4 Challenges to Agroecosystem Management

Petina L. Pert,[1]* Eline Boelee,[2] Devra I. Jarvis,[3] David Coates,[4] Prem Bindraban,[5] Jennie Barron,[6] Rebecca E. Tharme[7] and Mario Herrero[8]

[1]Commonwealth Scientific and Industrial Research Organisation (CSIRO), Cairns, Queensland, Australia; [2]Water Health, Hollandsche Rading, the Netherlands; [3]Bioversity International, Rome, Italy; [4]Secretariat of the Convention on Biological Diversity (CBD), Montreal, Canada; [5]World Soil Information (ISRIC) and Plant Research International, Wageningen, the Netherlands; [6]Stockholm Environment Institute, University of York, UK and Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden; [7]The Nature Conservancy (TNC), Buxton, UK; [8]Commonwealth Scientific and Industrial Research Organisation (CSIRO), St Lucia, Queensland, Australia

Abstract

As growth in population, gross domestic product (GDP) and consumption continues, further demands are placed on land, water and other resources. The resulting degradation can threaten the food security of poor people in fragile environments, particularly those whose livelihoods rely largely on agricultural activities. The concept of diversified or multifunctional agroecosystems is a relatively recent response to the decline in the quality of the natural resource base. Today, the question of agricultural production has evolved from a purely technical issue to a more complex one characterized by social, cultural, political and economic dimensions. Multifunctional agroecosystems carry out a variety of ecosystem services, such as the regulation of soil and water quality, carbon sequestration, support for biodiversity and sociocultural services, as well as meeting consumers' needs for food. In turn, these systems also rely on ecosystem services provided by adjacent natural ecosystems, including pollination, biological pest control, maintenance of soil structure and fertility, nutrient cycling and hydrological services. However, poor management practices in agroecosystems can also be the source of numerous disservices, including loss of wildlife habitat, nutrient runoff, sedimentation of waterways, greenhouse gas emissions, and pesticide poisoning of humans and non-target species. This chapter discusses the challenges to agroecosystem management, and how adopting a diversified approach will enable farmers to farm longer and more sustainably in an environment of greater uncertainty, in the face of climate change.

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* E-mail: petina.pert@csiro.au

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Background

The impacts of population growth and other demographic changes on ecosystems can vary over time. Population growth and urban sprawl will result in more people using more resources and placing more pressure on ecosystem services (see Chapter 2). Increasing populations require more habitable and arable land, which often results in the conversion of natural ecosystems and, ultimately, in the breakdown of ecosystems. There is increasingly negative feedback concerning the interactions between food security, agriculture, water and ecosystem services (Nellemann *et al*., 2009). Food security is further threatened by reduced yields associated with depleted water quantity, reduced water quality, degradation of other natural resources (such as soil fertility) and the simplification of agricultural systems that have lost their inherent biotic components for regulating pest and disease infestations. Unsustainable agricultural practices can have profound, damaging side effects on livelihoods and ecosystem functioning, and in the long term could potentially depress or reverse productivity gains and increase poverty. At the same time, the availability of other natural resources (land, phosphorus and energy) is predicted to start running out by the end of this century (McIntyre *et al*., 2008). Efforts to reactivate farmland, e.g. through the use of agrochemicals, have a substantial impact on other ecosystem functions. In turn, dysfunctional ecosystem services further affect the agroecosystems and their production systems.

The Millennium Ecosystem Assessment (MA) of 2005 suggested that in the next 50–100 years, major agricultural decisions would come in the form of trade-offs, especially 'between agricultural production and water quality, land use and biodiversity, water use and aquatic biodiversity, and current water use for agricultural production' (Nelson, 2005). Four scenarios and an adapted version of the MA framework were used in Australia to identify trade-offs between the ecosystem service of water regulation and stakeholders in the Great Barrier Reef's Tully–Murray Catchment (Butler *et al*., 2011). While the most direct trade-off was found to be food and fibre production versus water quality regulation, synergies were also identified with floodplain fisheries (Butler *et al*., 2011).

As discussed in Chapter 3, greater understanding and appreciation of the role of the services provided by a variety of ecosystems, including agroecosystems, could assist in moving beyond 'trade-offs' to address the challenges of ecosystem management for long-term sustainable food production in many ways. The growing demands for food, coupled with land and water management practices that cause degradation and erode the natural resource base, place substantial constraints on the ecosystem services provided by and inherent within these agroecosystems (Abel *et al*., 2003; Sandhu *et al*., 2010).

