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Ecosystem Services and Food Security: Economic Perspectives on Environmental Sustainability

by

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ECOSYSTEM SERVICES AND FOOD SECURITY: ECONOMIC PERSPECTIVES ON ENVIRONMENTAL SUSTAINABILITY

by

Robert B. Richardson

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EXECUTIVE SUMMARY

Food security in developing countries depends in part on the sustainable use of natural resources. Food security is usually examined through three dimensions, namely the availability, access, and utilization of food. Ecosystems directly and indirectly support each of these dimensions through the provision of critical ecosystem services that facilitate agricultural production, create income-generating opportunities, and provide energy for cooking. However, in some cases, household uses of natural resources undermine particular elements of food security, hindering national poverty reduction strategies and threatening the sustainability of critical ecosystem functions. I examine the role of ecosystem services in rural food security through the lens of its three dimensions, and highlight the tensions that stem from household-level interactions and uses. In some cases, uses of resources and services that support the access and utilization dimensions may undermine the ecosystem functions that support food availability. The conclusions underscore the importance for the integration of ecosystem services into food security plans and poverty reduction strategies in developing countries.

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ACRONYMS

CARRS	Department of Community, Agriculture, Recreation, and Resource Studies
USAID	United States Agency for International Development
MSU	Michigan State University
FAO	Food and Agriculture Organization of the United Nations
US$	U.S. Dollar
NTFPs	non-timber forest products
PES	payment for ecosystem services

1. GLOBAL FOOD SECURITY: BACKGROUND AND CHALLENGES

Food insecurity has been rising in the past decade, and rates of hunger are presently higher than at any time since 1970 (FAO 2009). Although food production has increased dramatically over the past 50 years, more than one in seven people still do not presently have access to sufficient quantities of food (Godfray et al. 2010). The Food and Agriculture Organization of the United Nations (FAO 2009) estimates that 1.02 billion people were undernourished worldwide in 2009, which is roughly 37% higher than just 20 years ago. Approximately 98% of these people live in developing countries, and their share of total hunger rates has also been increasing over recent years, despite significant gains in food security in particular developing countries. Other studies have estimated that 3.7 billion, or more than half the world's population, suffer from malnutrition, and over 40% of deaths are due to environmental degradation (Pimentel et al. 2007). This increase in global food insecurity has been associated primarily with high domestic food prices and the global economic downturn. Worse, lower incomes and increasing unemployment have reduced access to food by the poor. The trend in hunger rates and food insecurity was increasing well before the recent food and economic crises, which calls into question the effectiveness of agricultural policies and poverty reduction strategies that have been implemented over the last 40 years.

Food security has been defined as a condition "when all people at all times have physical and economic access to sufficient food to meet their dietary needs and food preferences for a productive and healthy life" (FAO 1996). Food security is usually conceptualized in three dimensions (Barrett 2010; FAO 1996; USDA 1996; Webb et al. 2006): (1) the availability of sufficient quantities of food of appropriate quality, supplied through domestic production or imports; (2) the access by households and individuals to adequate resources necessary to acquire appropriate foods for a nutritious diet; and (3) the utilization of food through adequate diet, proper food preparation, clean water, sanitation, and health care. The three dimensions are hierarchical in nature. Availability is necessary but not sufficient to ensure access to sufficient food; adequate quantities of food may be produced, but may be inaccessible to hungry households because of price, distribution, income constraints, or social and cultural factors. Similarly, access to food is necessary but not sufficient to ensure effective utilization, which requires safe and proper preparation of food and the nutritional quality of household diets (Barrett 2010; Pinstrup-Andersen and Herforth 2008; Webb et al. 2006).

Nearly thirty years ago, Sen (1981) argued that access accounts for most food insecurity, which has shifted attention to policies that aim to reduce poverty and provide social safety nets. However, no single measure of food security captures all its aspects and complexities. Although the international community has broadly accepted that food insecurity is not a monolithic condition easily measured in terms of output, income, or energy availability, fundamental measures for identifying how, when, and where the various dimensions of food security become more critical to meeting basic human needs or have a greater bearing on food security outcomes (Barrett 2010; Webb et al. 2006). Daily et al. (1998) suggest two criteria for assessing humanity's achievements in ensuring global food security: the share of the population with secure access to basic nutritional requirements, and the extent to which global food production is sustainable. Focusing solely on the impressive growth in cereal production (which provides more than 50% of the energy consumption for the world's poor) and gross output per capita obscures the critical roles of food access and utilization, which are underscored by the aforementioned increases in rates of hunger and malnourishment. These concepts relate directly to the two criteria proposed by the authors. Recent evidence suggests that the deterioration in food security is driven more by a lack of access to adequate diet (mostly because of insufficient income and very high rates of unemployment). Furthermore, there is increasing concern that increases in global food production are being realized at the expense of critical natural resources that support both food production and the utilization of food through household-level choices, as evidenced by the widespread degradation of soils, lowering of water tables, clearing of tropical forests (Pimentel et al. 1997), and the prevalence of water-borne diseases (Daily et al. 1998). Food production will certainly continue to play an important role in ensuring food security through its contributions to the availability of food. However, future increases in production are likely to be constrained by the finite resources provided by ecosystems in ways that scientists are only beginning to understand (Daily et al. 1998; Godfray et al. 2010; Millennium Ecosystem Assessment 2005; Pimentel et al. 1997; Webb et al. 2006).

Food security in most developing countries depends in part on the sustainable use of natural resources and the sustainable provision of ecosystem services. Ecosystem functions directly and indirectly influence each of the dimensions of food security through the provision of ecosystem services that support agricultural production, create income-generating opportunities, and provide energy for cooking; thus, sustaining these functions is crucial for ensuring global food security. Ecosystem services affect all three pillars of food security by supporting the production of food (i.e., availability), the provision of resources that are used to enhance livelihoods and earn income (i.e., access), and the production of resources for safe and sanitary food preparation (i.e., utilization). However, poverty and food insecurity have been associated with negative household coping behaviors that disrupt ecosystem services and functions and contribute to environmental degradation (Barrett 2010; Costanza et al. 1997; Daily 1997; Daily et al. 1998; Fisher 2004; FAO 1996; Lal et al. 2003; Millennium Ecosystem Assessment 2005; Pattanayak, Sills, and Kramer 2004; Pimentel et al. 1995; Pimentel et al. 1997; Pinstrup-Andersen and Herforth 2008; Sen 1981; USDA 1996; Webb et al. 2006; World Commission on Environment and Development 1987). In some cases, the pathway out of poverty reduces one kind of environmental degradation while increasing another (Pinstrup-Andersen and Herforth 2008), creating a kind of two-way causal relationship between ecosystem integrity and food security.

Global food security is threatened by population growth and economic expansion, and these forces increase the demands on the finite resources of the planet. The associated increase in competition for natural resources and the long-term environmental impacts of food production exacerbate the already formidable challenges of ending extreme hunger and poverty. The human population is expected to increase 50% by the middle of the century, and growing per capita wealth is expected to increase the demand for meat, fish, and other foods that require the expansion of scarce land for cultivation and the intensive use of natural resources for production (Daily et al. 1998; Godfray et al. 2010). These factors will likely lead to increased competition for land, water, and other natural resources, threatening critical ecosystem functions and services that support food security, and straining ongoing efforts to achieve the specific outcomes outlined in the Millennium Development Goals and the World Food Summit Goals. The 1996 World Food Summit (FAO 1996) was organized by the FAO, and it sought to renew global commitment at the highest political level to the eradication of hunger, food insecurity and malnutrition by 2015. The Millennium Development Goals (United Nations 2000) were outlined in the 2000 United Nations Millennium Declaration, which committed signatory nations to a global partnership that aims to achieve the time-bound targets of eight specific goals, which include eliminating poverty and hunger and ensuring environmental sustainability by 2015. Unfortunately, food insecurity is greater by most measures today than 1990, which was designated as the base year these Goals (Pinstrup-

Andersen and Herforth 2008). Meanwhile, deforestation and the global emission of greenhouse gases have worsened since the declarations that defined these goals, underscoring the improbability of fully achieving their desired outcomes during the next five years. Furthermore, evidence suggests that the production of biofuels from grain crops increases competition for land, water, and energy that are vital for food production, and exacerbates the problem of malnutrition worldwide (Pimentel et al. 2009).

Underscoring concerns about the impacts of global population and economic growth on food security is the ominous threat of climate change and the deleterious effects it is expected to have on all aspects of food production and distribution. Most models of the sensitivity of world agriculture to the impacts of climate change suggest that the net effects on global food production may be small; damages in some areas are expected to be offset by gains in others (Mendelsohn and Dinar 2009; Rosenzweig and Hillel 1998). However, the vulnerability of agriculture is systematically greater for developing countries, particularly those in lower latitudes. Several factors contribute to this greater vulnerability: many such countries are already at or near their temperature threshold for many crops; agriculture constitutes a relatively greater portion of national GDP than in industrialized countries; and most developing countries have less capacity to adapt to climate change. Cereal grain yields in particular are projected to decline with increasing temperatures and moisture stress. In tropical regions, higher temperatures may accelerate the release of CO2 in plants during the process of respiration, resulting in steep reductions in crop yields. Changes in precipitation can increase the occurrence of moisture stress, such as increased soil evaporation and plant transpiration, which can be harmful for plant formation and growth, especially during the flowering and pollination stages. Extreme climate events such as extended periods of high temperatures, intense storms, and droughts can disrupt crop production or reduce yields (Mendelsohn and Dinar 2009; Rosenzweig and Hillel 1998).

In the future, global food security will continue to face ongoing risks related to natural, industrial, and civil disasters as well as economic shocks. In fact, growing awareness of these systemic risks to food security have led to an acceptance of the notion of risk as a fourth dimension of food security, to emphasize the hazards of increasing climatic variability, civil conflict, economic shocks, and disease epidemics (Webb et al. 2006). For the purposes of this paper, I contend that such hazards ultimately disrupt one or more of the three established dimensions of food security; since risk represents a pervasive theme that extends across all domains of the conceptual framework of food security, and it will not be given separate treatment, but the role of systemic risks will be noted where appropriate. For example, the implications of climate change for food insecurity in developing countries will almost certainly require farm-level adaptations in order to maintain or prevent losses to existing levels of food security.

The world faces a daunting set of intersecting challenges (Daily et al. 1998; Godfray et al. 2010): to meet the dietary needs of a larger and more affluent population in ways that are environmentally and socially sustainable, while eliminating extreme poverty and hungry. Given the importance of ecosystem functions for global food security, it is critical to understand their role in food production, consumption, and preparation. This paper introduces the concept of ecosystem services and examines their role in each of the three dimensions of food security. I argue that the ecosystem services that are used by households to ensure access to food—and to some degree, utilization of food—may exploit the very ecosystem functions that support and facilitate availability through the provisioning of food production services. The implications of this tension undermine the very critical role that agricultural production plays for food availability that is necessary—even if not sufficient—for global

food security. Evidence from previous research in environment and development is presented to characterize the household uses of soil, forest, and wildlife resources and the implications for the sustainable provision of ecosystem services. The nature of the findings highlights the importance for the integration of ecosystem services in food security research and poverty reduction strategies in developing countries.

