The role of ecological theory and practice in poverty alleviation and environmental conservation

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The fight against global poverty has gained momentum following the creation of the Millennium Development Goals, which aim to halve extreme poverty by 2015. Traditionally, ecologists have not played leading roles in poverty alleviation. Yet, knowledge of ecosystem functions and processes can be applied to improve the lives of millions of people, suffering from hunger, lacking clean drinking water and reliable, efficient energy sources, dying from preventable diseases, and suffering disproportionately from natural disasters. Here, we describe ways in which ecologists can apply ecological theory and tools to help improve the efficacy of poverty alleviation programs.

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In September of 2000, the United Nations signed the Millennium Development Goals (Table 1), welcoming the new millennium with a renewed sense of hope for the eradication of extreme poverty by 2015. The highest concentrations of extreme poverty are found in tropical latitudes, coinciding with areas rich in biodiversity, high rates of environmental change, and accelerated species loss. This overlap has caused some ecologists to regard the development goals with trepidation, concerned that their implementation will increase environmental degradation. Others point out that environmental conservation measures have resulted in greater local impoverishment by limiting people's access to natural resources (Brockington and Schmidt-Soltau 2005).

Integrating environmental conservation into poverty alleviation initiatives requires changes in ecological research and development practices. Ecologists must focus research on interactions between ecosystems and societies in developing countries, while development experts need to understand that environmental management is a critical component of poverty alleviation strategies. Reconciliation of these two facets can be achieved by demonstrating how application of ecological theory and knowledge to development can simultaneously meet human needs and conserve ecosystems. Here, we outline specific examples of how theories, concepts, knowledge, and tools generated through ecological research can be used to eliminate extreme hunger, ensure a continuous supply of clean freshwater, secure reliable and clean sources of energy, mitigate the effects of disease, and enhance protection and resilience in the face of natural hazards. The examples presented will illustrate how ecological concepts and tools are a means of meeting development goals.

In a nutshell:

- Ecology offers many concepts and tools that can be used to reduce hunger, provide clean water and sustainable sources of energy, decrease disease burden, and diminish vulnerability to natural disasters
- Knowledge of species functional traits and ecosystem processes can be used to design more productive agroforestry systems, water-purifying wetlands, and protective ecosystems
- Landscape-scale perspectives on watershed management, disease transmission and prevention, and production of biomass fuels could inform development initiatives to improve the living conditions of millions of people
- More applied research is needed to elucidate the synergies between ecological interventions and improvements in human welfare; this will require new kinds of integrated collaborations between ecologists and development practitioners and institutions

Hunger

Despite the considerable advances made by agronomists during the Green Revolution, 852 million people globally remain chronically or acutely malnourished, particularly in sub-Saharan Africa, the only region in the world where undernourishment continues to grow (Sanchez *et al.* 2005). Ecologists have not traditionally focused on food production as a critical ecosystem service, defined as the provisioning, regulating, supporting, and cultural benefits obtained from ecosystems (Millennium Ecosystem Assessment 2005).

The challenges involved in hunger alleviation center around access, distribution, and productivity. The role of ecology in this situation is most clearly defined in "front-end" investments in the food chain, for instance in soil,

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Table 1. The UN Millenium Development Goals*

(1) Eradicate extreme poverty and hunger
(2) Achieve universal primary education
(3) Promote gender equality and empower women
(4) Reduce child mortality
(5) Improve maternal health
(6) Combat HIV/AIDS, malaria, and other diseases
(7) Ensure environmental sustainability
(8) Develop a global partnership for development

*www.un.org/millenniumgoals/

water, and plant resources, rather than in "tail-end" investments such as food distribution (P Sanchez pers comm). Investments in agriculture, such as the use of hybrids, agroforestry systems, or fertilizers, have been effective in reducing poverty in developing countries (Sachs 2005), notably in Africa, where a 10% increase in agricultural yield reduced the percentage of people living on $1 per day by 9% (Irz *et al.* 2001). Applying ecological knowledge to the relationship between biodiversity and productivity, species interactions, soil fertility, pollination, and pest and disease control can greatly increase productivity in poor areas, while conserving the resource base upon which agriculture depends.