Agriculture and ecosystem services are thus interrelated in at least four ways: (i) agroecosystems generate beneficial ecosystem services such as soil retention, food production and aesthetic benefits; (ii) agroecosystems receive beneficial ecosystem services from other ecosystems, such as pollination from non-agricultural ecosystems; (iii) ecosystem services from non-agricultural systems may be affected by agricultural practices; and finally (iv) the biological diversity within agricultural ecosystems provides regulating and supporting ecosystem services in addition to production services. For food security in the short term, provisioning services are crucial; however, for securing access to food for all in the future, and in the long term, regulatory and supporting services are just as important. The ecosystem services approach requires adaptive management, because its implementation depends on local, national or even global conditions.

Comparing the Economic Values of Ecosystem Services

Decisions on the management of agroecosystem services will typically involve balancing social, economic and environmental considerations, some of them among different services (Millennium Ecosystem Assessment, 2005; see Chapter 3). For example, managing a landscape to maximize food production will probably not maximize water purification for people downstream, and native habitats conserved near agricultural fields may provide both crop pollinators and crop pests (Steffan-Dewenter *et al*., 2001). The question about whether intensive or extensive agriculture best optimizes the various trade-offs associated with the provision of ecosystem services is an important issue requiring targeted research.

Connections between ecological sustainability and human well-being can be expressed by using the concept of 'ecological character': the various components and processes in an ecosystem that underpin the delivery of ecosystem services (Millennium Ecosystem Assessment, 2005). Without managing for the sustainability of ecological character, the long-term ability of an ecosystem to support human well-being may be compromised. These kinds of management trade-offs often require decision makers to estimate the marginal values of ecosystem services, and to capture the costs and benefits of a specific quantity and quality of services (Daily, 1997) for men and women and different social groups.[1] Marginal value is used in this process because monetary valuation cannot express the overall importance of environmental goods and services (see Chapter 3), only the value of the resource if there were to be a little more or a little less of it (Heal, 2000). Therefore, the value of an ecosystem service reflects its availability. Water is a good example here: it is important and renewable but not replaceable. However, water is often provided freely or at a minimal cost to consumers. The price to consumers only pays for the cost of transmitting water (e.g. water treatment plants), which does not reflect the value of the water itself and gives no information on what consumers would be willing to pay if there were a little more or a little less of the resource (Heal, 2000).

Ecosystem services can also be used to compare different ecosystem types in terms of their contributions to the availability of a certain service. Most commonly, 'total valuation' is the tool used to bring environmental services into decision-making processes where trade-offs between conservation and development need to be comparatively assessed (Emerton, 2005). Total valuation attempts to account for all of the characteristics of an ecosystem; these include 'its resource stocks or assets, flows of environmental services, and the attributes of the ecosystem as a whole' (Millennium Ecosystem Assessment, 2005). As mentioned above, this is an incomplete process that is limited in its capacity to value ecosystems fully, though as Daily (1997) points out, 'markets play a dominant role in patterns of human behavior, and the expression of value – even if imperfect – in a common currency helps to inform the decision-making process'.

For the quantification of the values of ecosystem services at the country level, a useful concept has been proposed by Dasgupta (2010), who argues that neither gross domestic product (GDP) nor the human development index (HDI) can determine whether development is sustainable. An assessment of *wealth* per capita is much more useful as it includes the total of all capital assets: infrastructure such as buildings and roads, health, skills, knowledge and institutions, and also natural capital, which may easily be left out of other assessments (Dasgupta, 2010).

These methods are increasingly important to today's decisions on agricultural water use. Bennett *et al*. (2005) point out that, with growing demands on food production and water use, demands on ecosystem services, in many cases, could surpass the capacity of certain ecosystems to supply these services. In these contexts, decision makers will need to draw a balance between the production of various services in ecosystems on the one hand, and the social and economic benefits and risks of using technology to provide them on the other (Bennett *et al*., 2005). With a clear understanding of ecosystem services and their values, agroecosystems and non-agricultural terrestrial ecosystems can be compared (Power, 2010). Many goods and provisioning services come from non-agricultural land (such as food, fodder, fibre and timber), and in decisions over water allocation the whole range of ecosystem services, their benefits (values) and costs (social, financial, water) have to be taken into account (TEEB, 2010). Only then can well-balanced decisions be made about which ecosystem services are to be enhanced, at the expense of which other services, or about how ecosystems can be optimized to provide the widest range of ecosystem services (Power, 2010).

