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Beyond Reserves: A Research Agenda for Conserving Biodiversity in Human-modified Tropical Landscapes

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ABSTRACT

To truly understand the current status of tropical diversity and to forecast future trends, we need to increase emphasis on the study of biodiversity in rural landscapes that are actively managed or modified by people. We present an integrated landscape approach to promote research in human-modified landscapes that includes the effects of landscape structure and dynamics on conservation of biodiversity, provision of ecosystem services, and sustainability of rural livelihoods. We propose research priorities encompassing three major areas: biodiversity, human–environment interactions, and restoration ecology. We highlight key areas where we lack knowledge and where additional understanding is most urgent for promoting conservation and sustaining rural livelihoods. Finally, we recommend participatory and multidisciplinary approaches in research and management. Lasting conservation efforts demand new alliances among conservation biologists, agroecologists, agronomists, farmers, indigenous peoples, rural social movements, foresters, social scientists, and land managers to collaborate in research, co-design conservation programs and policies, and manage human-modified landscapes in ways that enhance biodiversity conservation and promote sustainable livelihoods.

Key words: agricultural matrix; agroecology; conservation value; ecosystem services; remnant vegetation; restoration; traditional knowledge.

The active debate on the future of tropical biodiversity is largely driven by a deficit of information regarding the status of biodiversity in human-modified rural landscapes (Wright & Muller-Landau 2006, Gardner *et al.* 2007a). Biodiversity surveys and ecological studies have understandably focused on areas with a high concentration of plant and animal diversity—intact biological reserves and protected areas with low current levels of human intervention (Fazey *et al.* 2005). But these areas are not typical of most of the world's tropics, where more than 90 percent of tropical forest area lies beyond the borders of reserves and parks (WWF 2002). To truly understand the current status and forecast the future state of tropical diversity, we must also understand levels and patterns of biodiversity in landscapes actively managed and modified by humans for a wide variety of traditional and commercial purposes, including hunting and gathering, agriculture, extractive forestry, and plantations of native or exotic species. Further, we must investigate how these patterns are affected by different human practices, land-use dynamics, spatial contexts, and socioeconomic contexts along a gradient of landscape modification, from smallholder agriculture to large-scale forestry and industrial commodity production (Bawa *et al.* 2004). The information obtained from such investigations is essential to identify and promote appropriate management strategies for conserving biodiversity in tropical regions (Zuidema & Sayer 2003, Lindenmayer *et al.* 2008).

The fates of biodiversity in protected areas and surrounding landscapes are inextricably linked (Schelhas & Greenberg 1996, McNeely & Scherr 2003, Zuidema & Sayer 2003, Vandermeer & Perfecto 2007, Harvey *et al.* 2008). Most protected areas in tropical regions are embedded within a matrix of heterogeneous land uses and are often directly or indirectly affected by forest fragmentation, road construction, agrochemicals, hunting, cattle grazing, agricultural incursions, fire, invasive species, over-harvest of non-timber forest products, logging, and mining (Janzen 1983, Schelhas & Greenberg 1996, DeFries *et al.* 2005, Hansen & DeFries 2007). These human activities often threaten species in protected areas (Laurance *et al.* 2006, Giraõ *et al.* 2007, Michalski *et al.* 2007). On the other hand, certain types of agriculture, agroforestry,

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fallow vegetation, and forest patches surrounding protected areas can support significant levels of biodiversity (Daily *et al.* 2001, 2003; Mayfield *et al.* 2005; Peh *et al.* 2006; Barlow *et al.* 2007a), while also providing valuable ecosystem services, such as carbon sequestration and hydrological protection (Montagnini & Nair 2004, Potvin *et al.* 2007, Tschakert *et al.* 2007). Incorporation of 'biodiversity friendly' land uses into actively managed buffer zones or biological corridors can contribute to the long-term conservation value of protected areas (DeFries *et al.* 2007, Harvey *et al.* 2008). In landscapes lacking protected areas or intact forests, agriculture, agroforestry, remnant vegetation, plantations, and managed forest patches provide critical habitats and refugia for biodiversity (Harvey *et al.* 2006, Harvey & González 2007, Bhagwat *et al.* 2008).