Community ecology has demonstrated that increases in biodiversity can lead to increases in plant community productivity when species complement each other, or use resources differently. For example, planting species from different functional groups together, as in the Meso-American "three sisters" combination of corn (a grass), beans (a nitrogen-fixing legume), and squash (a low-lying creeper), maximizes trait differences and resource use efficiency between species (Risch and Hansen 1982).

Bioengineered communities based on species traits can be achieved with temporally or spatially distinct populations. When leguminous trees are interplanted with maize, the two species have temporally segregated light requirements, since the shrubs are coppiced during the corn's growing season, but capture light after the corn is harvested. The coppiced material from the legumes adds 50–200 kg N ha^{-1} $year^{-1}$, depending on species and management. Spatially segregated populations can also be complementary. For example, *Tithonia diversifolia*, a wild sunflower species, is used to "mine" phosphorus from off-site hedgerows and roadsides (Cong and Merckx 2005). Pruned *Tithonia* leaves are then mulched into fields, providing an affordable and readily available phosphorus fertilizer.

Pollination is also a crucial, albeit less managed, factor influencing food production. The amount of fruit obtained from insect-pollinated crops is frequently most limited by pollinator populations (Nabhan and Buchmann 1997). The diversity and frequency of bee species visiting coffee flowers determines fruit set and plantation productivity (Klein *et al.* 2003). In a field study of coffee (*Coffea canephora*) pollination, 60% of the fruit set was successfully pollinated when three bee species were present, but 90% of the fruit set was pollinated when 20 bee species were present (Klein *et al.* 2003). Ensuring that native pollinators have adequate semi-natural habitat located at minimal distances from crops helps to maintain productivity in pollinator-dependent plants.

Management of multi-trophic interactions offer several pest and disease control opportunities. Studies on plant-eating aphids have shown that aphid populations are 18% greater when ground-dwelling aphid predators are experimentally removed, 70% greater when flying predators and parasitoids are removed, and 172% greater when all enemy groups are removed (Schmidt *et al.* 2003). Islands of red clover have 19–60% fewer cases of herbivore parasitism compared to non-isolated communities, indicating that lack of habitat connectivity releases insects from predator control (Kruess and Tscharntke 2002). Semi-natural habitats adjacent to agricultural zones enjoy lower disturbance levels and therefore support larger predator and parasite populations (Thies and Tscharntke 1999). However, maintenance of semi-natural landscapes must be based on an understanding of the ecology of beneficial species. For example, a study of bumblebee densities showed that densities were positively correlated to availability of mass flowering crops rather than to the proportion of semi-natural habitats in landscapes (Westphal *et al.* 2003). Future research needs to be focused on how landscape configuration, complexity, and quality of semi-natural habitat affect agricultural productivity.

These are only a few examples of the increasingly important role ecology plays in hunger alleviation; countless others are currently being explored through groups such as the EcoAgriculture Partnership (www.ecoagriculturepartners.org) and DIVERSITAS (www.diversitas-international.org/).

■ Freshwater

Approximately 1.1 billion people do not have access to safe drinking water and 2.6 billion people lack access to basic sanitation (WHO and UNICEF 2000). Poor water quality, water scarcity, and inadequate sanitation negatively impact food security, livelihoods, health, and education across the developing world (Lenton *et al.* 2005; Figure 1). Practices such as watershed management, payment for ecosystem services, and wetland restoration highlight the important role of ecology in maintaining freshwater resources.