Finally, any successful decision making will depend on farmers and the farming community having the knowledge and leadership capacity to evaluate the benefits that any action will have for them (Jarvis *et al.*, 2011). This, in turn, will be dependent on systems that are in place that support activities taken by local, national and international organizations and agencies towards strengthening local institutions so as to enable farmers to take a greater role in the management of their resources.

Agroecosystems have an important role to play in food security but they have also been associated with negative impacts on other ecosystems. When compared with other groups of ecosystems, or biomes, the total value of ecosystem services from cropland is relatively low, even for food production alone. For example, in the Mississippi Delta, the total annual value of agricultural land ranged from US$195 to US$220/ha, of which US$85/ha was from food production; this level of production fell behind that of most other ecosystem types (including forests and, in particular, wetlands, where annual food production was valued at US$145 to US$3346/ha) (Batker *et al.*, 2010; and Box 3.2, Chapter 3).

In contrast, some other studies have found higher annual values for food production in cultivated systems: US$667/ha in South Africa, US$1516/ha in El Salvador, and as high as US$3842/ha and US$7425/ha in Israel (van der Ploeg *et al.*, 2010). However, it is not clear how this compares with the average values of other biomes as listed in Table 3.1 (Chapter 3). There have been very few studies that have attempted to value ecosystem services in agriculture, even though assessments indicate that the value to agriculture is enormous (Power, 2010), and various estimates do suggest a real underestimation of the benefits of non-agricultural ecosystems for food production and possibly for food security. In a study in Denmark, Porter *et al.* (2009) estimated via field-scale ecological monitoring and economic value-transfer methods, the market and non-market ecosystem service value of a combined food and energy (CFE) agroecosystem that simultaneously produces food, fodder and bioenergy.

Discrepancies in estimations of the economic values of ecosystem services occur, in part, because land and water use planning are based on limited sector-based considerations, which do not factor in the overall values of all services that any ecosystem delivers. Hence, agricultural land has such a low value in terms of output because it tends to be managed for a single service (food production), often with significant negative consequences on other services (e.g. through pollution). Another reason might be that the value of food production is measured in terms of market prices, whereas the value of other ecosystem services reflects avoided societal costs that are normally much higher but for which there are no marketplaces (with the exception of carbon). Nevertheless, food production will always remain a priority and does not necessarily have to come at the expense of other services (Bennett *et al.*, 2009; Keys *et al.*, 2012). Cases exist in which investments in sustainable agriculture have generated co-benefits in raising food production, while at the same time improving ecosystem services and functions (Pretty *et al.*, 2006; see examples in other chapters).

Understanding Agroecosystem Services

Managing agricultural land to deliver multiple services considerably improves the value of the land. However, in order to enhance improved services – such as carbon storage, erosion control, water retention, waste treatment, regulation of pests and diseases, and cultural and recreational values including tourism – their values must be understood in comparison with agricultural income. Ideally, these added services would not conflict with agricultural production in many cases but rather improve both its productivity and its sustainability, with beneficial impacts on surrounding ecosystems as well (see Chapter 9 for more information on managing a wider range of agroecosystem services).

Over the years, agricultural systems have evolved into diverse agroecosystems, some of which are rich in biodiversity and provide ecosystem services in addition to food production. Examples are wet rice–poultry farming systems and the practice of increased diversity of crop varieties within farmers' fields, which has been shown to reduce the risk of crop loss to pest diseases (Jarvis *et al.*, 2007; Mulumba *et al.*, 2012).

Water management in agroecosystems can create competition with wider environmental requirements and affect water flow downstream. Decisions on water use require mechanisms in which the needs of both the farmers and the ecosystem services are met, e.g. by buying irrigation water from farmers to sustain or rehabilitate ecosystems and their services (Molden and de Fraiture, 2004). These decisions need a broader consideration of ecosystem services in agroecosystems. This consideration should take into account which services are enhanced at the expense of which other ecosystem services, and which services benefit mostly poor women, men and other vulnerable groups. In agroecosystems, food production is again underpinned by a reliable availability of water. Tools, such as the polyscape tool, are being developed that allow the quantification of trade-offs and synergies among the impacts of water- and land-use interventions on different ecosystem services (Box 4.1).