Despite a growing recognition of the importance of assessing and conserving biodiversity in human-modified landscapes in the tropics (Schroth *et al.* 2004, Harvey & Sáenz 2007, Bhagwat *et al.* 2008), many key questions remain to be answered in order to provide clear guidelines for long-lasting conservation efforts (Fischer *et al.* 2006, Norris 2008). An integrated landscape approach is needed to understand the effects of landscape structure and dynamics on conservation of biodiversity, provision of ecosystem services, and sustainability of rural livelihoods (Tscharntke *et al.* 2005). This integrated landscape approach was the basis for a companion paper by Harvey *et al.* (2008) that focused on policy recommendations within Mesoamerican countries. Here, we propose 12 priorities for investigation within human-modified landscapes in rural areas of the tropics, encompassing three major areas: biodiversity, human–environment interactions, and restoration ecology (Table 1). Our message is directed toward researchers and organizations that support research in tropical biology and conservation, rather than policy makers. We highlight key areas where we lack knowledge and where additional understanding is most urgent for promoting conservation and rural livelihoods (Table 1). Finally, we recommend that research and management be participatory and multidisciplinary, and should feed back into planning and managing landscapes within an adaptive framework. We advocate a broadening of focus beyond conservation *biology* toward a broader discipline of conservation *science*. Lasting conservation efforts demand new alliances among conservation biologists, agroecologists, agronomists, farmers, indigenous peoples, rural social movements, foresters, social scientists, land managers, and government agencies to collaborate in research, create conservation programs and policies, and to manage human-modified landscapes in ways that enhance biodiversity conservation (Pretty 1995, Cullen *et al.* 2005, Kaimowitz & Sheil 2007, Harvey *et al.* 2008). The authors' major areas of expertise are Mesoamerican agroecosystems and forests, and our research priorities emerge from intimate associations with Latin American landscapes and cultures. Nevertheless, our intention is to provide a broad framework that can be applied to other tropical regions and that will stimulate the development of research programs best suited to the unique human and biological history and landscape context of particular geographic regions.

TABLE 1. *A research agenda for conserving biodiversity in tropical human-modified landscapes. Each of the 12 areas of research focus are described in more detail in the text.*

Major area	Research focus
Bio-diversity status and landscape ecology	1. Population biology and long-term monitoring
	2. Animal dispersal and habitat use
	3. Effectiveness of buffer zones and corridors
	4. Effects of specific land-use practices
	5. Modeling impacts of climate change
Interactions between people and their environment	6. Ecosystem services and land use
	7. Relationships between biodiversity and ecosystem functions
	8. Social and economic impact of conservation activities
	9. Relationships between human communities, local resources, and sustainable management
Restoration ecology	10. Landscape-level restoration
	11. Costs and benefits of restoration objectives
	12. Effects of livestock on restoration

AN INTEGRATED APPROACH TO RESEARCH IN HUMAN-MODIFIED LANDSCAPES

The burgeoning number of ecological studies in human-modified landscapes reflects an urgent need to examine biotic interactions between matrix habitats and embedded forest patches (Gascon *et al.* 1999, Jules & Shahani 2003, Klein *et al.* 2008, Lindenmayer *et al.* 2008). Ecological studies generally view the agricultural matrix as homogeneous and as a source of contamination of embedded forest patches (Janzen 1983, Nascimento *et al.* 2006), rather than viewing forest remnants as heterogeneous biodiversity sources and sinks within the broader landscape. By zooming out on the landscape matrix itself, we can investigate population dynamics and species interactions among component habitat types (agriculture, secondary vegetation, forest fragments) in a metapopulation or metacommunity context (Daily *et al.* 2001, Vandermeer & Carvajal 2001, Perfecto & Vandermeer 2002, Bennett *et al.* 2006, Kupfer *et al.* 2006, Pulido *et al.* 2007, Greenberg *et al.* 2008). Forest fragments and isolated remnant trees provide sources of propagules for re-populating surrounding areas and serve as resources, stepping stones, and refugia for wildlife that use multiple habitats (Bengtsson *et al.* 2003, Guevara *et al.* 2005). Like forest fragments, agroforestry systems can also function as biological corridors and stepping stones for many animal species (Estrada *et al.* 1997, Laurance 2004, Schroth *et al.* 2004). In some tropical regions, coffee, cacao, rubber, or other agroforestry systems are the dominant form of tree cover and therefore play a key role in biodiversity conservation at the landscape level (Alcorn 1990, Young 1994, Perfecto *et al.* 1996, Moguel & Toledo 1999, Peters 2000, Abarca 2006, Monro *et al.* 2006, Bhagwat *et al.* 2008).