Watershed management can benefit from a variety of ecological tools, including Geographic Information Systems (GIS; Figure 2), remote sensing, topographic models, and ecological tracers to identify the extent and impacts of landscape degradation and model pollution flow paths (Power *et al.* 2005). Remote sensing and GIS can be used to map terrain and land-use activities, such as agriculture and deforestation, at different spatial and tem-

Figure 1. *Contaminated water sources, such as this pool in Mayange, Rwanda, are often the only source of water available to rural communities.*

Courtesy of The Earth Institute at Columbia University

poral scales, while tracers (isotopes, trace elements, xenochemicals, and genetic fingerprints) can be coupled with these maps to track biotic, hydraulic, and elemental flows related to specific land uses. The improved scope and resolution of these tools offer new possibilities for assessing ecosystem states, controls, and trajectories, which in turn can be used to model the impacts of various management and policy options (Power *et al.* 2005).

Knowledge of species functional traits can be applied to improve water quality. For example, the Bear Creek watershed in Iowa suffered from high sediment loads and chemical pollution from agricultural runoff (Schultz *et al.* 2004). Restoration was achieved by planting functionally diverse riparian communities of grass, shrub, and tree strips to intercept, trap, and filter surface runoff and subsurface flow before it entered the stream. Planting 9 m-wide riparian buffers resulted in the removal of 97% of the sediment and 80% of nitrates and phosphates; improved infiltration; increased soil carbon by 66%, and achieved a fourfold increase in denitrification (Schultz *et al.* 2004). Secondary benefits of the riparian buffer included wildlife habitat, hunting opportunities, and biomass generation (Schultz *et al.* 2004).

"Payment for ecosystem services" is another effective watershed management option. In Costa Rica, ecosystem valuation methods have been used to determine the monetary value of forest protection, based on the ecosystem functions of carbon sequestration and water purification (WRI *et al.* 2005). Landowners are paid approximately US\$50 ha^{-1} year^{-1} to maintain forest cover on their property. While this strategy shows promise, further research is needed in a variety of ecosystems to determine the optimum forest cover, landscape configurations, and species assemblages needed to maintain desired water quality and quantity.

Wetlands are vital for treating wastewater, maintaining water quality, controlling floods, and recharging the groundwater supplies that provide approximately 1.5–3 billion people with fresh drinking water (Millennium Ecosystem Assessment 2005). Restored or ecologically engineered wetlands can provide many of these services and are appealing because they require little maintenance, are adaptable to a range of size and functional requirements, and are especially suitable in many developing countries where biological activity and removal efficiency are enhanced by warm, tropical climates (Blanco *et al.* 2006). Constructed wetlands treat wastewater at a cost of US\$170–410 per m^3 day^{-1} compared to US\$800–1000 per m^3 day^{-1} for engineered wastewater treatment systems (Blanco *et al.* 2006). It is important to remember that these prices are estimations based on case studies from the US. Prices may vary across differ-