Box 4.1. Polyscape tool for comparing impacts on ecosystem services.

One of the new tools under development for assessing ecosystem services is the polyscape tool (adapted from Jackson *et al.*, 2013). This allows the quantification of trade-offs and synergies among the impacts of land-use interventions such as the changing of tree cover. Small catchment maps indicate with colours where, for example, new tree cover would be most desirable to enhance woodland habitat connectivity, reduce flow accumulation, have minimum impact on farm productivity and reduce sediment transport (Fig. 4.1). When the four benefits are traded off in the large map, there is only a small area of the catchment where tree placement benefits all goals. To substantially enhance some ecosystem services by increasing tree cover, farmers would need to be well compensated for loss of production; for other ecosystem services, only certain farms in the landscape would be important, i.e. different bits of the landscape would have different values for each service considered.

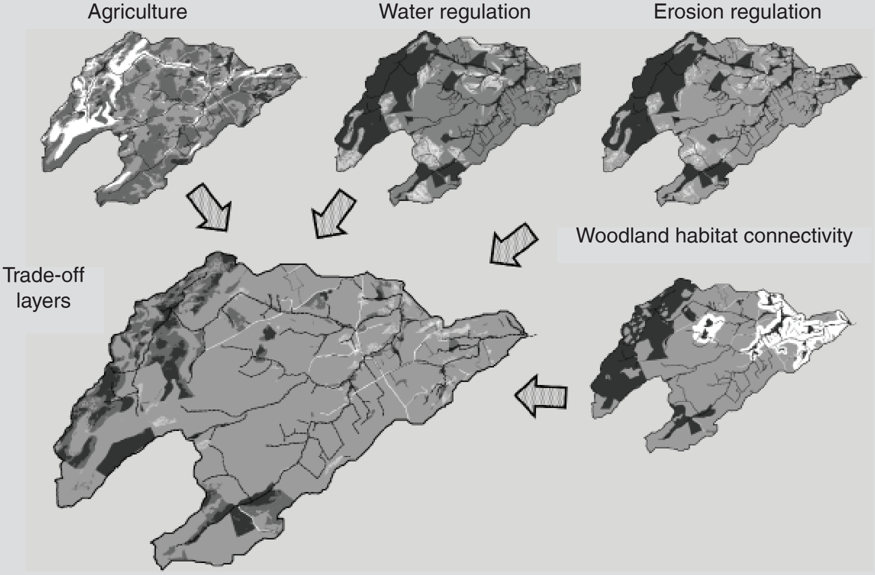

Fig. 4.1. Example of the application of the polyscape tool (figure components provided by Tim Pagella) to explore trade-offs and synergies of the impacts of tree cover on ecosystem services. In the four individual maps, darker areas represent high value for the service and lighter areas opportunities for improvement. In the combined map, darker areas represent trade-offs (where improvements in one service could be at the expense of others), whilst lighter areas mean that changes will provide multiple benefits (synergies).

Agriculture is thus faced with significant challenges regarding water use and availability. Solutions, which are based largely on the more efficient use of water in agriculture, do exist (see Chapters 5 and 8), but agriculture can also be managed differently, in such a way as to enhance ecosystem services and increase the capacities of low-income male and female farmers (Molden, 2007; see also Chapter 9). This change in thinking, and in the way that agroecosystems are managed, is crucial for global food security. The major challenge then lies in quantifying values and measuring feedback cycles (Nicholson *et al.*, 2009; Taffetani *et al.*, 2011), and more research is required into ecosystem services, especially those associated with water (Carpenter *et al.*, 2009) and with other components of the agricultural production systems.

Ecosystem services and fish

Important fisheries that depend on healthy aquatic ecosystems are endangered. Because fish provide 21% of animal protein in Africa, and 28% in Asia (World Commission on Dams, 2000), a loss of fisheries can be detrimental for food security. The link with management of inland aquatic ecosystems is clear, as almost 50% of global fish consumption comes from aquaculture, and in Africa almost half is from inland fisheries (UNEP, 2010). In order to avoid further degradation, fundamental changes are required to establish an ecosystem-based catchment management approach (IUCN, 2000).