Agricultural production systems vary widely in their impact on biodiversity, ecosystem services, land-use dynamics, and potential for regeneration when abandoned (Donald 2004, Chazdon *et al.*

2008, Philpott *et al.* 2008a). The negative impacts of large-scale industrial agriculture (cotton, soybeans, sugarcane, bananas, rubber, African oil palm) on biodiversity are widely acknowledged to be significantly greater than those of traditional, small-scale agroforestry systems (McNeely & Scherr 2003, Donald 2004, Schroth *et al.* 2004, Scherr & McNeely 2007). In heterogeneous human-modified landscapes, forest fragments provide ecosystem services that benefit crop production (Swift *et al.* 2004, Maass *et al.* 2005). Biodiversity in forest fragments and landscape heterogeneity can enhance pollinator activity for crops (Kremen *et al.* 2002, Ricketts *et al.* 2004, Balvanera *et al.* 2005, Klein *et al.* 2008), promote pest control (Pickett & Bugg 1998, Klein *et al.* 2006, Romero *et al.* 2006), and reduce fungal infection and weed growth (Soto-Pinto *et al.* 2002). Forest fragments also provide products for local use, protect watersheds, store carbon, and meet other economic and cultural needs (Khumbongmayum *et al.* 2005, Bongers *et al.* 2006). Empirical and theoretical studies show that conservation of crop diversity can enhance agricultural productivity and ecosystem services (Tscharntke *et al.* 2005, Perrings *et al.* 2006, Jackson *et al.* 2007, Omer *et al.* 2007).

The objectives of an integrated approach to conservation within human-modified landscapes are not only to maximize protection of a wide range of taxa and ecosystem services, but also to improve agricultural productivity, food security, collective resource rights, and human welfare. These objectives are consistent with the findings of the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD 2008), which advocate a multifunctional perspective on agriculture, incorporating the need to protect biodiversity and ecosystem services. Trade-offs are unavoidable, but can be reduced in many cases through implementation of participatory, adaptive management (also referred to as adaptive co-management or community-based resource management). Adaptive management represents an important strategy for ongoing, systematic learning and adjustment to changing circumstances (Salafsky *et al.* 2008). This approach emphasizes *how* people learn and with *whom* rather than *what* they learn, and the ultimate goal is mobilization of local stakeholders and institutions leading to sustained action (Pretty 1995). Participation in research and decision making by multiple stakeholders is more likely to generate information and actions that meet both social and ecological needs than research by one or a few 'experts'. Although it is not a panacea, adaptive management can serve as an important tool to integrate conservation with sustainability of rural livelihoods. Further research is needed to improve learning methods and outcomes (Armitage *et al.* 2008), to promote equity of participation among stakeholders (Sanginga *et al.* 2006), and to determine the optimal level of experimentation to maximize ecological and social returns over different timescales (Hauser & Possingham 2008).

RESEARCH AGENDA

The research priorities discussed below address the urgent need for basic information required for adaptive management of human-modified ecosystems and landscapes, as well as for baseline data for long-term studies. We highlight 12 research priorities within three major areas for investigation in human-modified landscapes: (1) biodiversity status and landscape ecology; (2) interactions between people and their environment; and (3) restoration ecology (Table 1).

BIODIVERSITY STATUS AND LANDSCAPE ECOLOGY.—In one of the first books to focus on the mosaic of landscape fragments in the tropics, Schelhas and Greenberg (1996) stated, "We must learn more about which species can survive and thrive in different types and arrangements of forest patches" (p. xvi; Introduction). We expand this question to include the full range of habitat types within existing human-modified landscapes, including agricultural systems, remnant trees in pastures or in nearby areas, riparian strips, living fences, shade trees in cropping systems, home gardens, secondary vegetation, and remnant forest patches. Further, we advocate approaches that look beyond individual habitat types to the linkages and dynamics across habitat types and landscapes. Few studies have quantified patterns of biodiversity within one or more taxa across entire gradients of landscape modification (Nichols *et al.* 2007, Philpott *et al.* 2008a). We highlight five research priorities addressing this broad realm.