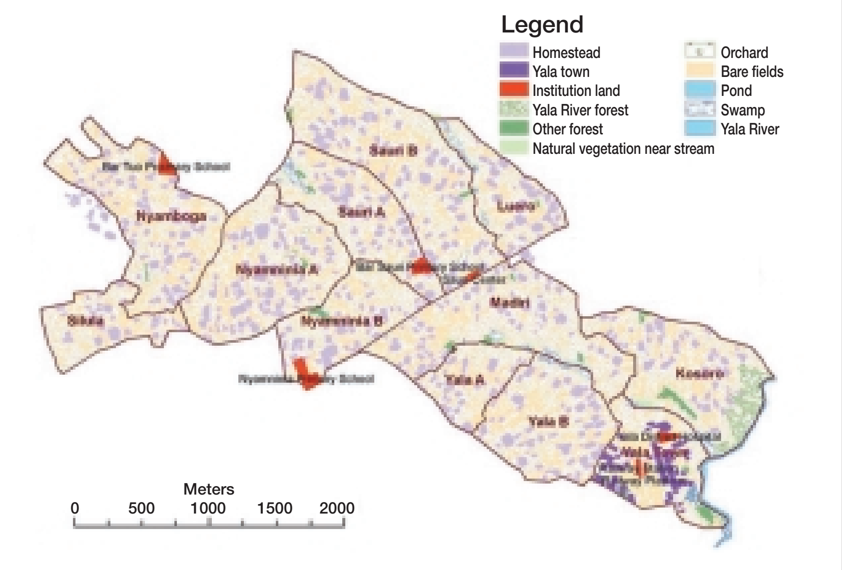

Figure 2. *GIS tools for mapping watersheds and land use are critical to integrated strategies for sustainable development, including mapping sensitive areas such as wetlands, and managing landscape biodiversity to maximize ecosystem services and minimize negative impacts of development on conservation. This map of Sauri, Kenya, one of 12 Millennium Villages, is representative of ecology's application in integrated development planning.*

ent locations and some parts of the system will be more expensive than others (Belmont *et al.* 2004).

A pilot project in Santa Maria Navitas, in arid central Mexico, used a constructed wetland consisting of native plants to treat contaminated water used for crop irrigation. The wetland reduced total suspended solids by 96%, chemical oxygen demand by 85%, and total nitrogen concentrations by 62% (Belmont *et al.* 2004). Other project benefits included the opportunity to grow ornamental flowers for sale and the production of biomass for composting. Further efforts are needed to enable the "scaling up" of such pilot projects, so that they can benefit larger areas (Belmont *et al.* 2004) and meet the multiple, potentially competing, land-uses that exist at a larger scale.

These examples show how ecological knowledge of species and ecosystem functions can be combined with ecological tools to improve water quality and availability. However, more research is needed to predict ecological thresholds, identify the scales at which vital biogeochemical processes operate across the land/water interface, and to extend lessons learned from successful water management projects to other areas.

■ Disease

Improving the health of the world's poorest people is central to meeting all of the Millennium development goals. The effects of HIV/AIDS, malaria, and tuberculosis, which together were responsible for 6 million deaths in 2004, decimate communities and undermine economic development (Ruxin *et al.* 2005). The economic burden of endemic malaria in Africa is estimated to slow economic growth by 1.3% per year (Sachs and Malaney 2002). A quarter of the global disease burden and a third of the disease burden among children are due to modifiable environmental factors (Prüss-Üstün and Corvalán 2006). Diarrhea, lower respiratory infections, and malaria have a particularly high environmental component and are especially prevalent in the developing world (Prüss-Üstün and Corvalán 2006). Such environmentally mediated diseases can be addressed with coordinated ecological and public health approaches.

Disease ecologists have a long tradition of integrating population biology, ecology, evolutionary biology, and behavioral ecology with medical knowledge to successfully address public health issues. River blindness (onchocerciasis) was eliminated through a World Health Organization program that used empirical models of black fly ecology and disease epidemiology to guide the use of effective chemical control agents (Smith *et al.* 2005). Knowledge of food web interactions and malaria epidemiology led to disease reduction projects in southeast Asia, where larvivorous fish were introduced to paddy fields to reduce populations of malaria-carrying mosquito larvae as well as to provide a source of protein (Foley *et al.* 2005).

New insights into disease ecology are now emerging from landscape ecological studies of the relationship between land-use change and disease emergence. Patz *et al.* (2004) found that deforestation, forest fragmentation, and road building increase the incidence of leishmaniasis and malaria. Similarly, irrigation projects, population migrations, increased livestock production, and introduction of invasive species have been tied to outbreaks of malaria, Nipah virus, and schistosomiasis in the developing world (Patz *et al.* 2004). Through the spatial integration of biogeochemical data, remotely sensed vegetation classes, and mosquito abundance data, Pope *et al.* (2005) linked phosphorous runoff from agricultural fields in Belize to increased abundance of cattails (*Typha domingensis*) in adjacent marshes. The increase in cattails may have heightened malaria risk by creating mosquito habitat close to areas of human residency. This kind of spatial understanding of disease risk could be used to inform strategic landscape planning that incorporates water and nutrient management as well as using natural barriers to reduce disease transmission.