Faced with declining wild fish stocks, over-exploitation of target species and by-catch of other species, the fishing industry is giving way to aquaculture, which is reported to be the world's fastest growing food sector – at an average growth rate of 6.8%/year (Medialdea, 2010). In 2006, it was reported that 53 million t of fish (or half of all fish consumed in the world) were produced by the aquaculture industries (Medialdea, 2010). At the same time, fisheries are increasingly less 'wild', as stock enhancement and the establishment of culture-based fisheries are increasingly viewed as potential means of bolstering catches. None the less, the potential negative ecological and social impacts of such practices demand comprehensive and rigorous assessment, with appropriate mitigation and control measures, before they are implemented. For example, antibiotics and other chemicals used in fish farms can seep into surrounding waters, and sensitive coastal areas and wetlands are also disrupted or destroyed in the development of the industry. Additionally, aquaculture appropriates a range of environmental goods and services that may lead to adverse environmental impacts, and affect the ability of stocks and flows of ecosystem services to sustain other productive activities, which could again result in disputes and conflicts.

Ecosystem impacts of livestock production

Livestock systems occupy about 30% (Steinfeld *et al.*, 2006) to 45% (Herrero *et al.*, 2010) of the planet's ice-free terrestrial surface area. This makes livestock the single largest agricultural use of land globally, either directly through grazing or indirectly through the consumption of fodder and feed grains. Livestock is also a significant global asset, with a value of at least US$1.4 trillion in the least developed countries, excluding the value of infrastructure and land (Herrero *et al.*, 2010). The accelerating demand for livestock products (see Box 2.2, Chapter 2) is increasingly being met by intensive (industrialized) production systems, especially for chickens and pigs in Asia (Thornton, 2010). Thus, between 1995 and 2005, bovine and ovine meat production increased by about 40%, pig meat production rose by nearly 60% and poultry meat production doubled (Steinfeld *et al.*, 2006). Livestock production has important implications for ecosystem services, with environmental impacts on water scarcity, nutrient cycling, climate change and land degradation, as well as human impacts such as public health and the exclusion of smallholder producers.

Livestock production emits large amounts of greenhouse gases (Box 2.3, Chapter 2). However, the mitigation potential in the livestock sector is very large (1.74 Gt CO_2 eq./year; see Smith *et al.*, 2008; World Bank, 2009), with improved feeding practices, manure and land use management practices representing over 80% of this potential (Smith *et al.*, 2008; Chapter 9).

A well-known linkage between livestock and soil productivity is the cycling of biomass (natural vegetation, crop residues) through animals (cattle, sheep, goats) into excreta (manure, urine) that fertilize the soil. Globally, manure contributes 14% of nitrogen, 25% of phosphorus and 40% of potassium nutrient inputs to agricultural soils (Bouwman *et al.*, 2011). The types and amounts of manure nutrients available for recycling are highly influenced by differences in land use and in the spatial and temporal distribution of livestock as dictated by animal management, and also by seasonal differences in animal diet. When not carefully managed, nutrient surpluses from livestock waste and fertilizer used for feed production may result in eutrophication of surface waters and groundwater contamination in places where large animals congregate, such as in industrial peri-urban systems. These ecosystem disservices posed by water contamination from livestock excreta and dung residues can cause health hazards (Herrero *et al.*, 2009).

Then again, there are numerous potential situations where co-benefits emerge between livestock production and the maintenance of ecosystem services (see Chapter 9). These examples may not be readily available, as they require in-depth analysis of scientific as well as indigenous evidence, and therefore come at a (knowledge-intensive) cost. Herrero *et al.* (2009) formulated useful guiding questions on livestock, ecosystems and livelihoods to help to identify knowledge gaps. In analysing environmental impacts and ecosystem services, it is important to distinguish between extensive and intensive livestock production. Although livestock grazing is the largest user of land globally, most of the world's animal production comes from intensive industrialized production in developed countries, closely followed by rainfed mixed crop–livestock systems in developing countries. These intensively farmed areas are the focal points for ecosystem degradation. For example, in Ethiopia, 45% of the estimated soil loss occurs from the 13% of the country under cultivation, but grazing lands, which cover about half of the country, account for only 21% of the soil loss (Hurni, 1990). Some livestock herding systems in Africa have managed large areas in a semi-natural state, maintaining vegetation cover and indirectly preserving vital ecosystem services.

Sustainable growth and intensification of livestock production systems will be required to cater for increasing demands for livestock products, while mitigating the negative effects of the sector (Tarawali *et al.*, 2011). Substantive investments and policies are essential to implement the measures above (World Bank, 2009). With more sustainable livestock production systems, the increased demands for animal products could be satisfied at the same time as maintaining environmental flows and services.