2. ECOSYSTEM SERVICES

Ecosystems provide a range of benefits to all people, including the benefits of provisioning, regulating, cultural, and supporting services (Millennium Ecosystem Assessment 2005). The services and functions of ecosystems are critical for the support of life on Earth, and they contribute to human welfare both directly and indirectly (Costanza et al. 1997). Ecosystem services are the functions of an ecosystem that generate benefits or value to humans; they are the conditions and processes through which natural ecosystems sustain and fulfill human life (Daily 1997; Daly and Farley 2004). Ecosystem services are generated as emergent phenomena by the interacting elements of ecosystem structure. Emergent phenomena are properties of a system that are not recognizable by an understanding of individual parts (Daly and Farley 2004; Holling 2001). This aspect suggests the need for an awareness of the complex interactions between elements of the system. As emergent phenomena, ecosystem services interact with other systems and with each other, but the estimation of the impact of changes in the flows resulting from these interactions is often beset by high levels of uncertainty because of nonlinear influences and threshold effects (Daly and Farley 2004). For example, local environmental impacts of population growth may accumulate and rise in greater proportion than population growth rates themselves (Daily et al. 1998). The importance of ecosystem services for sustaining human welfare has motivated the recent and ongoing expansion of new scientific inquiry about these flows and their values, and how they contribute to human welfare (Millennium Ecosystem Assessment 2005). Specific ecosystem services have been identified and categorized depending on their role in enhancing human well-being. Examples of the benefits of ecosystem services include the provision of clean air and water (for both human well-being and economic security), essential support for the production of renewable resources (such as agriculture and forest products), the regulation of atmospheric gases, and the absorption and treatment of waste matter.

Costanza et al. (1997) documented 17 major categories of the world's ecosystem services and estimated their values per unit area, by biome or ecosystem. Values of the flows of global ecosystem services for 16 biomes were estimated to average US$33 trillion per year. Other authors and initiatives have categorized ecosystem services differently, combining or disaggregating some functions and services (Millennium Ecosystem Assessment 2005). Although ecosystem services provide essential inputs into aggregate global production (e.g., agriculture, raw materials, energy, fuels), most ecosystem services are not recognized in markets, so their values are unpriced and they typically are not reflected in benefit-cost analyses of the long-term impacts of production decisions. Ecosystem services are listed and described below in Table 1 grouped by the type of service (Costanza et al. 1997; Millennium Ecosystem Assessment 2005). Most of the ecosystem services can be distinguished as fund-service resources (Georgescu-Roegen 1971)—that is, an ecosystem *fund* provides a service at a fixed rate measured by physical output per unit of time. Examples of fund-service resources include hydrological flows, climate and gas regulation, nutrient cycling, pollination, and soil formation. Fund-service resources may be disrupted or degraded but they cannot be depleted, nor can they be stored for future use.

Table 1. Types and Descriptions of Ecosystem Services

Ecosystem service	Type	Description
Provisioning Services		
1. Food production	Stock-flow	Production of crops, meat, fish, fruits by subsistence farming, hunting, gathering, fishing
2. Raw materials	Stock-flow	Production of lumber, fuels, fiber, fodder, and other raw materials
3. Water supply	Fund-service	Provisioning of water by watersheds, aquifers, and springs for use and retention
4. Pollination	Fund-service	Provisioning of pollinators that support movement of floral gametes and the reproduction of plant species
5. Refugia and habitat	Fund-service	Provisioning of habitat for resident and migratory populations of species
6. Genetic resources	Fund-service	Provisioning of unique biological materials that provide medicines, resistance to plant pathogens
Regulating Services		
7. Gas regulation	Fund-service	Regulation of atmospheric chemicals (e.g., CO_2/O_2 balance,O_3 and SOx levels
8. Climate regulation	Fund-service	Regulation of global temperature and precipitation by greenhouse gas regulation, evapotranspiration
9. Disturbance regulation	Fund-service	Capacitance, integrity and resilience to storms, flooding, drought and other environmental variability
10. Water regulation	Fund-service	Regulation of hydrological flows that provide water for irrigation, transportation, and industrial processes
11. Waste absorption	Fund-service	Treatment of organic waste, recovery of mobile nutrients, breakdown of excess compounds
12. Biological control	Fund-service	Regulation of biological population through predator control of prey species, including pests
Supporting Services		
13. Erosion control	Fund-service	Retention of soil, prevention of loss by wind, runoff, and siltation
14. Soil formation	Fund-service	Accumulation of organic matter and weathering of rock in soil formation processes
15. Nutrient cycling	Fund-service	Processing and acquisition of nutrients through nitrogen fixation, assimilation of decayed matter
Cultural Services		
16. Recreation	Fund-service	Provisioning of resources that support recreational activities such as hiking, wildlife viewing, swimming
17. Cultural	Fund-service	Provisioning of resources that support artistic, educational, or spiritual uses and values of ecosystems

Adapted from Costanza et al. 1997; Millennium Ecosystem Assessment 2005.

By contrast, two of the ecosystem services—food production and raw materials—are essentially stock-flow resources, where a finite stock of some renewable resource provides a flow of benefits through their use, consumption, or extraction. Stock-flow resources are characterized by the fact that they can be harvested at any rate by humans, subject to available technology; and they may be used immediately or stored for future use. Furthermore, these services can be used up (*i.e.*, depleted), but they cannot be degraded or worn out like fund-service resources. This distinction is important, since the extraction of a stock-flow resource such as raw materials (e.g., fuelwood or timber from forests) partly depletes the stock of resources and degrades numerous fund-services from forest ecosystems (Daly and Farley 2004). Several unique characteristics of ecosystem services present particular challenges for the efficient allocation of resources and the achievement of food security objectives. First, the values of ecosystem services are not recognized in commercial and financial markets, and their benefits are not quantified in terms that are analogous to the uses of manufactured capital and economic services that are traded in markets (Costanza et al. 1997; Daly and Farley 2004). Thus, their values are frequently ignored or overlooked in private investment decisions and public policy deliberations. An economic system that prioritizes incentives only for the production and distribution of market goods will systematically ignore externalities that threaten the provision of critical public goods, including life-sustaining ecosystem functions and services (Daly and Farley 2004).

Market goods and services are characterized by excludability (where private property rights convey the privilege of use to owners that is denies to others) and rivalrous (where private use of a resource inhibits or precludes its use by others by reducing its overall availability). By contrast, pure public goods such as most ecosystem services are both non-excludable and non-rival, which implies that *users* of public goods do not pay for the benefits of these goods. For example, the benefits of storm surge protection, flood control, and waste absorption provided by floodplains and mangrove systems are free. Benefits accrue to local residents and businesses in coastal areas, to the producers and consumers of fish and seafood products harvested in these wetland areas, and to people who value the recreational opportunities to spend time fishing, canoeing, and wildlife viewing in such areas, and they do not pay for these services that clearly enhance or add value to their various uses of wetlands or coastal areas. None of these beneficiaries can be excluded from deriving value from the benefits afforded by the ecosystem service of disturbance regulation, and the benefits that accrue to them do not reduce the overall availability of benefits or the capacity of the wetlands to provide these benefits to other users.

However, if the functions of mangroves are impaired through physical damage or extraction, local residents, businesses, fishing operations, and recreational users all suffer damages. Since the benefits of ecosystem functions and services are unpriced and ignored by markets, there is no incentive to invest in their conservation or restoration—no profit and no apparent return on investment. So, if the production of other goods and services (e.g., agriculture, development of coastal infrastructure) impairs or destroys the functions of wetlands, there is no penalty or private cost for the damages imposed on the users of the services. Therefore, with no information about their values and no institutional structure to ensure that suppliers of ecosystems services are paid for the benefits they provide, public goods will be provided at levels that are below their efficient amounts in market economies. This inability of markets to recognize the value of public goods is known as a *market failure*. Ecosystem fund-services are pure public goods, and market economic theory is deficient in its treatment of the production and allocation of public goods, and as such, their provision is usually arbitrary and unevenly distributed (Daly and Farley 2004).

Economic approaches to environmental management have narrowly focused on the identification of the efficient level of environmental quality by focusing attention on the measurement of the marginal costs of pollution reduction (also known as abatement costs) and the marginal benefits of non-market environmental goods. The efficient level of environmental quality is the point where the marginal costs of pollution abatement are just equal to the marginal benefits of environmental improvement (Baumol and Oates 1988). Benefits of environmental improvements have historically been conceptualized in terms of the associated economic gain from productivity gains (through increases in agricultural production from better water quality or fewer days of work lost to illness because of improvements in air quality). The absence of a market for ecosystem services implies that their values will not be reflected in policy alternatives, which leads to the underestimation of the net benefits of pollution abatement and the establishment of environmental policies that permit inefficient or wasteful levels of emissions, ultimately threatening the sustainability of ecosystems where critical functions are impaired.

Furthermore, unlike market goods, which generally provide benefits only to the owner, public goods such as ecosystem services provide benefits to different populations, depending on the function and service, and the scope of their benefits. For example, the disturbance and water regulation services of wetlands provide valuable protection from flooding and storms, and the benefits of these services are primarily local public goods. By contrast, the climate regulation services of forests provide carbon storage benefits that mitigate the harmful effects of climate change, and these services are global public goods that generate the same benefits regardless of where the forests are located. This complication introduces scale and distributional issues that are highly relevant to the consideration of environmental, agricultural, and trade policy alternatives and choices (Daly and Farley 2004).

3. ECOSYSTEM SERVICES AND SOCIOECONOMIC WELFARE

All humans benefit from the Earth's ecosystems and the services they provide (Millennium Ecosystem Assessment 2005). The basic needs for human life are provided by these services, and as such, all people depend completely on the sustainable provision of food, water, clean air, climate, and the recreational and spiritual fulfillment derived from ecosystems. Disruptions to the flows of ecosystem services alter terrestrial and aquatic ecosystems and directly affect the benefits and costs of local human activities and household-level decisions, and the conditions for sustaining human welfare. These impacts have economic consequences for regions, individuals, and groups of people, and the environmental policies that govern the use of ecosystem services are ultimately social decisions. However, rural households are more dependent upon natural resources for subsistence and livelihoods (Daly and Farley 2004), and any policy or action to improve the flow of ecosystem services or restore ecosystem stocks is likely to involve benefits for some people and losses for others, owing to the competing uses of resources. Translating individual preferences regarding the environment to social choices is a fundamental challenge to the social sciences, including economics (Kolstad 2000). Individual attitudes and preferences about environmental management may be influenced by particular philosophical perspectives or worldviews, such as biocentrism, anthropocentrism, individualism, collectivism, or sustainability.