The emerging field of conservation medicine, which focuses on the intersection of the environment, ecology of human and non-human hosts, pathogens, and conservation biology, aims to reduce the spread of emerging infectious diseases. A conservation medicine approach revealed the spillover of the SARS virus from bats to civets to humans and helped identify potential control points in the transmission pathway (Dobson 2005). Conservation medicine encourages the pursuit of health and conservation goals in tandem, improving human welfare through greater conservation of ecosystem services and species protection. With humans increasingly encroaching into natural areas, and the heightened potential for rapid disease transmission through global travel, research in this field is directly related to improving human well-being and conserving biodiversity.

■ Energy

Globally, three billion people depend on biomass fuels (wood, charcoal, dung, and crop residues) for their daily energy needs (Ezzati 2005). The task of fuelwood collection falls disproportionately on women and children, taking time away from education and other productive activities (Kituyi 2004; Figure 3). Further negative effects of burning biomass include forest degradation, greenhouse gas emissions, decreased use of crop residues and animal waste as fodder or fertilizer, and increased indoor air pollution. Emissions released from indoor biomass burning are responsible for 1.6 million premature deaths a year, due to acute respiratory infections, pneumonia, and other respiratory illnesses (Ezzati 2005).

A transition to cleaner burning fuels in households accompanies economic development and urban migration, but requires substantial infrastructure investment which is unlikely in low income, rural areas (Ezzati 2005). Even when cleaner burning technologies are available, such as in parts of China, cultural preferences often lead to continued use of fuelwood for cooking (Ezzati 2005). The application of knowledge of forest and community ecology to create more sustainable biomass production systems could contribute greatly to the goal of providing reliable and sustainable sources of biomass energy.

Courtesy of P Sanchez

Figure 3. *Women and children spend a disproportionate amount of their time finding fuel for cooking and boiling water.*

Community foresters have long encouraged rural farmers to plant trees in woodlots, hedgerows, and agricultural lands that are left fallow to meet their fuelwood and other timber needs. Newer initiatives encourage farmers to diversify and plant a mixture of multi-purpose trees (fuel, food, fodder, and medicine) in multi-strata agroforestry systems (ICRAF 2005). This "mixed-portfolio" approach to agroforestry exploits the functional traits of complementary species, such as sprouting ability, nitrogen fixation, and timing of fruit production to maximize the services provided by woodlots. Benefits include fuelwood production (using the stems of coppiced trees) close to households, improved food security and nutrition, the potential for income generation and diversification through the production of goods for sale, increased soil fertility (more soil nitrogen using the leafy material from coppiced trees and from planting nitrogen-fixing species), decreased soil erosion (through the presence of tree roots and soil cover), watershed protection, biological carbon sequestration, preservation of species and genetic diversity, greater landscape diversity, and decreased pressure on surrounding forests (Leakey 2001). Hedgerows in small landholder farming communities in western Kenya contain a substantial proportion of landscape-level native plant species diversity, and contribute to the functional complexity of landscapes, even where human population densities are high (Backes 2001). These more diverse agroforestry systems may be more stable, productive, and able to support a greater number of species that are important to agricultural production (such as pollinators and pest-regulating species).

New ways of accelerating the reforestation of degraded lands in the tropics have been used to satisfy community fuelwood needs (Lamb *et al.* 2005). In Vietnam, exotic timber plantations act as nurse trees to create a favorable environment for the establishment of native tree species, and were gradually harvested to meet community timber needs and pay for reforestation (Lamb *et al.* 2005). Other methods to restore forest cover and diversity include: active reforestation with a high diversity ensemble of native species, high density plantings to outcompete exotic species or competitive grasses, multiple waves of native species plantings to mimic succession and enrichment plantings of late successional, dispersal-limited species (eg large-fruited species; Lamb *et al.* 2005). These reforestation methods draw on studies of natural forest succession and knowledge of species traits, regeneration mechanisms, and propagation methods to accelerate successional processes. Reforestation of degraded lands may be an important source for community fuelwood, but careful management is needed to designate where, how much, what size, and what species can be collected to prevent depletion over time.