1. **Population biology and long-term monitoring within human modified landscapes**
   Monitoring studies provide baseline information to assess which component habitats in the landscape matrix can support particular taxa, and to evaluate short- and long-term effects of land-use change, landscape structure and heterogeneity, and successional dynamics on biodiversity and life-support systems. Which taxa can persist in human-modified landscapes and which cannot? These data will also provide a comparative context for monitoring studies conducted within intact forest areas within the same geographic region. Inventory data for particular taxa suggest that a subset of forest species can be found within human-modified landscapes (Dunn 2004, García-Estrada *et al.* 2006, Harvey *et al.* 2006, Sekercioglu *et al.* 2007, Barlow *et al.* 2007a, Gardner *et al.* 2007b, Kabir & Webb 2008), but we lack monitoring data over time to evaluate persistence of species in a range of habitats within and across landscapes (*e.g.*, Harvey *et al.* 2008, Suazo *et al.* 2008). Moreover, few studies have examined the effects of short-term or seasonal population fluctuations on observed landscape patterns of biodiversity (Barlow *et al.* 2007c).

   We know virtually nothing about the long-term dynamics of populations and their genetic structure and variation within human-modified landscapes (but see Boshier *et al.* 2004), as most studies of plant and animal diversity within agricultural landscapes have focused solely on describing static patterns of abundance and species richness. How are population processes affected by different land-use practices, landscape configurations, and levels of landscape modification and degradation (Cascante *et al.* 2002, Boshier *et al.* 2004, Komar 2006, Pulido *et al.* 2007). The minimum amount of habitat needed to sustain species' population dynamics in a predictable time frame is defined as landscape threshold (Reunanen *et al.* 2004). Landscape thresholds can be identified for certain taxa and study sites (Lindenmayer & Luck 2005, Radford *et al.* 2005), but for conservation planning we need much more information to identify these thresholds for keystone species, migratory species, commercial species, or species of conservation concern in different types of agricultural landscapes (Harvey 2007). These thresholds may also change over time, especially with the added stress of climate change.

Second-growth forests provide the only forested habitats within some human-modified landscapes. Long-term studies of natural regeneration are urgently needed to understand rates of vegetation change (Chazdon *et al.* 2007), suitability for management/harvesting, and conservation status of flora and fauna (Barlow *et al.* 2007b, Gardner *et al.* 2007b). We are far from understanding the role of plant–plant, microbial–plant, and animal–plant interactions on biodiversity change in successional environments. For example, we have scant information about effects of changes in seed dispersal, pollination, seed predation, and herbivory on vegetation composition in secondary forests in human-modified landscapes (Cramer *et al.* 2007).

2. **Animal dispersal and habitat use within human-modified landscapes**
Habitat utilization studies are needed to identify key habitats, foraging and nesting sites, and dispersal routes of animals in planning conservation units, buffer zones, and biological corridors and agricultural habitat components. How do habitat patches influence breeding behavior, dispersal, and species interactions within the agricultural mosaic? To what extent do remnant habitats serve as refugia for agricultural pests and their natural enemies (Schmidt *et al.* 2004)? Some taxa move readily across a complex landscape matrix, despite a high degree of habitat modification and fragmentation (*e.g.*, bats in pastoral and fragmented landscapes; Estrada *et al.* 2004, Bianconi *et al.* 2006, Medina *et al.* 2007). Other species are highly sensitive to even small changes in fragmentation and forest loss (*e.g.*, dung beetles; Klein 1989), insectivorous forest understory birds (Antongiovanni & Metzger 2005), small amphibians, and some turtle species (Suazo *et al.* 2008)) or to structural changes in agricultural habitats (Cruz-Angón *et al.* 2008). Understanding animal movement is critical to reducing the negative effects of climate change on wildlife populations (Donald & Evans 2006) and will enable effective planning of biological corridors and stepping stones in human-modified landscapes.

3. **Effectiveness of buffer zones and corridors for the conservation of target species, sources of forest regeneration, and production of ecosystem services**
Despite some research in temperate regions (Tewksbury *et al.* 2002), we lack experimental studies to determine the most effective design and management of buffer zones and biological corridors (Fischer *et al.* 2006). What habitat types and spatial arrangements provide effective buffer zones and corridors for different taxa? How can we incorporate existing agricultural lands, riparian strips, and remaining forest patches into buffer zones and biological corridors to increase the capacity of landscapes to protect biodiversity? How can we increase the value of buffer zones and biological corridors to local people through provision of ecosystem services that enhance agricultural productivity and protect against catastrophic landslides and floods (Schelhas & Greenberg 1996)? Presently, few landscape-level investigations address these urgent questions (Williams-Guillén *et al.* 2006, Anzures-Dadda & Manson 2007).