Nevertheless, neoclassical economists use the utility function to represent individual preferences in consumption (Baumol and Oates 1988; Goodstein 2008; Kolstad 2000). An individual *i*'s utility is represented as U_i in the following utility function:

$$U_i = U_i(X_1, X_2, \ldots X_n, E) \tag{1}$$

where $X_1, X_2, \ldots X_n$ represents the quantities of market goods consumed by individual *i*, and *E* represents the benefits of the flows of ecosystem services (such as water supply, pollination, and raw materials). It follows then that U_i represents the utility or satisfaction that *i* derives from the consumption of market goods and the quality and quantity of ecosystem services. A basic microeconomic view of the environment would use indifference curves to depict the combinations of market goods (material consumption) and ecosystem services that an individual would consume to maximize her or his utility (Kolstad 2000). The economic effect of a disruption in the flow of ecosystem services would be reflected in the impact of that change in environmental quality on individual well-being, and would be conceptualized as the quantity in material consumption that would be necessary to compensate for the losses associated with environmental damages.

It follows then that collectively, social preferences are represented by a social welfare function, which is comprised of the utility functions of individuals in a society (Baumol and Oates 1988; Goodstein 2008; Kolstad 2000). Accordingly, social welfare is generated by the flows of economic and ecosystem services (Daly and Farley 2004). The social welfare function may simply be the sum of individual utilities (which assumes equal marginal utility of consumption across individuals in a society), or individual utility functions may be weighted to promote certain social objectives, such as equity, fairness, human rights, or sustainability (Goodstein 2008). For a society with m individuals, social welfare is represented as *W* in the following social welfare function:

$$W(U_1, U_2, \ldots U_m) = \sum_j \Theta_j U_j, \Theta \geq 0 \tag{2}$$

where Θ_j represents a weighting of the utility of individual j (Θ may be equal across society, or it may vary among individuals, perhaps on the basis of income to increase socioeconomic equity, or on the basis of safety or sustainability to give some weight to the utility of pollution victims or future generations) (Goodstein 2008). The benefits of consumption are weighed against the costs of pollution and degradation of ecosystem services, and economic efficiency is achieved when net benefits are maximized (i.e., where no other preferable allocation exists). Critics of the utilitarian theory emphasize that individual utility functions are not fixed, and preferences about consumption or demand for environmental quality are subject to influence by advertising, technological developments, or knowledge about the effects of changes in the quality of ecosystem service flows (Goodstein 2008).

Neoclassical microeconomic theory is predicated on the assumption that individuals will maximize utility subject to a budget constraint, which ultimately generates a demand curve for the consumption of particular goods and services (including market goods and ecosystem services). A demand function depicts the quantities of a good that are consumed at various prices. Measures of the gain (or loss) in welfare associated with consumption can be obtained by comparing what a consumer would be willing to pay for a quantity of goods with the market price; the difference is known as consumer surplus, which is interpreted as the extra value consumers get over and above the price paid (Kolstad 2000). However, in most cases, the demand for ecosystem services is not known because most environmental *goods* are not valued in the market, so there are no observations for how much of an ecosystem service would be *consumed* at various prices (after all, there are no prices to observe). This problem poses particular challenges for understanding the value of gains or losses in individual or social welfare related to environmental damage or disruptions in the flows of ecosystem services.

In addition to the measurement and valuation problem related to the public good nature of ecosystems, the provision, allocation, and protection of ecosystem functions and services are also characterized by limited knowledge and information. There is insufficient understanding of the value of ecosystem services, despite their critical role in supporting the very existence of life on Earth. Furthermore, most ecosystem services are characterized by limited substitutability (Daly and Farley 2004). Although there are examples in history where substitutes for scarce resources were developed when price increases provided incentives for innovation, but scarce resources with public good characteristics offer no such incentives in the absence of prices and profits, and in many cases, adequate substitutes for ecosystem services simply may not exist.

Although knowledge about the economic contribution of ecosystem services to socioeconomic welfare is generally still nascent, the values of specific ecosystem services and the various methods for valuation are well documented (de Groot, Wilson, and Boumans 2002; Farber, Costanza, and Wilson 2002). While some may argue that ecosystems are invaluable, the economic benefits of ecosystem services may be conceptualized in a number of ways. Some services are associated with market goods that carry a price (e.g., habitat for fish in coral reef systems, or climate regulation for agricultural production), and their values can be derived from changes in market prices associated with a marginal change in the flow of ecosystem services. Alternatively, individuals who benefit from ecosystem services can be directly asked what they would pay for these services using stated preference approaches (e.g., contingent valuation) (Loomis et al. 2000). Indirect valuations may be used to measure society's willingness to pay for other services for which there are no markets.

A perhaps more intuitive approach to valuing ecosystem services is to calculate the cost savings from (or costs avoided by) protecting the ecosystem's functional capacity to continue providing the services (Farber, Costanza, and Wilson 2002). For example, in the case of carbon sequestration properties of forests, marginal benefits of climate regulation services can be understood as either the cost savings over the next cheapest storage option, or the economic value of the emission generating activity if emissions limitations become binding on a particular emitter. Values for individual ecosystem functions should be based on sustainable use levels, taking account of both the carrying capacity for individual functions (such as food-production or waste recycling) and the combined effect of simultaneous use of more functions. Intact ecosystems should be able to provide all the functions listed in Table 1 simultaneously and indefinitely (this is the essence of environmental sustainability), but there are numerous examples of ecosystems whose services have been disrupted or degraded because of overuse or unsustainable extraction and exploitation (e.g., tropical forests, coral reefs).

Although economic approaches to environmental policy have historically been based on command-and-control regulation (Baumol and Oates 1988), such approaches are difficult to enforce and have been associated with low rates of compliance. Nevertheless, in rural areas, households and individuals are ultimately the ones responsible for how ecosystem stocks and funds are used (Daly and Farley 2004), and in many cases, household-level choices result in environmental externalities that deplete ecosystem stocks and degrade their fund-services. Externalities (such as pollution or degradation of ecosystem services) exist when some consumption or production choice impacts another entity's utility or production function without permission or compensation. The value of the externality may not be known because of the absence policies that require compensation to victims. For example, the social value of the flow of benefits from the ecosystem services of forests has been found to far outweigh the private returns to an individual farmer who may be motivated to deforest the land for farming or withdraw water from an aquifer (Costanza et al. 1997; Daily et al. 1998). But the benefits of the ecosystem services are shared among the farmer and the rest of society, all of whom are probably unaware of the true value of the public goods generated by ecosystems. The individual farmer's decision ignores the fact that this extraction will increase the costs of extraction to other people by a marginal reduction in forest biomass or lowering of the water table. In this way, even though the farmer would impose a small additional cost on others, the social cost of agricultural production exceeds the farmer's private costs because the sum of the costs of these activities across society could be substantial. In the absence of a market for such services or some institutional framework that promotes cooperation among the beneficiaries, the benefits from timber and agricultural production accrue privately to the individual farmer, who is likely to manage the land for personal gain, to the detriment of ecosystem services and their passive consumers.

4. THE ROLE OF ECOSYSTEM SERVICES IN FOOD SECURITY

An inquiry into the role of ecosystems in advancing food security illuminates the interesting complexity in the relationship between food security and environmental sustainability. The structure, function, and services of ecosystems are complex in their own right, and the numerous flows of benefits and stressors between ecosystems and the dimensions of food security for humans are not yet fully understood by ecologists, economists, and other scientists. Nevertheless, there are several examples of studies and reviews that have documented the benefits of particular systems and their contributions to socioeconomic welfare and food security (de Groot, Wilson, and Boumans 2002; Farber, Costanza, and Wilson 2002; Loomis et al. 2000; Pimentel et al. 1997; Richardson 2008). Focusing solely on the example of the goods and services provided by forest ecosystems, Pimentel et al. (1997) reviewed studies of the contributions and values of forest resource uses and concluded that the integrity of forests is vital to world food security, mostly because of the dependence of the poor on forest resources. In assessing the role of forests and non-timber forest products (NTFPs) in the food system of developing countries, they categorized forest uses into ten groups, described below in Table 2.

These authors assessed the total amount of foods produced from trees, the wild foods gathered and animals hunted from forests, and the forest resources used in generating non-farm income and wage employment. They estimated that between 60 and 70% of the

Table 2. Forest Products and Services that Support World Food Security

Forest Products	Examples
1. Wild foods	Wild plant roots, leaves, fruits, nuts; animal meat, fish, insects
2. Cultured tree crops	Banana, coconut, citrus, mango, palm oil, papaya, peach, apple, plum breadfruit, and cacao
3. Food production support	Agro forestry, water retention; nitrogen fixation from leguminous trees
4. Fodder	Trees, shrubs, grasses as fodder for livestock production
5. Employment	Wage employment in forestry or forest-based enterprises; self employment in the gathering and sale of forest products
6. Forest-related fuels	Biomass fuels for cooking and heating, such as fuelwood, charcoal, crop residues, and dung
7. Shelter	Polewood, soils, and mud for home construction; leaves and other plant matter for roofing
8. Soil erosion	Trees in forests and used in agro forestry practices help control soil erosion and protect cropland, pastoral land, and forest ecosystems
9. Water conservation	Forests slow water runoff, help prevent flooding
10. Biodiversity preservation	Forests enhance food yields by protecting biodiversity that is essential to human survival; waste treatment, nutrient cycling, pollination of crops and other vegetation, pest control

population in developing countries live and work near forested areas, and many households subsist in part by collecting leaves, roots, fruits, and nuts from trees and other wild plants, and by hunting wild animals, fish, and insects for consumption. Many people living in and around forest reserves harvest a range of products from forests for sale, trade, or barter, such as wood for timber, fuelwood, roof thatching materials, construction poles, honey, mushroom, caterpillars, medicinal plants. Approximately 300 million people worldwide earn part or all of the living from harvesting food and other products from tropical forests for income generation.

Ecosystems such as forests have a profound impact in rural livelihoods and food security in the developing world. In the example of forests, the goods and services of forests described in Table 2 all support the pillars of food security in numerous ways. Complicating matters further, while most of the ecosystem services of forests are fund-services that provide a flow of benefits at a fixed rate (and generally meet the criteria of pure public goods), the benefits of forest-based fuels and goods extracted for shelter are stock-flow resources. They can be harvested at any rate, and as such, they are subject to depletion. However, the widespread dependence on forest products for cooking and heating fuel, and the clearing of forest land for agriculture obscure the implications for natural resource conservation policy.

The convoluted and multifarious links between ecosystem services and food security may be better understood through the lens of the individual dimensions of food security. In this section, I examine the contribution of ecosystem services to household-level food security through the lens of the three dimensions of availability, access, and utilization. The services of ecosystems and natural capital clearly sustain all three dimensions of food security both directly and indirectly by supporting the production of food, the provision of livelihood opportunities and income, and the production of resources for food preparation and sanitation. However, I will demonstrate how uses of ecosystem services that primarily support the dimensions of access and utilization may threaten the sustainability of vital ecosystem services that directly support the very critical dimension of food availability.