Multi-functional agroforestry systems and sustainable harvesting of reforested areas that are a source of fuelwood may also provide certain ecological and economic benefits, but do not address the health consequences of indoor wood burning, unless combined with improved combustion and smoke removal technologies. These technologies need further development, testing, and distribution throughout the developing world.

■ Disasters

The world's poorest people are disproportionately affected by disasters and are often the least able to recover (Mutter 2005). In such events, access to food, water, and energy are compromised and public health is imperiled. Concepts from socioecological resilience, disturbance ecology, and ecological restoration can help guide management of ecological systems to reduce human vulnerability to extreme events and ensure a rapid recovery.

In 2004 and 2005, the world witnessed a succession of natural disasters. These events revealed how analysis of

Courtesy of G Franco

Figure 4. *A hotel outside of the Yala National Park in Sri Lanka that was completely exposed to the ocean and experienced the full force of the 2005 tsunami, resulting in extensive destruction of the hotel structures and high mortality rates. A few kilometers away, on the same coastline, another hotel had conserved an extensive sand dune system, which absorbed much of the force of the tsunami and protected the hotel structures and occupants (JCI and CMR pers observ).*

socioecological resilience and adaptive management could have reduced vulnerability. For example, in Sri Lanka, intact coral reefs, sand dunes, and mangroves protected inland human settlements from the 2005 Indian Ocean tsunami, while communities located inland of similar, but degraded ecosystems suffered high levels of mortality (Danielsen 2005; Fernando and Mcculley 2005; Figure 4). Furthermore, deforestation may have amplified the devastating effects of Hurricane Jeane in Gonaives, Haiti (New York Times 2004). Identification of habitat degradation thresholds at which human security is threatened could help guide the limits of resource use in hazard-prone areas and help prevent such disasters. This type of resilience analysis, if adapted as social and ecological conditions change, could indicate how close the system is to crossing a threshold at which important functions are lost (Walker *et al.* 2004). Economic valuation of the services provided by intact ecosystems could be coupled with this analysis and used to convince policy makers that ecosystem management is vital to risk reduction.

Considerable ecological research has focused on understanding the impact of small, frequent disturbances on ecosystems (Holling 1973), and has been accompanied by work on ecological resilience (Gunderson 2000), ecological thresholds (May 1977), and alternative stable states (Sheffer *et al.* 2001). However, empirical studies of large, infrequent disturbances (LIDs) are rare because of the unpredictable nature of these events (Turner and Dale 1998). As a result, LIDs are rarely addressed in management plans, even though the severity of their impacts can occasionally be mitigated by management. Most of the discussion of LID management is in the context of sparsely populated areas; as a result, there is a paucity of knowledge on how LIDs affect human-dominated ecosystems. To fill these knowledge gaps, ecologists should be included in disaster assessment teams in order to document the ecological impact of LIDs on human–environment interactions.

Ecological tools are not only able to increase the resistance of communities to natural disturbances, but can also be used to accelerate ecosystem recovery and help restore livelihoods among communities dependent on the affected ecosystems. Ecological concepts such as assembly rules, succession, and intraspecific facilitation can be directly applied to improve and accelerate the restoration of disturbed landscapes and minimize the influx of exotic species so that ecosystem-based activities can resume.

Although much knowledge is available from socioecological resilience theory, disturbance ecology, and restoration and successional ecology, the application of such concepts in disaster prevention and recovery strategies is not widespread. Identification of human vulnerability thresholds within ecosystems in hazard-prone areas and an increased role of ecologists in post-disaster assessments could provide valuable information for risk reduction policies.