4. **Effects of specific land-use practices on plant and animal communities**
Comparative studies of biodiversity in alternative land-use scenarios are particularly important to inform policy makers about the potential impacts of changes in land use on both conservation and livelihood goals (Gillison *et al.* 2004). Further research is needed to evaluate the utility of indicator groups for monitoring changes in biodiversity under changing land-use practices (Schulze *et al.* 2004, Barlow *et al.* 2007a, Gardner *et al.* 2008). Few studies have examined how agrochemicals, fire, machinery, introduced plant species, rotational grazing, tree pruning, polycropping, harvesting of natural products, or combinations of these practices affect biodiversity in the agricultural matrix or in forest remnants (including biological reserves). Studies should also include effects of 'cryptic' habitat degradation in intact forests, resulting from fires, logging, hunting, or climate change (Barlow & Peres 2006).

Abrupt and large-scale changes in land use often occur as market prices for certain commodities rise or fall, as international trade agreements take effect, or as domestic or international policies or subsidies change. How do these land-use changes affect biodiversity? In the Talamanca region of Costa Rica, diverse cacao and banana agroforestry systems are being converted to plantain monocultures due to increased market demand, leading to the loss of mammal, bird, and dung beetle diversity (Harvey *et al.* 2006, Harvey & González 2007). Bats were negatively affected by the use of chemical products in intensive agriculture in Chiapas, Mexico, but not by organic agricultural production (García-Estrada *et al.* 2006). We lack information to assess the impacts on biodiversity of rapid, large-scale changes in agricultural land-use due to expanding global markets and increasing rate of biofuel production (Righelato & Spracklen 2007).

Determining species complementarity among different landscape patches and modeling landscape patch dynamics can provide insights for planning landscape configurations critical for the conservation of species assemblages (*e.g.*, Cuarón 2000). Few studies have examined to what degree current species assemblages are relicts of previously forested areas or reflect community assembly processes arising *de novo* within the human-modified landscape (Davis *et al.* 2001). Further, we have a poor understanding of the influence of habitat connectivity on alpha, beta, and gamma diversity within these landscapes.

5. **Modeling potential impacts of climate change on biodiversity and species migration across human-modified landscapes**
Climate change will have major impacts on agricultural production as well as on biodiversity within both human-modified landscapes and protected areas throughout the tropics (Williams & Hilbert 2006). Climate change threatens biodiversity by changing the availability and distribution of suitable habitat and microclimates, thereby placing additional stress on species already threatened by deforestation, habitat degradation, hunting, and other human activities (Malhi *et al.* 2008). As temperatures increase and precipitation regimes change, many species will need to move to higher elevations or toward the poles to find suitable habitat, as occurred during early Holocene warming (Bush 2002). Migration to cooler and moister conditions will be impeded if human modifications create barriers for species movement. In regions such as the Amazonian-Andean ecotone, continuous habitat corridors across rainfall, elevational and latitudinal gradients will be needed to avoid catastrophic species loss due to climate change (Bush 2002). We urge the development of models to investigate landscape-level effects of climate change on biodiversity and to provide guidance in landscape planning to mitigate the effects of climate change (Hannah *et al.* 2002). On the ground, adaptive management will be crucial to enhance ecosystem resistance, resilience, and the ability to adapt to changing climates at regional and local scales (Millar *et al.* 2007). Research is needed to identify how agricultural landscapes can be carefully designed and managed to maximize carbon sequestration and reduce emissions from deforestation and degradation (REDD), thereby ensuring these landscapes contribute to reducing the rate of climate change (Verchot *et al.* 2007). Feasibility studies are needed to evaluate REDD policies on biodiversity conservation, displacement of land-use change within and between countries, and other ecosystem values (Miles & Kapos 2008).