4.1. Availability

The role of ecosystem services in ensuring the availability of food is straightforward. As a stock-flow resource, the ecosystem service of food production supports the provision of land, water, sunlight, and plant and animal species. Food production flows are measured as the portion of gross primary production extractable as food. When combined with human labor, energy, and other inputs, this ecosystem service allows rural households in developing countries to produce crops, meat, and fish through subsistence farming, hunting, gathering, and fishing. As an ecosystem service, the contribution of food production to the global availability of food has played a fundamental role in sustaining life throughout human history. During the Paleolithic Age, Homo sapiens had primarily subsisted by gathering plants and hunting or scavenging wild animals without significant recourse to domestication of food resources (Hillel 1991). Early humans lived in mixed habitats that allowed them to collect nuts, fruits, seafood, and eggs, in addition to scavenging from the carcasses of animals that were killed by natural predators or died by natural causes. Later in the Upper Paleolithic Age (approximately 75,000 BP), some bands of hunter-gatherers began to specialize in the development of hooks, bone harpoons, and fishing nets that led to more hunting of game and less gathering of plant resources.

Agriculture first evolved in the Neolithic Age (around 10,000 to 20,000 BP) in Western Asia (the Middle East), and spread south and east to the Nile, Indus, and Yangtze valleys of Asia and Africa (Hillel 1991). It has been an elemental factor in the development of human civilization, since the vast majority of humans labored in agriculture for nearly 10,000 years, up until the time of the Industrial Revolution. Hunting and gathering practices continued alongside agricultural production for several millennia, but the expansion of agriculture and the intensification of land use contributed to the perpetual decline in the practices of collecting food and hunting for meat, as areas which were formerly available to Neolithic humans were encroached upon by the settlements of agriculturalists. Since its early development, agriculture has expanded immensely both in geographical scale and yields, largely due to the expansion and intensive use of land under cultivation and the development of core agricultural techniques such as irrigation, mono-cropping, and the use of specialized labor.

Modern agriculture has been characterized by a rapid expansion of cultivated land, substantial gains in productivity, water pollution, government subsidies, and substitution of labor by synthetic fertilizers and pesticides. Monoculture, the agricultural practice of producing a single crop over an expansive, is used widely in industrial agriculture, and it has been associated with increases in pest infestation that are controlled through the increased use of pesticides. Concerns about the external environmental effects of intensive agriculture and its sustainability have given rise to the promotion of organic agricultural practices and resistance to the development of genetically modified food in parts of Europe and North America, and these movements are small but nascent. Intensive agricultural practices have contributed to the degradation of soils throughout many parts of the developing world, and worries over the effects of chemical fertilizers and pesticides on the environment have increased, particularly as population and economic growth continue to expand the global demand for food (Daily et al. 1998).

Ecosystems provide raw materials such as fodder and forage that also contribute to food availability through the production of livestock for meat and dairy consumption. Seeds, grains, herbaceous legumes, tree legumes, crop residues, grass, hay, leaves, seaweed, and fishmeal are all used as feed for domesticated livestock animals. As a stock-flow resource, raw material production shares many of the characteristics of food production, including the fact that raw materials can be produced at any rate by humans, used up immediately, or stored for future use, subject to human objectives and decisions; that is, humans have control over the rate of resource flows produced by ecosystem stocks. Furthermore, stocks of raw materials can be depleted through overuse, but they are not degraded or worn out like fund-service resources (Daly and Farley 2004).

Food availability is directly supported by numerous ecosystem fund-services as well, and many of the services that underpin the production and availability of food are under increasing threat (Daily et al. 1998). Ongoing losses of fertile cropland around the world pose perhaps the most significant threat to food production. The contributions of the regulation and supply of water, the regulation of global climate and atmospheric chemical composition, soil formation, erosion control, and other ecosystem services to food availability is apparent and unambiguous (Daily et al. 1998; Lal et al. 2003; Sen 1981). The provision of water for agriculture through irrigation, for industrial uses in food processing, and for transportation of inputs and food products all directly support the availability of food for human consumption. Soil formation processes, nutrient cycling, and pollination all directly support the reproduction and growth of plant-based foods. Finally, in ways that scientists may only be beginning to understand, the ecosystem structural elements that create genetic resources clearly and directly support food availability by providing the unique biological materials that promote crop resistance to plant pathogens and pests.

However, as previously emphasized, unlike stock-flow resources, the benefits of ecosystem fund-services are provided at a fixed rate of flow (measured by output per time), and they may be degraded or worn out, but not stored, used up, or depleted. Increases in flows from food production are often realized by household choices about the expansion of cultivated land and intensive land use practices. In such cases, the increased flows from food production come at the expense of ecosystem fund-services. The clearing of forest land for agriculture and the application of synthetic fertilizers and pesticides contributes to the depletion of natural capital stocks and degrades critical ecosystem fund-services that also support food availability indirectly (Daily et al. 1998).

Furthermore, annual grain production has been found to compromise essential ecosystem services, pushing some beyond sustainable thresholds. Soil erosion by wind and water, excessive soil cultivation, and overuse have contributed to the loss of about 30% of arable and fertile cropland over the past 40 years, and the problem is severe in many regions of the world. Deforestation and overgrazing have been associated with disturbances in hydrological cycles that lead to encroaching deserts, increased salinity, and erosion (Godfray et al. 2010). However, natural vegetation and biological soil crusts protect the important function of erosion control. Natural vegetation and soil aeration protects soil from wind and water erosion. Soil stability and productivity often depend upon physical and surface soil crusts that develop slowly over many dozens of years. These crusts are easily destroyed, and soil recovery is a slow process. The practice of conservation agriculture usually involves some or all of a set of farming practices that includes dry-season land preparation using minimum tillage systems, crop residue retention, seeding and input application, mulch farming, nutrient management using manure and compost, nitrogen-fixing crop rotations, and agro forestry. Restoration of degraded soils using these practices is an important strategy for enhancing ecosystem services and advancing food security.

Vegetative ecosystems have been found to play an important role in climate modulation and regulation through the net CO2 exchange in tropical, arid, and semi-arid ecosystems. Vegetation and soils in forests, grasslands, and deserts also provide climate regulation services by sequestering carbon that would otherwise contribute to climate change (Lal 2009; Luo et al. 2007). In addition to enhancing food security, carbon sequestration has the potential to offset fossil fuel emissions. However, agricultural production practices alter the carbon cycle and affect the carbon sequestration properties of soils. Therefore, adoption of restorative land uses such as reforestation as well as farming techniques associated with conservation agriculture can enhance ecosystem funds of soils and organic carbon and improve soil quality. Furthermore, the climate regulation services of soil carbon sequestration helps mitigate climate change by offsetting emissions of fossil fuels and improving water quality by reducing nonpoint source pollution (Lal 2009; Lal et al. 2007).

Hillel (1991) asserted that “if soil is the material substrate of life, water is literally its essence” (p.16). The ecosystem fund-services of water regulation and supply directly support food availability by providing the hydrological flows that facilitate crop irrigation, the storage and retention of water, and the milling, processing, and transportation of food products. The availability of food would not be possible without the sustainable provisioning of water by watersheds, aquifers, and reservoirs.

The role of gas and climate regulation in food availability is not fully understood, but recent research on the impact of climate change for agricultural production indicates that damages from climate change are likely to be economically significant and distributed unevenly around the world, based on physical vulnerability and adaptive capacity. The availability of food is highly dependent on suitable climatic conditions, and the sustainable production of food and raw materials is vulnerable to changes in temperature, precipitation, and concentrations of carbon dioxide. The geographic and regional dimensions of climate change threaten the security of food availability through disruptions to crop yields, production possibilities, trade flows, and technology. At the same time, the production and transportation of agricultural goods and raw materials also contribute to global environmental change, as they are associated with land clearing and deforestation activities that ultimately lead to emissions of carbon dioxide, methane and nitrogen (Godfray et al. 2010).

Integrated assessment models have been used to connect relevant biophysical and socio-economic variables to measure the impacts of climate change on economic sectors such as agriculture, forestry, and fisheries. Integrated assessment models rely on causal relationships, extending from fossil fuel emissions to increased greenhouse gas concentrations, changes in temperature and atmospheric water, and eventual damages to society resulting from climate change (Nordhaus 1994). There is considerable inertia in these causal relationships as well as lag effects, so the impacts of climate change will follow greenhouse gas concentrations, even if emissions are dramatically reduced (Mendelsohn and Dinar 2009). Estimates of how emissions will affect agriculture depend upon predictions of climate sensitivity, farm productivity, and technological change.

Cross-sectional models, agronomic-economic models, and ecological zonal models have been used to estimate the effects of changes in temperature, precipitation, soil, and technology on agricultural output and patterns on global and regional scales. Generally, these models have estimated near-term gains to agricultural production in North America and Europe, and net losses for Africa, Asia, and Latin America. Findings from estimates of the economic impacts of climate change suggest that agriculture in developing countries is relatively more sensitive to climate variability than agriculture in developed countries (Mendelsohn and Dinar 2009). Rain-fed cropland is generally more sensitive to climatic variability than irrigated cropland and crop agriculture is more sensitive than livestock production. Inquiries into farm-level adaptation reveal that farmers adjust to environmental change by varying crops and livestock species, implementing irrigation practices, and rotating between livestock and crops. Impacts and adaptations vary a great deal across landscapes, suggesting that adaptation policies must be location specific and consider traditional ecological knowledge.

More than 99% of the global food supply comes from the land, so ample amounts of land, water, and biodiversity will be necessary to ensure an adequate food supply in the future. In the past, increases in food production were met largely by the expansion of more land for agriculture and the exploitation of new fish stocks (Godfray et al. 2010). Yet gains to crop production in recent years have far outpaced the increase in land devoted to arable agriculture, which reveals the limits to which additional expansion of land can contribute to future increases in food availability. Bringing significant amounts of new land into cultivation seems implausible, particularly given the competition for land from urbanization and the growing awareness of the need to protect biodiversity and ensure the sustainability of public goods such as ecosystem services. The use of grain crops for biofuel production increases the demand for food, contributing to food shortages and worsening the ongoing problems of malnutrition and food security (Pimentel et al. 2009).

Furthermore, food scarcity manifests itself locally, so efforts to secure the availability of food must reflect local conditions, which are increasingly characterized by rural household vulnerability to insecure land tenure and declining farm size among smallholders (Daily et al. 1998). Land tenure and property rights are crucial elements in supporting the availability of food, since securing property rights in land or improving land access enables household investment of land, labor, and capital in food production. Since roughly 1960, the ratio of land under crop cultivation to agricultural population (a rough proxy for per capita farm size) has been shrinking gradually but consistently (Jayne et al. 2003). Some relatively densely populated countries in Sub-Saharan Africa have seen this ratio cut in half over the past 40 years.

In summary, the availability of food will continue to be bolstered by food production, but increases in production will face unprecedented constraints by the finite stocks and funds of the Earth's ecosystems (Godfray et al. 2010). Still, production forecasting models estimate that food production will increase at rates that will be sufficient to meet the dietary, energy, and nutrient needs of the nine billion people that are expected to populate the Earth by 2050 (Pinstrup-Andersen and Herforth 2008). The discussions below of the other two dimensions of food security illustrate how the challenges of advancing food security may be less about increasing the global productivity of agriculture, but rather about income generation that provides household-level access to food, and about the utilization of food in ways that support a healthy life and environmental sustainability.