Land degradation and erosion

Soil degradation, such as by water or wind erosion, compaction, salinization, nutrient depletion and fertility decline, physical deterioration, contamination and sealing, is considered to be a main cause of hampering growth in agricultural productivity (Sanchez *et al.*, 1997). The impact of soil degradation on yields in China was estimated as a reduction in food production capacity on the current arable land area from 482 Mt in 2005 to 412 Mt by 2050, with the same relative yield loss projected in the next 15 years as in the past 15 years (Bindraban *et al.*, 2012), though such estimates do not account for underlying processes; hence, for identifying viable solutions, more detailed studies at a lower level will be required. In addition to physical factors, land degradation has many social roots, including lack of land tenure, careless extractivism, indifferent or corrupt governments, lack of access to finance and resources, population pressure and a dearth of educational opportunities.

In many parts of the world, land degradation has increased over the past two decades, mostly as a result of poor land management, including uncontrolled soil erosion, overgrazing, and the limited application and availability of appropriate types of fertilizers. In sub-Saharan Africa, more than 40% of the land is threatened by land degradation (Vlek *et al.*, 2010). Loss of organic matter, e.g. through entire crop removal, and the physical degradation of soil not only reduce nutrient availability but also result in lower water infiltration rates and porosity, and these may affect the resilience of agroecosystems, local and regional water productivity, and even global carbon cycles. Accelerated on-farm soil erosion leads to substantial yield losses and contributes to downstream sedimentation, which can degrade natural water bodies and fill up water storage reservoirs and irrigation infrastructure (Vlek *et al.*, 2010; Bouma *et al.*, 2011).

The occurrence of land degradation is thus linked with low water productivity and impaired ecosystem services (Bossio *et al.*, 2008), and is often associated with high population pressure; nevertheless, its extent and its causative mechanisms are highly site specific (Muchena *et al.*, 2005). One way of dealing with this is to facilitate outmigration of people from vulnerable areas through the provision of education and credit services offering alternative livelihoods (World Bank, 2009). However, high population pressure and market demand can in itself trigger investments in labour-intensive conservation practices and natural resources management (Nelson, 2005).

Another argument for taking a landscape approach (more on that in Chapter 11), is the role of trees. Recent assessments suggest that almost half of all agricultural land has more than 10% tree cover, indicating that trees are a mainstream component of agricultural landscapes (Zomer *et al.*, 2009) and may provide forest functions to some extent. Tree cover in farming landscapes can have a large impact on the infiltration and penetration of water and, thereby, on catchment hydrology (Carroll *et al.*, 2004; Fig. 3.1, Chapter 3). Furthermore, when tree cover is changed, other ecosystem services besides water flow may also be affected, such as pollination and carbon storage, and these can also influence agricultural productivity (Harvey *et al.* 2006). The impact of changing tree cover on various ecosystem services depends on its amount, spatial configuration, species composition and management, so there is a need to get beyond generalizations and look at tree cover at the landscape scale in order to meet specific objectives, including the consideration of trade-offs and synergies among the ecosystem services affected (Jackson *et al.*, 2013).

Conclusions

In recent years, there has been an inexorable rise in the demand for food and for water to grow food. Particularly, the high demand for water and land in commercial farming systems and, with it, the increased risks of pollution have led to the need for more economically, socially and environmentally viable agricultural systems in order to avoid ecosystem destruction. This chapter has explored these demands and challenges within an agroecosystems management context.

Growing concerns about the negative changes produced by agriculture on various ecosystems across the world (key ‘disservices’ from agriculture) have been analysed. The Millennium Ecosystem Assessment showed that agriculture has dramatically increased its ecological footprint, not only in terms of negative impacts but also in terms of its supply of ecosystem services for rural communities. A discussion of the value of ecosystem services has provided a better understanding of the linkages between agriculture and ecosystem services, paving the road for management options that are addressed in subsequent chapters.

Note

[1] Differentiating the groups here is important because different groups, for example men and women, young and old, or poor and rich, make very different use of the services available to them and may value these services very differently. The different use various social groups make of water and ecosystems, and the impacts of that in relation to development and conservation projects, are discussed in more detail in other publications (e.g. Thompson and Swatuk, 2000; Goma Lemba *et al.*, 2001; Sudarshan, 2001; Hassan *et al.*, 2005; www.genderandwater.org).

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