INTERACTIONS BETWEEN PEOPLE AND THEIR ENVIRONMENT.—Tropical landscapes have been shaped by the people who have lived in them and used them in both sustainable and unsustainable ways over past centuries (Denevan 2001, Whitmore & Turner 2001, Heckenberger *et al.* 2003, Toledo *et al.* 2003). For example, local indigenous knowledge and innovation in Chiapas, Mexico have been instrumental in designing coffee agroforests for multiple productive and subsistence uses (Soto-Pinto *et al.* 2007). Traditional as well as modern forms of sustainable land-use emphasize the values of ecosystem services derived from productive landscapes. According to the Millennium Ecosystem Assessment framework (MEA 2003), ecosystem services affecting human well being (basic material for a good life, health, good social relations, security and freedom of choice and action) include four broad categories: (1) provisioning (*e.g.*, food, fresh water, genetic resources, fiber, fuelwood, biochemicals); (2) regulating (*e.g.*, climate regulation, water regulation and purification, erosion regulation, disease regulation, pollination); (3) cultural (*e.g.*, recreation, spiritual values, social relations, aesthetic values); and (4) supporting (*e.g.*, primary production, soil formation, nutrient cycling). Further research is needed to link production, ecosystem services, and biological conservation (Maass *et al.* 2005, Bennett & Balvanera 2007). Environmental service payments are increasingly applied as incentives for some regulating ecosystem services such as carbon capture and hydrological control through forest conservation, silvopastoral systems, agroforestry, and reforestation within tropical regions (Montagnini & Nair 2004, Pagiola *et al.* 2004, Tschakert *et al.* 2007). These payments could potentially apply to a broader range of land uses and ecosystem services. Understanding how human-modified landscapes provide these services is particularly crucial against the backdrop of rapid climatic change and the emergence of international carbon markets that can fund reforestation and forest conservation activities (Boyd *et al.* 2006, Wara 2007, Miles & Kapos 2008). We propose four research priorities in this broad area.

6. **Assessing ecosystem services across a range of habitat types in human-modified landscapes**
Further research is needed to quantify the life support value of hydrologic, nutrient storage, and carbon storage services in a wide range of habitat types within human-modified landscapes, including silvopastoral systems, swidden agriculture, and agroforestry systems (Soto-Pinto *et al.* 2005, Tschakert *et al.* 2007). Quantifying these costs and benefits will ensure a more rigorous scientific basis for targeting environmental payment schemes and other incentives for conservation (Tscharntke *et al.* 2005, Wunder 2005, Steffan-Dewenter *et al.* 2007). How do different landscape configurations affect ecosystem services that farmers and local residents depend on and benefit from? How do ecosystem services vary across a gradient of human modification? Are levels of ecosystem services correlated with biodiversity across habitats and landscapes (Chan *et al.* 2006)?

7. **Examining relationships between biodiversity and ecosystem functions**
Over the last decade, relationships between biodiversity and ecosystem function have been heavily studied in grassland systems, with a primary focus on relationships between biomass accumulation and nutrient retention in relation to plant diversity (*e.g.*, Loreau *et al.* 2001). Yet, understanding relationships between all types of biodiversity and all ecosystem functions and services in human-modified landscapes is extremely important. Didham *et al.* (1996) called for ecologists to delve into understanding the consequences of insect biodiversity loss in forest fragments for ecological function. Some advances have been made in assessing ecosystem services in human-modified landscapes. Several studies have shown the importance of bee diversity and off-farm plant diversity for pollination of coffee and other crops (Klein *et al.* 2003, Ricketts *et al.* 2004), the importance of birds and bird diversity for predatory services (*e.g.*, Perfecto *et al.* 2004, VanBael *et al.* 2008), and how

changes in agricultural management affect predatory effects of ants (Philpott *et al.* 2008b), but more such studies are required. A major challenge in determining direct links between biodiversity and ecosystem function stems from the difficulty of assessing the mechanisms driving positive biodiversity and ecosystem function relationships. Although it is clear that species complementarity (*e.g.*, differences in species resource use), facilitation, and dominance may all be important (Loreau *et al.* 2001), the tools available for distinguishing between mechanisms are not applicable to the majority of ecosystem services. For pollination, evidence that biodiversity is important is somewhat substantial, but our understanding of the relationships between vital ecosystem services and animal, microbial, and fungal diversity is still in its infancy and should receive attention. To advance our understanding, we need empirical studies of biodiversity and ecosystem function relationships in agricultural and forestry systems in the tropics, and we need to develop analytical tools for detecting patterns (Balvanera *et al.* 2005) and understanding underlying mechanisms. For which services is biodiversity important? How does functional richness relate to species richness? What are the mechanisms that drive biodiversity–ecosystem function relationships in agroecosystems? What agroecosystems and landscape configurations provide the highest levels of ecosystem functions?