4.2. Access

The second dimension of food security refers to access by households and individuals to adequate resources to acquire appropriate foods for a nutritious diet. Access is probably the least understood dimension of food security, and constraints to food access are complex, multifaceted, and difficult to measure (Webb et al. 2006). Nevertheless, improving access to food may be more important in advancing food security goals than merely expanding food availability through increases in agricultural production. The hierarchical nature of the three dimensions of food security imply that the availability of food is necessary but not sufficient to ensure access to sufficient food; adequate quantities of food may be produced, but may be inaccessible to hungry households because of price, distribution, insufficient income, or social and cultural factors. Similarly, access to food is necessary but not sufficient to ensure effective utilization, which includes safe and proper preparation of food and the nutritional quality of household diets (Barrett 2010; Pinstrup-Andersen and Herforth 2008; Webb et al. 2006).

Food security theories and initiatives have long been dominated by concerns about the availability of food. It followed from the common practice of conflating hunger and famine with a lack of food availability (Webb et al. 2006). The primary concern in food security research and policy considerations was food availability, particularly domestic food supplies. However, Sen (1981) offered a broader interpretation of food security. He argued that people commonly suffer from extreme hunger and food deprivation not because food is unavailable, but because their access to food is impeded or constrained. He emphasized that access accounts for most food insecurity, and his conceptual contribution redefined the way that food security is conceptualized in food security research and development literature. The ensuing debate sparked distinct three developments in how constraints in access to food are conceptualized (Webb et al. 2006). First, there has been a shift away from focusing on measures of food availability and utilization to indicators of inadequate access. Second, there has been a shift from a focus on objective to subjective measures of access. Finally, the previous reliance on distal, proxy measures of food access is gradually being replaced by a growing emphasis on fundamental measures. This broader interpretation of food security has focused attention on policies that aim to reduce poverty and provide social safety nets. The locus of debate shifted from macro-level concerns about the food supply to household-level food access and the ability of households to obtain food in the marketplace or from other sources such as transfers or gifts (Daily et al. 1998; Jayne et al. 2003).

Although the role of ecosystem services in ensuring access to food may not be as initially evident as it is in ensuring food availability, ecosystem functions directly and indirectly support household-level access to food in numerous ways. These include the provision of services that allow for the transportation and processing of food as well as for the production of agricultural goods and raw materials that can be sold to generate income. In some cases, the production of ecosystem services creates non-farm employment opportunities that provide wage income to households. Many rural households engage in the harvesting and use of wood and NTFPs for numerous purposes that help them to enhance their livelihood and increase their access to food (Pattanayak, Sills, and Kramer 2004; Pimentel et al. 1997), and nearly one-third of the world's forests are primarily used for the production such products. Given the seasonal nature of agriculture, the production and sale of charcoal, food, and other NTFPs sustains many rural households during the off-season (Osemeobo and Njovu 2004). In rural areas, much of the use of forest products supports access to food by providing opportunities that help poor households purchase necessities. Opportunities to use stock-flow resources for self-employment or for participation in business activities such as the sale of food and fuelwood in markets are particularly important to ensure food access for female-headed households. In some cases, women are excluded from participating in certain business activities depending upon cultural norms and rules, and many women commonly engage in the sale of food products and raw materials in markets to help them purchase food and other necessities where employment opportunities are scarce.

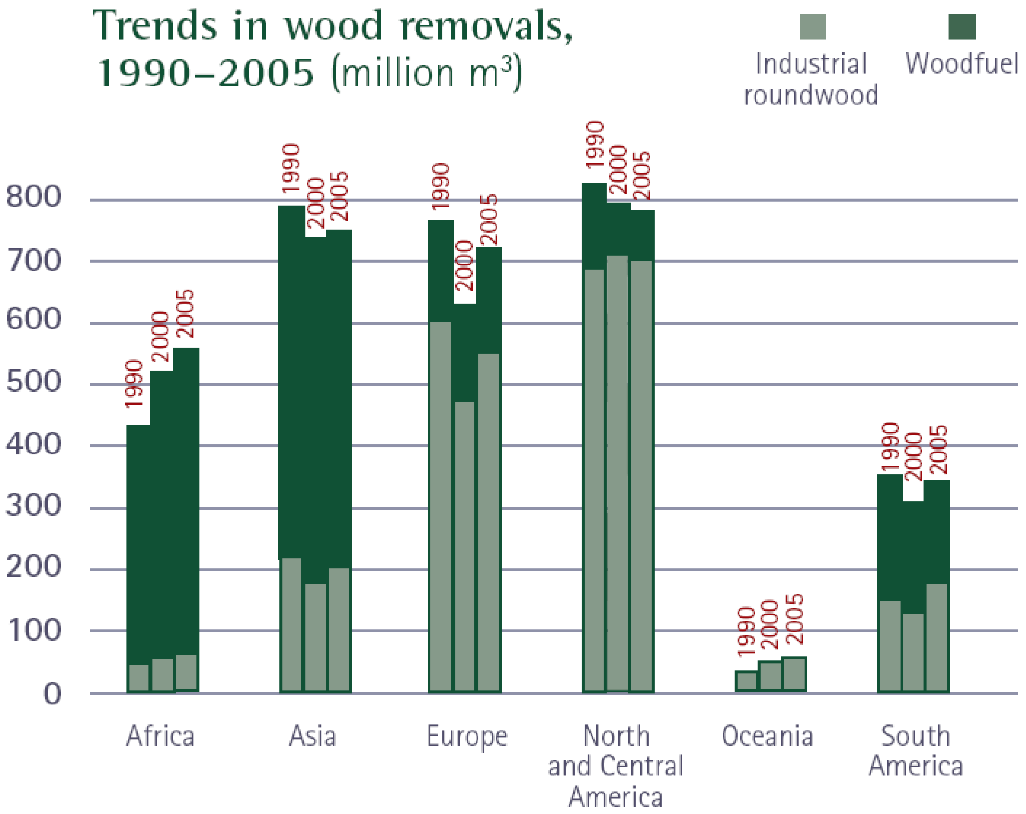
Empirical studies show that non-farm activities are typically positively associated with income and wealth and the ability to manage risks and cope with adverse shocks (Barrett, Reardon, and Webb 2001; Reardon 1997), a fact that underscores the importance of ecosystem services for non-farm income that increases access to food. Both push and pull factors help explain the role of non-farm business activities in supporting access to food. Rural households may be drawn to such activities with the intent of using ecosystem goods or services to enhance their livelihood through the gathering, production, and sale of food, fuelwood, and other NTFPs. Such pull factors are associated with entrepreneurial participation, where the household investment in capital and production reveal a longer-term outlook for participation in such activities. Alternatively, they may be compelled to exploit ecosystem services for the sale of products in order to deal with adverse price, income, employment shocks, to supplement inadequate crop harvests, or to cope with drought, flooding, or natural disasters. Such push factors are associated with more casual engagement with non-farm business activities that rely on ecosystem resources and services, and participation may be occasional and erratic (Haggblade, Hazell, and Reardon 2007). Globally, food products account for the greatest share of NTFPs harvested, which underscores the importance of forests for sustaining access to food. Households subsist in part by gathering leaves, roots, fruits, and nuts from trees and other wild plants, and collecting mushrooms, caterpillars, and medicinal plants, they sell them in markets for income (Pimentel et al. 1997). Estimates of the value of non-wood forest product vary widely. The reported value of global NTFP removals in 2005 was estimated at about US$18.5 billion (FAO 2010). An estimated value of harvested food and other NTFPs of about US$50 per hectare per year (Godoy, Brokaw, and Wilkie 1995) would yield about $90 billion in NTFPs harvested for use or sale each year (Pimentel et al. 1997). However, estimates of the volume and value of NTFP removals are plagued by problems of poor quality data and missing information from many countries in which forest products are highly important. Therefore, the true value of subsistence use is rarely captured. As a result, estimates based on reported statistics probably cover only a fraction of the true total value of harvested NTFPs (FAO 2010).

Evidence from food security research in Sub-Saharan Africa indicates that NTFPs represent a growing source of off-farm income. Studies of the contribution of NTFPs to rural household income have estimated income shares that range from 25 to 75% for households that engage in livelihood activities related to such products (Arnold, Köhlin, and Persson 2006; Osemeobo and Njovu 2004; Shackleton and Shackleton 2006). Asset-poor households have been found to depend upon NTFPs more acutely than wealthier households, primarily because of the absence of personal savings or safety nets to moderate the extreme effects of economic or environmental shocks (Shackleton and Shackleton 2006). The direct use value of fuelwood in poor households was found to be roughly double that for wealthy households.

In addition to non-wood forest products, many people living in and around forest reserves harvest wood for timber and fuelwood, as well as roof thatching materials and construction poles. World deforestation, mostly through the clearing of tropical forests for expansion of agricultural land use, has fallen slightly in the past decade but continues at troublingly high rates in some of the most vulnerable countries, threatening environmental sustainability as well as access to food and raw materials by rural households. Approximately 13 million hectares were converted to other uses or lost to natural causes each year between 2000 and 2010, down from around 16 million hectares in the 1990s (FAO 2010). South America and Africa continue to have the largest net loss of forest. The area of planted forest is increasing, but remains a very small share of total forest area. Globally, per capita growth in forest resource production and agricultural expansion cannot keep pace with human needs, especially given the expected rates of population growth (Pimentel et al. 1997).

After declining slightly in the 1990s, annual wood removals have begun to increase again. Globally, reported wood removals amount to about 3.4 billion cubic meters annually, which is equivalent to approximately 0.7% of the total growing stock. Figure 1 illustrates trends in annual wood removals for industrial and fuelwood uses by region between 1990 and 2005. Often farmers clear land and convert trees into charcoal. Investment costs for charcoal production are low, and returns on investment are reported to be high (Osemeobo and Njovu 2004). Given the extent and stability of the demand for charcoal and fuelwood, the ease of market entry, and low startup costs, participation in the production and sale of these products is an attractive opportunity as a source of household income. Although the demand for charcoal will be discussed in the next section, the use of forest resources for the production and sale of raw materials such as fuelwood exemplifies the role of forest ecosystems in ensuring access to food. Note that the share of regional wood removals for fuelwood uses is greatest in Africa and Asia, where food security generally, and access to food specifically, is most vulnerable.

Figure 1. Trends in Wood Removals for Industrial and Fuelwood Uses, by Region, 1990-2005



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As a largely open access resource, the fuelwood problem results from a lack of enforceable property rights (i.e., excludability) (Daly and Farley 2004), which complicates the long-term outlook for meeting the energy and fuel needs of rural households for the sustainable utilization of food. To make more effective decisions about the regulation and monitoring of forest product use, policymakers will require better information on the stocks, collection, processing, distribution, and demand for fuelwood in developing countries. Although the consequences of widespread deforestation are global in nature, the fuelwood problem and its solutions are fundamentally local.