Ways forward

In this era of heightened concern over global poverty, and the growing appreciation of the importance of ecological services to human well-being (Millennium Ecosystem Assessment 2005), it is clear that ecologists have an important role to play in poverty reduction efforts. If they are to become more involved in development efforts, issues of scale, research design, and institutional support should be addressed from a crossdisciplinary perspective.

The issue of scale has long been a fundamental concept in ecology (Levin 1992). This is also important to development practitioners who seek to "scale up" successful pilot projects. To make ecological findings relevant within the development and poverty reduction agenda, ecologists need to present their findings at spatial and temporal scales of importance to human well-being and at which political decisions are made. This may require reworking data or reframing ecological research to be of more value to communities and policy makers.

Social scientists have long recognized that poverty is a complex phenomenon, involving components such as income, health, education, and vulnerability, all interacting across spatial and temporal scales (Agrawal and Redford 2006). Similarly, ecologists work in multidimensional systems, composed of organisms, energy, and the physical environment interacting at various spatial and temporal scales, which can be described in terms of composition, structure, functions, fluxes, resilience, or other dynamics (Pickett and Cadenasso 2002). Successful implementation of environmental interventions to reduce poverty will require recognition of the complexities inherent in issues of poverty and the environment and the existence of trade-offs, synergies, and interactions operating among the different components. Historically, most development interventions have not been multisectoral in scope. Infrastructure development and macroeconomic reforms such as market liberalization usually addressed only certain aspects of poverty and often had major, unintended effects on other development goals. For instance, efforts to boost agricultural productivity through irrigation canal construction unintentionally increased malaria incidence by increasing the amount of standing water present (Patz *et al.* 2004). More recent development initiatives, particularly the UK's Sustainable Livelihoods program, are more multisectoral and strive to maximize the benefits of multiple poverty reducing interventions by recognizing trade-offs where they exist while minimizing unintended adverse effects. This approach has also been adopted by the Millennium Villages Project, in which 12 village clusters in each of Africa's agroecological zones will be the site of simultaneous and integrated investments in agriculture, health, education, environment, and infrastructure, to end extreme poverty and achieve the Millennium Development Goals (Sachs 2005). These village-level interventions are science-based, shaped by local community input, and are rigorously monitored to assess the progress, cost, and efficacy of interventions. This approach differs from many other development projects by simultaneously addressing the multiple facets of poverty through the joint work of community leaders and multidisciplinary teams of specialists.

In settings such as the Millennium Villages, research needs can best be addressed through "problem-based" research and the development of an "action-centered" research network, where researchers, development professionals, and local communities together design research, monitor, and evaluate projects. This permits hypothesis testing, adaptive learning, and the reformulation of development projects if needed. Rigorous development experiments with appropriate controls, measurable outcomes, long-term monitoring, and the use of statistical tools should include the input of ecologists and other researchers. This scientific approach would provide a more detailed understanding of the effects of development interventions, highlight important contextual factors, determine the long-term sustainability of such initiatives, and facilitate the scaling-up of effective interventions (Agrawal and Redford 2006).

Ecologists alone are unlikely to successfully impact poverty reduction strategies. Institutions must recognize the growing appreciation of multidisciplinary efforts to achieve development goals, particularly as the acceptance of an idea in development often precedes implementation by many years (Ellis and Biggs 2001). Yet, the human–environment problems we face require an urgency at odds with the time scales at which such change often occurs within academies, non-governmental organizations, and government agencies. The inclusion of ecology in the strategic planning of such organizations might allow governments and development agencies to shift away from piecemeal responses to crises and towards crisis prevention.

Ecologists are already well-equipped to address many of the environmental problems that underpin poverty and, as this article has highlighted, are already doing so in many locations. They have learned to appreciate complexity, to consider effects across spatial and temporal scales, to identify the existence of critical thresholds, and to recognize the true value of ecosystems. These contributions are critical if development is to be economically viable as well as environmentally sustainable (Firey 1999).

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