8. **Assessing the social and economic impact of conservation activities within human-modified landscapes**
   Planning sustainable production landscapes requires evaluation of trade-offs and synergies (Brown 2005), so that appropriate schemes can be created to ensure adequate financial benefits, equity, rights, and choices for rural people whose livelihoods and well-being depend upon sustainable agricultural production or resource extraction. There is a critical need to estimate and model opportunity costs of conservation within and across landscapes, as exemplified by studies of Naidoo and Ricketts (2006) in the Atlantic Forests of Paraguay. In these studies, models were used to plan locations of proposed biological corridors that maximized biodiversity conservation as well as ecosystem services benefits. Further, assessments of the social or economic impact of existing conservation efforts, such as environmental services payments and agri-environment schemes, can help to refine and improve them within a framework of adaptive management (Pagiola *et al.* 2005, Donald & Evans 2006).

9. **Understanding relationships between human communities, local resources, and sustainable management**
   Investigators have amassed a considerable body of research on traditional ecological knowledge and its relevance to conservation and environmental management issues (Berkes 1999, Inglis 1993). These topics have been a focus of collaboration between natural and social scientists for many decades (Posey & Balee 1989, Redford & Padoch 1992). In Africa, researchers in national programs and nongovernmental agencies examine traditional methods for natural resource management (Abate *et al.* 2000). In Venezuela, indigenous groups are building an online database to encourage more widespread, equitable exchange and use of traditional knowledge in solving environmental problems (http://www.slais.ubc.ca/COURSES/libr500/05–06-wt2/www/D_Ionson/index.htm). Indigenous groups are demanding to be incorporated in the whole research process, to have access to data and published information, and to participate as active stakeholders in the design of conservation research agendas (Mauro & Hardison 2000). But conservation research is still failing to address both conservation and social needs throughout the tropics (Meijaard & Sheil 2007). We need to define strategies for greater participation of rural resource users and other stakeholders in conservation research, including exploration of the ethical and human rights aspects of conservation policies (West 2006). Scientific understanding of sustainable practices should be integrated with the knowledge and innovations of rural resource users, including indigenous and non-indigenous peoples, landowners, and landless peasants (Diemont *et al.* 2005, Sayer *et al.* 2007). How can we use local and scientific knowledge to satisfy both conservation and rural peoples' needs, including the needs of impoverished people (Kaimowitz & Sheil 2007)?

   We need to investigate the social, political, economic, and institutional organization of local resource use, availability, access, and tenure and how these dynamics interact at local, regional, national, and transnational scales (Dietz *et al.* 2003). How do institutional, political, and legal frameworks constrain or support conservation in human-modified landscapes? Further, we need to develop and document the new relationships among agricultural, biological and social scientists, farmers, consumers, and local and regional governments that can arise from a landscape approach. Designing successful conservation strategies requires an understanding of how and why local residents manage their landscapes and adapt to environmental and demographic changes (Shanker *et al.* 2005, Harvey *et al.* 2007).

RESTORATION ECOLOGY.—Extensive areas of the tropics have been heavily degraded by inappropriate land use, especially extensive cattle grazing (Lamb *et al.* 2005). An estimated 350 million ha in the tropics are classified as degraded due to inappropriate use of fire, land clearing, poor grazing management, and destructive harvesting of ecosystem resources (Maginnis & Jackson 2005). In contrast with the global north, where most restoration research has taken place and where most people are urban, in the global south large, often impoverished rural populations live and work in direct contact with tropical landscapes. This situation creates a distinct set of challenges and opportunities for restoration (Armesto *et al.* 2007): (1) restoration budgets are minimal, requiring low-cost restoration approaches or techniques that pay for themselves within a production context; (2) local residents can often bring deep ecological knowledge and traditional management techniques to bear on restoration challenges; and (3) criteria for restoration success in tropical landscapes should include the well-being of local people, the strengthening of cultural ties with the landscape, and synergies between traditional and scientific knowledge. In such a context, restoration goals must build from and respect cultural landscape history (Higgs 2003), while avoiding criteria rigidly based upon some previous historic moment or notion of pristine wilderness. Creative approaches to meeting these challenges will require collaboration among multidisciplinary teams, decision makers and local people (Chazdon 2008). During the past decade, many reforestation and restoration activities and agroforestry projects have been developed to meet specific conservation goals, but few studies have evaluated the impact of these programs on biodiversity or ecosystem services at the landscape scale (Chazdon 2008). Here, we present three research priorities in restoration ecology.