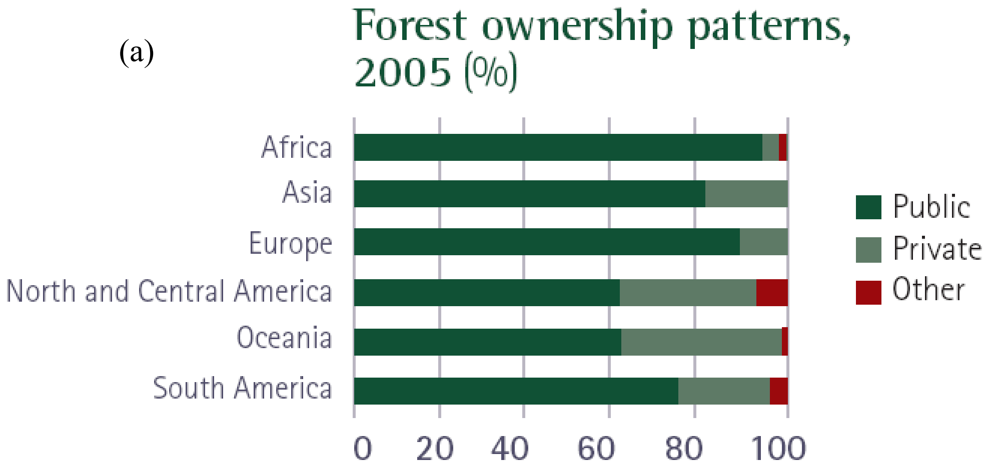
While deforestation certainly requires enforcement of existing laws that regulate the industrial clearing of forests, efforts to control the extraction of timber and wood products from forests should take into consideration the motivation for household participation in business activities that help to provide access to food. Many rural households appear to engage in resource extraction and selling in order to supplement agricultural income, particularly in years of low crop productivity. Non-timber forest products represent a growing area for income generation, and their production and sale is particularly important for the livelihoods of the poor. The regulation and monitoring of entrepreneurial use of forests for fuelwood production activities may be less complicated than that of the casual and irregular engagement in such activities as coping strategies to reduce vulnerability to exogenous shocks that threaten food access.

Food security, broadly conceived, depends in part on secure access to land and on the sustainable use of natural resources. Land tenure and property rights are important elements in supporting the access to food. Securing property rights or improving land access enables households to engage in the production of agricultural goods and other products for sale. Many households use land and natural resources as a safety net for securing livelihoods when markets are weak or absent, or when coping with political uncertainty or natural disaster. Furthermore, securing property rights for businesses encourages investment and provides wages and income to rural households that enable them to purchase food.

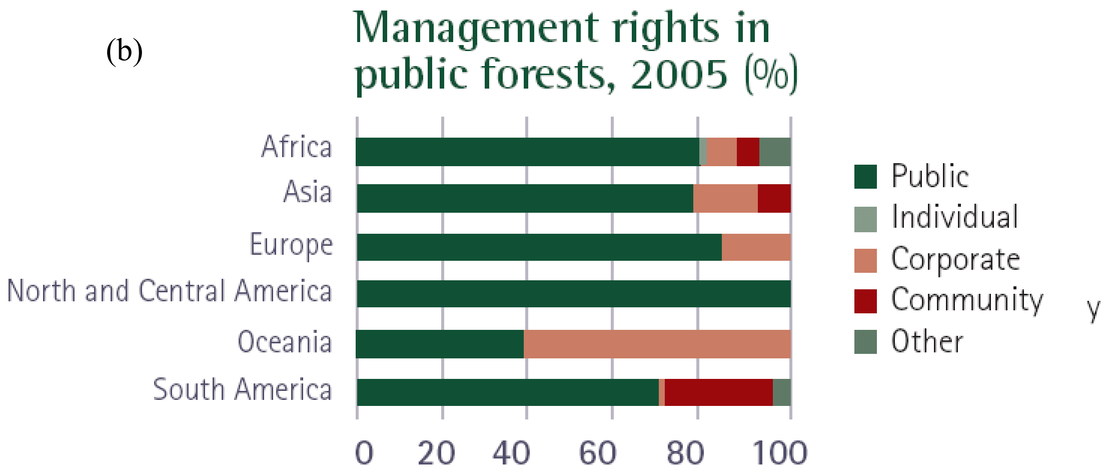
Approximately 80% of the world's forests are publicly owned, and the share of publicly owned forests is greatest in Africa. However, despite the prevalence of public ownership of forests in most parts of the world, ownership and management of forests by communities and individuals is on the rise (FAO 2010). In particular, individuals and communities are given significant management rights in public forests in some regions of the world, in some cases through community-based natural resource management programs. Figures 2a and 2b illustrate the shares of global ownership and management rights of forests, by region, 2005.

Figure 2a. Global Forest Ownership Patterns, by Region, 2005
Figure 2b. Global Management Rights in Public Forests, by Region, 2005

(a)



(b)



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In summary, policies that have failed to alleviate food insecurity in spite of gains in agricultural productivity were driven by an overreliance on domestic agricultural solutions to problems that are in many ways driven by constraints to food access and the inability of households to obtain food in the marketplace or from other sources (Webb et al. 2006). Rural households use the services of ecosystem stocks and funds in a variety of ways to produce food, fuel, and other goods that are sold in markets to generate income. Household-level purchasing power is the key to increasing access to food, and the benefits of ecosystem resources and flows provide numerous opportunities to enhance livelihoods and increase household income to support the purchase of food. However, the excessive and arbitrary extraction of stock-flow resources such as wood for timber and fuel products threatens the sustainability and integrity of forest ecosystems that underpin the very livelihood opportunities that improve food access, ultimately jeopardizing the objectives of food security generally. The following discussion of the utilization of food highlights several forces that contribute to this tension between food access and environmental sustainability, including the growing pressure of urbanization, which fuels demand for the production and transport of charcoal used in the preparation of food for safe and sanitary consumption.

4.3. Utilization

The food security dimension of utilization is concerned with how households use the food to which they have access, which depends upon safe and sanitary cooking practices and the nutritional quality of household diets (Barrett 2010; FAO 2010; Godfray et al. 2010; Webb et al. 2006). As with the hierarchical nature of food availability and access, food access is a necessary but insufficient condition to ensure effective utilization, which includes safe and proper preparation of food and the nutritional quality of household diets (Barrett 2010; Pinstrup-Andersen and Herforth 2008; United States Department of Agriculture 1996; Webb et al. 2006). Utilization had received a fair bit of attention in research and policy analysis even under narrower interpretations of food security, because of the apparent links between food utilization and nutrition (Sen 1981; Webb et al. 2006). However, the relationship between ecosystem services and the utilization of food may not be readily evident. Widely accepted indicators have been used as proxies to measure impaired utilization, including malnutrition, morbidity, disease outbreaks, and excess mortality, but these do not directly capture the contribution of ecosystems to food utilization. Instead, they represent only a narrow, usually indirect, measure of what is a larger, multifaceted phenomenon that does not fully capture the complexities of the relationship between food security and environmental sustainability (Webb et al. 2006).

Nevertheless, ecosystem services contribute to the utilization of food by rural households and smallholders in numerous ways, including the provision of water for safe drinking and food preparation; the fuels and energy for hygienic heating, cooking, and storage of food; the materials for sanitation and health care; and the micronutrients necessary for an adequate diet (Costanza et al. 1997). As an ecosystem service, water supply provides essential water resources that are necessary for hydration, food preparation, and general cleaning, and reservoirs and aquifers retain water to support use during dry seasons. The regulation of hydrological flows supports human health by controlling water-borne diseases, which are ubiquitous in much of the developing world. And the service of erosion control helps to minimize siltation in streams and rivers used by rural households, and it helps to moderate air quality limiting the emission of discrete soil particles known as particulate matter, which is a major source of air pollution associated with poor visibility and severe risks to human health (Millennium Ecosystem Assessment 2005; Richardson 2008).

A crucial element of food utilization is the safe and sanitary preparation of food. Cooking is essential for preventing disease, improving nutrition, and increasing the taste of many foods (Pimentel et al. 1997). Many poor countries derive virtually all of their energy from biomass sources. Various biomass fuels are used by households in developing countries for cooking and heating, and they amount to about 4.1 billion dry tons burned for fuel annually. About half of this is fuelwood, and even with its widespread use in cooking, more than half of the people who depend on this resource for fuel have inadequate supplies. Still, wood is the largest source of renewable energy, accounting for 5% of world energy supply, and it is by far the most important source of energy in many of the poorest countries; in half the countries of Africa, wood is the source of more than 70% of total energy consumed (Murray and de Montalembert 1992). In this way, wood and other biomass plays a significant role in supporting the appropriate utilization of food, particularly in countries where other options do not exist.

Although fuelwood collection from small woodlands in predominantly agricultural landscapes can result in substantial land degradation, fuelwood collection is a relatively minor factor in overall tropical deforestation, as compared to the pressures of clearing forests for the expansion of land for agricultural cultivation (Pattanayak, Sills, and Kramer 2004). Trees are usually pruned for the production of charcoal and fuelwood, rather than felled (although charcoal production contributes more extensively to deforestation in cases where smallholders are compelled to clear forest land for agricultural expansion and produce charcoal and fuelwood from the timber and remnants).

The livelihood opportunities associated with the production and sale of forest products described earlier are made possible by the growing demand for charcoal in urban areas for cooking fuel to support the appropriate utilization of food throughout the developing world. The increasing demand for charcoal has contributed to rural livelihoods and enabled the expansion of domestic markets, particularly in urban areas where fuelwood is scarce (Arnold, Köhlin, and Persson 2006). The growing pressures of household migration from rural areas to urban centers has been driven in part by rural population growth, limited rural employment opportunities, and constraints on the access to alternative cooking fuels because of poverty, high prices, and under-developed infrastructure. In many developing countries, there are simply few other options; forests are too far away to allow for the collection of fuelwood for household use, and electricity, gas, and fuel oils are often prohibitively expensive. Only 68% of the population in developing countries even has access to electricity (Pinstrup-Andersen and Herforth 2008). The growing demand for biomass fuels in urban areas and the need for income-generating opportunities in rural areas combine to create a relatively stable market for charcoal and fuelwood that in most cases contributes to the food security of both urban and rural households. Hence, charcoal may offer opportunities for income generation and poverty reduction in rural and urban areas. However, growth in local and regional markets for charcoal and fuelwood markets is not sustainable if the values of ecosystem services are not reflected in household-level choices about food preparation; prices will not reflect the full cost of extraction, likely leading to overexploitation. The concurrent challenge of advancing food security and ensuring environmental sustainability is underscored again in this example of the conflict between the need for cooking fuels to satisfy a rapidly expanding urban population and the need to reduce pressure on forests.

