, Rome.

WRI, UNDP, UNEP and World Bank (2008) *World Resources 2008: Roots of Resilience: Growing the Wealth of the Poor – Ownership – Capacity – Connection.* World Resources Institute in collaboration with United Nations Development Programme, United Nations Environment Programme and World Bank. World Resources Institute, Washington, DC.

WWF (2009) Wetland restoration: Sand River, South Africa. WWF Africa (World Wildlife Fund for Nature) South Africa, Claremont, South Africa. Available at: wwf.panda.org/who_we_are/wwf_offices/south_africa/index.cfm?uProjectID=ZA0313 (accessed October 2010).

Xie, J., Hu, L., Tang, J., Wu, X., Li, N., Yuan, Y., Yang, H., Zhang, J., Luo, S. and Chen, X. (2011) Ecological mechanisms underlying the sustainability of the agricultural heritage rice–fish coculture system. *Proceedings of the National Academy of Sciences* 108, E1381–E1387. doi:10.1073/pnas.1111043108