10. **Landscape-level restoration research**
    Restoration research in degraded tropical lands has generally been conducted at small spatial scales, yet we need to begin to adopt a landscape-level approach to restoration of habitats as well as agricultural productivity (Holl *et al.* 2003, Dudley *et al.* 2005, Lindenmayer *et al.* 2008). This perspective requires restoration efforts linking existing forest remnants within the landscape to form buffer zones, regeneration nuclei, and biological corridors. How can degraded areas be rehabilitated to enhance agricultural productivity, biodiversity, and human welfare at the landscape level? What is the role of spatial configuration and matrix composition in site restoration (Shono *et al.* 2006)? What is the effect of local site restoration on neighboring forest patches, protected areas, or regenerating forests? Munro *et al.* (2007) emphasize the need to better understand the balance between quantity and quality of revegetation for assessing responses of different animal groups. Although planting of local native plant species is expected to benefit local fauna, few studies have directly addressed this assumption (Munro *et al.* 2007).

11. **Evaluating costs and benefits of different restoration objectives**
    We lack a framework for assessing the costs and benefits of different objectives of habitat-based restoration. These costs and benefits need to be assessed on both economic and biological bases, and should include benefits of ecosystem services. Further, we lack experimental studies that evaluate the potential to combine a range of objectives through reforestation, such as commercial timber harvest, restoration of soil fertility, carbon sequestration, and wildlife habitat. Which of these goals are spatially and temporally compatible within a single restoration project? Can restoration projects have different short-term versus long-term goals?

12. **Evaluating effects of livestock on restoration**
    Interactions among livestock, grazing management practices, fire regime, invasive species, and seed dispersal during early stages of succession are poorly investigated with regard to restoration processes (Miceli-Méndez *et al.* 2008). Although it is often assumed that active cattle pastures have little regenerative potential, studies indicate that extensively managed pastures often retain significant regenerative ability. For example, in Muy Muy, Nicaragua, 37 of 85 tree species were able to regenerate successfully under extensive grazing systems (Esquivel *et al.* 2008). Although fencing off pasture areas around remnant trees can enhance regeneration (Laborde *et al.* 2008), in some cases livestock can potentially assist early stages of forest regeneration by dispersing seed and reducing grass cover and fuel loads, improving site conditions for seedling establishment (Janzen & Martin 1982, Posada *et al.* 2000). Cattle browsing on forest edges, for example, might be managed so as to spread seeds of useful trees in open pasture, improving habitat for birds and insects while diversifying fodder (Miceli-Méndez *et al.* 2008). In a landscape restoration context, these cattle-dispersed trees might then serve as regeneration nuclei, as do remnant trees in pastures (Laborde *et al.* 2008). Similarly, the inclusion of live fences and windbreaks within agricultural landscapes can help facilitate natural regeneration processes, by attracting native seed-dispersing animals, such as bats and birds, and by ameliorating microclimatic conditions for seedling establishment (Harvey 2000, Harvey *et al.* 2005).

CONCLUSIONS

The conservation challenges that we face today in the tropics appear more intractable than they were only a few decades ago. We have acquired a new vision of the complexity and interrelatedness of tropical rural landscapes that calls for a new approach to research and management. Conserving biodiversity requires taking bold steps beyond the protection of areas minimally impacted by past or present human activities. A new conservation paradigm must incorporate human-modified landscapes in assessment of biodiversity and ecosystem services, planning of corridors and buffer zones, and restoration of degraded lands. This paradigm requires strong scientific foundations across a range of land uses and landscapes, including smallholder agroforestry (Schroth *et al.* 2004, Bhagwat *et al.* 2008), swidden agriculture (Tschakert *et al.* 2007), rangelands (Harvey *et al.* 2007), monoculture plantations (Cyranoski 2007, Koh & Wilcove 2007, Turner *et al.* 2008), and logged forests (Meijaard & Sheil 2007), to name a few. The big picture must also incorporate incentives and opportunity costs for multiple stakeholders.

The research agenda we propose is best accomplished within an interdisciplinary framework, involving teams of researchers from the biological and social sciences with backgrounds in ecology, taxonomy, systematics, agronomy, agroecology, economics, geography, forestry, communication, sociology, anthropology, law and other social sciences. Successful outcomes will advance by building new partnerships in research, management, assessment, and policy. Viewing human-modified landscapes as a research arena creates direct linkages between conservationists, social and natural scientists, and local communities, so that farmers and other peoples can enjoy sustainable rural livelihoods (Harvey *et al.* 2008). These steps will help to guide adaptive management responses to sustain biodiversity and ecosystem services in a rapidly changing world.

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