The market for charcoal can be characterized as dispersed, poorly developed, and weakly regulated. Most analyses of wood fuel demand have estimated negative income elasticities (Arnold, Köhlin, and Persson 2006; Shackleton and Shackleton 2006), implying that households will convert to modern fuels with an increase in income. Both fuelwood and charcoal are assumed to be *normal* goods for lower-income households and *inferior* goods for higher-income households, meaning that the income elasticities of demand become negative with increasing income. However, urban households are generally more likely to use charcoal due to wood scarcity, thus the switch to an inferior good occurs at a higher income level for charcoal users (Arnold, Köhlin, and Persson 2006). Fuelwood is usually collected, but studies of cooking fuel demand has found that 28% of poor households bought fuelwood sometimes or regularly, and 48% of wealthy households did so (Shackleton and Shackleton 2006). However, charcoal is frequently a transition fuel to which households switch first. The growth rate in charcoal consumption in Africa between 1990 and 2000 was roughly double that of fuelwood consumption (Arnold, Köhlin, and Persson 2006).

In addition to the biomass provided by the ecosystem service of food production discussed earlier in the context of availability, human health, development, and longevity are supported by the genetic resources of plant materials, fruits, nuts, meats, and fish to provide the micronutrients and macrominerals necessary for a nutritious diet. The provision of the services of these genetic resources is vital for the adequate utilization of food. The foods collected and hunted from forests provide humans with calories, protein, minerals (e.g., iron), and vitamins (e.g., A, Bs, C, D, and E). Micronutrients are dietary nutrients needed by the human body in very small quantities throughout life. Macrominerals (such as iron, chromium, iodine, manganese, and zinc) are required by the human body in larger quantities. Genetic resources also provide the origin for many medicines used to treat illnesses and health disorders, and the diversity of genetic resources helps to maintain resistance to pests that spread diseases and infect crop and livestock production (Costanza et al. 1997). Twelve percent of the world’s forests are designated for the conservation of biological diversity, which also protects genetic diversity in most cases. The area of forest where conservation of biological diversity is designated as the primary function has increased by more than 95 million hectares since 1990, of which the largest part (46%) was designated between 2000 and 2005 (FAO 2010). These forests now account for 12% of the total forest area, or more than 460 million hectares, and most are located inside protected areas.

5. DISCUSSION AND CONCLUSIONS

The relationship between environment and development has been given much greater attention in the past 30 years, inspired in part by the publication of Our Common Future (also known as the Brundtland Report) (World Commission on Environment and Development 1987). Several global initiatives followed soon thereafter that attempted to illuminate the challenges and opportunities in integrating the dual objectives of environmental sustainability and eliminating poverty and hunger. However, an appraisal of the success of these initiatives in meeting their objectives reveals a gloomy image of a daunting challenge facing humanity. In spite of notable gains in agricultural productivity in recent decades, the number of food insecure people globally has not decreased since the Brundtland Report. And although nearly all of the nations of the world agreed to divert resources and attention to achieving the Millennium Development Goals (United Nations 2000) and the World Food Summit Goals (FAO 1996), food insecurity is greater by most measures today than 1990, which was designated as the base year for both sets of goals (Pinstrup-Andersen and Herforth 2008). World deforestation fell slightly in the past decade but continues at unsustainably high rates in some of the most vulnerable countries in the developing world, threatening critical ecosystems as well as access to food and raw materials by rural households. The ongoing crisis of poverty combined with a greater awareness of the scale and effects of environmental degradation is attracting greater attention in policy circles in an effort to explore and implement new initiatives that will reduce hunger and poverty and provide incentives to protect or enhance ecosystems and the services they provide (Millennium Ecosystem Assessment 2005).

Policies and initiatives that have failed to advance food security have been driven by an overreliance on boosting domestic agricultural production as a solution to a problem that is fundamentally based on local and household-level constraints to food access and the inability of households to obtain food in the marketplace or from other sources (Daily et al. 1998; Webb et al. 2006). A broader conceptualization of food security has led to a gradual shift from focusing primarily on objective indicators of food availability and utilization to the integration of fundamental measures of access, including subjective measures (Webb et al. 2006). Attempts to characterize and measure access to food have illuminated the tension between the goals of environmental sustainability and the production and sale of food and raw materials that ensure access. In some cases, the path out of poverty may reduce one kind of environmental degradation while increasing another (Pinstrup-Andersen and Herforth 2008). An ongoing policy debate central to the study of environment and development is the question of whether the poor are agents or victims of environmental degradation such as deforestation, and if poverty alleviation measures will reduce pressure on ecosystems. Some argue that poverty contributes to environmental degradation, while others contend that dependence by the poor on natural resources leads them to protect it. For example, it may be argued that the designation of forests as reserves or protected areas can impose significant human costs on the poor by excluding resource use. Alternatively, protected areas have been shown to generate important local benefits by preserving access to the resource through cooperative management and by stimulating employment from tourism growth (Bandyopadhyay and Tembo 2010; Fernandez et al. 2009; Richardson 2008). Referring to the example of forests, Fisher (Fisher 2004) concluded that the activities of the wealthy, who are most likely to participate in timber extraction activities, pose a greater ecological threat to poverty and food security, leaving poor households vulnerable to the degradation and depletion of forest resources.

Nevertheless, it is important to note that the absence of any policies or management practices governing the use of ecosystem services and resources will lead to the degradation of environmental stocks and funds, including some damages that may be irreversible, and the poor are likely be the most affected in such an event. Regulation clearly has a role to play in minimizing environmental degradation by prohibiting or hindering the rate of use or extraction of stock-flow resources; however, command-and-control approaches to environmental protection are difficult to enforce and are associated with low compliance. Educational initiatives may be of limited value, since the mere provision of information has not been found to be effective at motivating behavioral change (Steg and Vlek 2009). Incentives to encourage new behavioral patterns such as subsidies for tree planting and soil conservation practices have led to temporary changes in behavior that do not continue after the subsidies are removed (Kerr et al. 2007). Finally, integrated conservation and development projects have been implemented to promote conservation by creating alternative economic opportunities that do not involve the exploitation of natural resources, but the lack of a direct connection between incentives and conservation have limited their effectiveness (Ferraro and Kiss 2002).

Initiatives that offer payment for conservation-oriented behavior have been introduced as a way of providing a direct incentive to farmers, landowners, and other rural households to manage their land for the conservation of natural resources and the provision of particular ecosystem services. Such payments may be conceptualized as compensation for service provision relative to other activities (e.g., pollution or extraction). Services provided may be asset building (e.g., planting trees), resource protecting (e.g., implementing soil conservation practices), or use restricting (e.g., avoiding resource extraction in protected areas). These so-called *payment for ecosystem services* (PES) programs can be distinguished from earlier policy tools by the feature of conditionality—that is, payment is conditional on the provision of the service or the achievement of the conservation objective. Applications of PES initiatives have been implemented broadly and in a variety of contexts, and payments have taken several forms, including individual, group, cash, and non-pecuniary incentives. However, as discussed earlier, most ecosystem services are characterized by the non-excludability of their uses and by the reduction in marginal benefits that each additional user imposes on other users. The absence of property rights introduces the problem of open access, a common feature of the rural economies of developing countries, where smallholders forests, pastures, and water sources are frequently managed through collective action (Ostrom 1990). Interest in the collective management of such common-pool resources emerged in response to the prevailing view that the collective ownership of resources inevitably results in the tragedy of resource depletion. Common-pool resources pose particular challenges for PES initiatives that utilize individual payments because of the extensive transaction costs associated with organizing, negotiating, monitoring, enforcing and executing PES contracts. Furthermore, individual users can undermine the conservation objectives if they are dissatisfied with the arrangements or if they perceive opportunity costs from participation. Collective action may be necessary in such cases in order to provide equitable sharing of program benefits or to ensure environmental service provision through coercion.

Communities and groups may engage in collective action for a variety of purposes and motivations. Some groups may cooperate for the mere purpose of income (e.g., cooperatives, micro- and small enterprises, while others may be formed through government programs, grassroots initiatives, organized resistance to some perceived threat or the collective interest of building group resilience. Microeconomic labor theory proposes that the income elasticity of labor supply is positive—that is, under the conditions of self-interest and free will, an increase in financial or psychic income will yield additional effort, so it makes sense that the offer of payment would stimulate behavior change. However, the detrimental effects of monetary incentives may conflict with social motivations to cooperate, and the resulting effects on group development and trust may put the environmental service at risk or threaten social cohesion (Ferraro and Kiss 2002; Kerr et al. 2007; Ostrom 1990). Collective action among well-established groups with institutional arrangements that transparently address financial matters is unlikely to be negatively affected by the introduction of monetary incentives for the provision or protection of ecosystem services. However, the offer of financial incentives in groups that undertake norm-based collective action could interfere with the intrinsic motivation of participants and yield perverse outcomes that undermine collective norms or overall program objectives. Non-cash rewards in PES programs may include secure land tenure for local residents, local development benefits (e.g., water wells, school, health care facilities, infrastructure), or capacity-building support for community organizations and members. The design of PES initiatives should carefully consider the potential effects of the payment structure (individual versus group) and type of incentive (monetary versus non-cash) on group development and collective action if they are to be effective at achieving the conservation and development objectives.

Providing secure access to land may be one of the most effective policy tools to address the dual challenges of food security and ecosystem sustainability, since secure land tenure contributes to increased productivity, household income, and environmental sustainability. However, a large majority of the rural poor lacks secure access to land, other natural resources, and productive assets. Insecure access to land is associated with low levels of investment, productivity, and employment. Wider, secure, and sustainable access to land, water, and other natural resources that support rural livelihoods is essential to the alleviation of extreme poverty and hunger and contributes to overall objectives of sustainable development.

Finally, the challenge of food security is not simply a rural development problem. The lack of income-generating opportunities in many rural areas has repercussions that extend far beyond the local community. Rural and urban communities are interdependent, and major issues such as rural-urban migration, food security, poverty, and environmental sustainability must be addressed through an integrated approach, with balanced attention to local needs and traditional ecological knowledge (Daily et al. 1998). The rural labor market in many developing countries is characterized by high levels of underemployment, low productivity, insufficient wages, and a predominance of casual labor, employment insecurity, and unsafe working conditions. Development of productive opportunities for wage- and self-employment in rural areas will be critical for reducing rural-urban migration and the pressures of that process on urban demand for ecosystem services such as charcoal. Most rural adults in developing countries are self-employed in smallholder agriculture, and they frequently work below their full employment potential.

Rural poor people try to cope with these insecurities by relying on diverse sources of income and support, many of which depend upon the sustainable provision of ecosystem services. Smallholders supplement their agricultural earnings by hiring themselves out as wage laborers or gathering non-timber forest products for sale through off-farm enterprises. Agricultural laborers are typically among the poorest and most vulnerable workers, seldom receiving the legal and regulatory protection enjoyed by more organized labor in urban areas.

The examination of the role of ecosystem services in food security through the lens of its three pillars—availability, access, and utilization—reveals the complex interactions between the Earth's ecosystems and the chronic problems of hunger and poverty that so severely constrain development in the poorest countries of the world. In many cases, household uses of resources and services that support the access and utilization dimensions may undermine the ecosystem functions that support food availability. The implications of these interactions underscore the importance for the integration of ecosystem services into food security plans and poverty reduction strategies in developing countries. The intersecting challenges of advancing food security and ensuring environmental sustainability will only be effectively resolved through policies that integrate overlapping objectives and reflect the two-way causal relationship between food access and environmental quality that underpins the points in this paper.

REFERENCES

Arnold, J.E. Michael, Gunnar Köhlin, and Reidar Persson. 2006. Woodfuels, Livelihoods, and Policy Interventions: Changing Perspectives. *World Development* 34: 596-611.

Bandyopadhyay, Sushenjit and Gelson Tembo. 2010. Household Consumption and Natural Resource Management around National Parks in Zambia. *Journal of Natural Resources Policy Research* 2: 39-55.

Barrett, C.B. 2010. Measuring Food Insecurity. *Science* 327: 825-28.

Barrett, C.B., T. Reardon, and P. Webb. 2001. Nonfarm Income Diversification and Household Livelihood Strategies in Rural Africa: Concepts, Dynamics, and Policy Implications. *Food Policy* 26: 315-31.

Baumol, William J. and Wallace E. Oates. 1988. *The Theory of Environmental Policy*. Cambridge, UK: Cambridge University Press.

Costanza, Robert, Ralph d'Arge, Rudolf de Groot, Stephen Farber, Monica Grasso, Bruce Hannon, Karin Limburg, Shahid Naeem, Robert V. O'Neill, Jose Paruelo, Robert G. Raskin, Paul Sutton, and Marjan van den Belt. 1997. The Value of the World's Ecosystem Services and Natural Capital. *Nature* 387: 253-60.

Daily, Gretchen C. 1997. *Nature's Services: Societal Dependence on Natural Ecosystems*. Washington, D.C.: Island Press.

Daily, Gretchen, Partha Dasgupta, Bert Bolin, Pierre Crosson, Jacques du Guerny, Paul Ehrlich, Carl Folke, Ann Mari Jansson, Bengt-Owe Jansson, Nils Kautsky, Ann Kinzig, Simon Levin, Karl-Göran Mäler, Per Pinstrup-Andersen, Domenico Siniscalco, and Brian Walker. 1998. Food Production, Population Growth, and the Environment. *Science* 281: 1291-92.

Daly, Herman E. and Joshua Farley. 2004. *Ecological Economics: Principles and Applications*. Washington, D.C.: Island Press.

de Groot, Rudolf S., Matthew A. Wilson, and Roelof M.J. Boumans. 2002. A Typology for the Classification, Description, and Valuation of Ecosystem Functions, Goods, and Services. *Ecological Economics* 41: 393-408.

Farber, Stephen C., Robert Costanza, and Matthew A. Wilson. 2002. Economic and Ecological Concepts for Valuing Ecosystem Services. *Ecological Economics* 41: 375-92.

Fernandez, Ana, Robert B. Richardson, David Tschirley, and Gelson Tembo. 2009. *Wildlife Conservation in Zambia: Impacts on Rural Household Welfare*. Food Security Research Project Working Paper No. 41. Lusaka: Food Security Research Project.

Ferraro, Paul J. and Agnes Kiss. 2002. Direct Payments to Conserve Biodiversity. *Science* 298: 1718-19.

Fisher, M. 2004. Household Welfare and Forest Dependence in Southern Malawi. *Environment and Development Economics* 9: 135-54.

Food and Agriculture Organization of the United Nations (FAO). 1996. Rome Declaration on World Food Security and World Food Summit Plan of Action. World Food Summit. Rome: FAO.

Food and Agriculture Organization of the United Nations. 2009. *The State of Food Insecurity in the World*. Rome: FAO.

Food and Agriculture Organization of the United Nations. 2010. The Global Forest Resources Assessment 2010. Global Forest Resources Assessment. Rome: FAO.

Georgescu-Roegen, Nicholas. 1971. *The Entropy Law and the Economic Process*. Cambridge, MA: Harvard University Press.

Godfray, H.C.J., J.R. Beddington, I.R. Crute, L. Haddad, D. Lawrence, J.F. Muir, J. Pretty, S. Robinson, S.M. Thomas, and C. Toulmin. 2010. Food Security: The Challenge of Feeding Nine Billion People. *Science* 327: 812-18.

Godoy, Ricardo, Nicholas Brokaw, and David Wilkie. 1995. The Effect of Income on the Extraction of Non-Timber Tropical Forest Products: Model, Hypotheses, and Preliminary Findings from the Sumu Indians of Nicaragua. *Human Ecology* 23: 29-52.

Goodstein, Eban S. 2008. *Economics and the Environment*. Hoboken, NJ: John Wiley & Sons.

Haggblade, S., P. Hazell, and T. Reardon. 2007. Transforming the Rural Nonfarm Economy: Opportunities and Threats in the Developing World. Baltimore, MD: Johns Hopkins University Press.

Hillel, Daniel. 1991. *Out of the Earth: Civilization and the Life of the Soil*. New York, NY: Free Press.

Holling, C. S. 2001. Understanding the Complexity of Economic, Ecological, and Social Systems. *Ecosystems* 4: 390-405.

Jayne, T. S., Takashi Yamano, Michael T. Weber, David Tschirley, Rui Benfica, Antony Chapoto, and Ballard Zulu. 2003. Smallholder Income and Land Distribution in Africa: Implications for Poverty Reduction Strategies. *Food Policy* 28: 253-75.

Kerr, John, Grant Milne, Vesudha Chhotray, Pari Baumann, and A. J. James. 2007. Watershed Management Externalities in India: Theory and Practice. *Environment, Development, And Sustainability* 9: 263–81.

Kolstad, Charles D. 2000. *Environmental Economics*. New York: Oxford University Press.

Lal, Rattan. 2009. *Soil Carbon Sequestration and the Greenhouse Effect*. Madison, WI: Soil Science Society of America.

Lal, Rattan, Ronald F. Follett, B.A. Stewart, and John M. Kimble. 2007. Soil Carbon Sequestration to Mitigate Climate Change and Advance Food Security. *Soil Science* 172: 943-56.

Lal, Rattan, David O. Hansen, Norman Uphoff, and Steven Slack. 2003. *Food Security and Environmental Quality in the Developing World*. Boca Raton, FL: Lewis Publishers.

Loomis, John, Paula Kent, Liz Strange, Kurt Fausch, and Alan Covich. 2000. Measuring the Total Economic Value of Restoring Ecosystem Services in an Impaired River Basin: Results from a Contingent Valuation Survey. *Ecological Economics* 33: 103-17.

Luo, Hongyan, Walter C. Oechel, Steven Hastings, J. Rommel Zulueta, Yonghai Qian, and Hyojung Kwon. 2007. Mature Semiarid Chaparral Ecosystems Can Be a Significant Sink for Atmospheric Carbon Dioxide. *Global Change Biology* 13: 386-96.

Mendelsohn, Robert O. and Ariel Dinar. 2009. *Climate Change and Agriculture an Economic Analysis of Global Impacts, Adaptation and Distributional Effects*. Cheltenham, UK: Edward Elgar Publishing Limited.

Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-being: Synthesis.* Washington, D.C.: Island Press.

Murray, C. H. and M. R. de Montalembert. 1992. Wood, Still a Neglected Energy Source. *Energy Policy* 20: 516-21.

Nordhaus, William D. 1994. *Managing the Global Commons: The Economics of Climate Change*. Cambridge, MA: MIT Press.

Osemeobo, Gbadebo J. and Felix Njovu. 2004. An Evaluation of Woodland Utilization by Smallholders in the Central and Copperbelt Provinces of Zambia. *International Journal of Applied Economics and Econometrics* XII: 219-36.

Ostrom, Elinor. 1990. *Governing the Commons: The Evolution of Institutions for Collective Action*. New York, NY: Cambridge University Press.

Pattanayak, Subhrendu K., Erin O. Sills, and Randall A. Kramer. 2004. Seeing the Forest for the Fuel. *Environment and Development Economics* 9: 155-79.

Pimentel, D., S. Cooperstein, H. Randell, D. Filiberto, S. Sorrentino, B. Kaye, C. Nicklin, J. Yagi, J. Brian, J. O'Hern, A. Habas, and C. Weinstein. 2007. Ecology of Increasing Diseases: Population Growth and Environmental Degradation. *Human Ecology* 35: 653-68.

Pimentel, David, C. Harvey, P. Resosudarmo, K. Sinclair, D. Kurz, M. McNair, S. Crist, L. Shpritz, L. Fitton, R. Saffouri, and R. Blair. 1995. Environmental and Economic Costs of Soil Erosion and Conservation Benefits. *Science* 267: 1117-123.

Pimentel, David, Alison Marklein, Megan Toth, Marissa Karpoff, Gillian Paul, Robert McCormack, Joanna Kyriazis, and Tim Krueger. 2009. Food versus Biofuels: Environmental and Economic Costs. *Human Ecology* 37: 1-12.

Pimentel, David, Michael McNair, Louise Buck, Marcia Pimentel, and Jeremy Kamil. 1997. The Value of Forests to World Food Security. *Human Ecology* 25: 91-120.

Pinstrup-Andersen, Per and Anna Herforth. 2008. Food Security: Achieving the Potential. *Environment* 50: 48-60.

Reardon, T. 1997. Using Evidence of Household Income Diversification to Inform Study of the Rural Nonfarm Labor Market in Africa. *World Development* 25: 735-47.

Richardson, Robert B. 2008. Conceptualizing the Value of Ecosystem Services in Deserts. In *Creating Sustainability within Our Midst,* ed. Robert L. Chapman. New York, NY: Pace University Press.

Rosenzweig, Cynthia and Daniel Hillel. 1998. *Climate Change and the Global Harvest*. New York, NY: Oxford University Press.

Sen, Amartya Kumar. 1981. *Poverty and Famines: An Essay on Entitlement and Deprivation*. New York, NY: Oxford University Press.

Shackleton, Charlie M. and Sheona E. Shackleton. 2006. Household Wealth Status and Natural Resource Use in the Kat River Valley, South Africa. *Ecological Economics* 57: 306-17.

Steg, Linda and Charles Vlek. 2009. Encouraging Pro-Environmental Behaviour: An Integrative Review and Research Agenda. *Journal of Environmental Psychology* 29: 309-17.

United Nations. 2000. *United Nations Millennium Development Goals*. New York, NY: United Nations.

United States Department of Agriculture. 1996. The U.S. Contribution to World Food Security: The U.S. Position Paper Prepared for the World Food Summit. Washington, D.C.: United States Department of Agriculture. Found on line at: http://www.fas.usda.gov/icd/summit/1998/country.doc

Webb, Patrick, Jennifer Coates, Edward A. Frongillo, Beatrice Lorge Rogers, Anne Swindale, and Paula Bilinsky. 2006. Measuring Household Food Insecurity: Why It's So Important and Yet So Difficult to Do. *Journal of Nutrition* 136: 1404S-1408S.

World Commission on Environment and Development. 1987. *Our Common Future*. New York, NY: Oxford University Press.