BIOLOGICAL REVIEWS
Cambridge Philosophical Society

Biol. Rev. (2011), **86**, pp. 457–474.
doi: 10.1111/j.1469-185X.2010.00155.x

Using learning networks to understand complex systems: a case study of biological, geophysical and social research in the Amazon

Jos Barlow[1]*, Robert M. Ewers[2], Liana Anderson[3], Luiz E. O. C. Aragao[4], Tim R. Baker[5], Emily Boyd[6], Ted R. Feldpausch[5], Emanuel Gloor[5], Anthony Hall[7], Yadvinder Malhi[3], William Milliken[8], Mark Mulligan[9], Luke Parry[1], Toby Pennington[10], Carlos A. Peres[11], Oliver L. Phillips[5], Rosa Maria Roman-Cuesta[3,12], Joseph A. Tobias[13] and Toby A. Gardner[14]

[1] *Lancaster Environment Centre, Lancaster University, Lancaster, LA1 4YQ, UK*
[2] *Department of Life Sciences, Imperial College London, Silwood Park Campus, Ascot, SL5 7PY, UK*
[3] *Environmental Change Institute, School of Geography and the Environment, University of Oxford, South Parks Road, OX1 3QY, Oxford, UK*
[4] *School of Geography, University of Exeter, Amory Building, Rennes Drive, Exeter, EX4 4RJ, UK*
[5] *School of Geography, University of Leeds, Leeds, LS2 9JT, UK*
[6] *School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK*
[7] *Department of Social Policy, London School of Economics, Houghton Street, London, WC2A 2AE, UK*
[8] *Royal Botanic Gardens, Kew, Richmond, Surrey, TW9 3AB, UK*
[9] *Environmental Monitoring and Modelling Research Group, Department of Geography, King's College London, Strand, London, WC2R 2LS, UK*
[10] *Tropical Diversity Section, Royal Botanic Garden Edinburgh, 20a Inverleith Row, Edinburgh, EH3 5LR, UK*
[11] *School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ, UK*
[12] *Centre of Ecological Research and Forestry Applications (CREAF), Facultat de Ciencies, Universitat Autonoma de Barcelona, 08193, Bellaterra (Barcelona), Spain*
[13] *Edward Grey Institute, Department of Zoology, Oxford University, South Parks Road, OX1 3PS, UK*
[14] *Department of Zoology, University of Cambridge, Downing Street, Cambridge, CB2 3EJ, UK*

(*Received 6 February 2010; revised 14 July 2010; accepted 5 August 2010*)

ABSTRACT

Developing high-quality scientific research will be most effective if research communities with diverse skills and interests are able to share information and knowledge, are aware of the major challenges across disciplines, and can exploit economies of scale to provide robust answers and better inform policy. We evaluate opportunities and challenges facing the development of a more interactive research environment by developing an interdisciplinary synthesis of research on a single geographic region. We focus on the Amazon as it is of enormous regional and global environmental importance and faces a highly uncertain future. To take stock of existing knowledge and provide a framework for analysis we present a set of mini-reviews from fourteen different areas of research, encompassing taxonomy, biodiversity, biogeography, vegetation dynamics, landscape ecology, earth-atmosphere interactions, ecosystem processes, fire, deforestation dynamics, hydrology, hunting, conservation planning, livelihoods, and payments for ecosystem services. Each review highlights the current state of knowledge and identifies research priorities, including major challenges and opportunities. We show that while substantial progress is being made across many areas of scientific research, our understanding of specific issues is often dependent on knowledge from other disciplines. Accelerating the acquisition of reliable and contextualized knowledge about the fate of complex pristine and modified ecosystems is partly dependent on our ability to exploit economies of scale in shared resources and technical expertise, recognise and make explicit interconnections and feedbacks among sub-disciplines, increase the temporal and spatial scale of existing studies, and

---

* Address for correspondence: E-mail: josbarlow@gmail.com

improve the dissemination of scientific findings to policy makers and society at large. Enhancing interaction among research efforts is vital if we are to make the most of limited funds and overcome the challenges posed by addressing large-scale interdisciplinary questions. Bringing together a diverse scientific community with a single geographic focus can help increase awareness of research questions both within and among disciplines, and reveal the opportunities that may exist for advancing acquisition of reliable knowledge. This approach could be useful for a variety of globally important scientific questions.

Key words: biodiversity, learning networks, interdisciplinary research, deforestation, REDD, degradation, hydrology, fire, conservation, livelihoods, taxonomy.

CONTENTS

I. INTRODUCTION

The global research community is extremely prolific, but the huge volume of information presents a major challenge to scientists attempting to keep up with the latest developments, and to those responsible for developing science-based policy recommendations. In many cases researchers are simply unaware of the research that is being conducted in either their own or parallel disciplines, or are too focused or busy to make the connections. Moreover, traditional reward systems in academia can favour practices that result in a narrow and more assured set of outcomes (e.g. low-risk, single-discipline research products) that limit the range and scale of scientific pursuits and the scope of interdisciplinary collaboration (Uriarte *et al.*, 2007). This isolation and fragmentation process can drive a positive feedback: the more fragmented academic research becomes, the more challenging it is to synthesise for newcomers to a field, and the greater the risk that it becomes increasingly inaccessible or inappropriate for potential end-users. This can lead to parallel research initiatives being conducted within the same geographic region, and a lack of clear incentives for researchers to interact or learn from one another (Salafsky & Margoluis, 1999).

A more interactive research environment may be stimulated through the development of learning or research networks (Salafsky & Margoluis, 1999; Brown & Salafsky, 2004), which could prevent the fragmentation of science and increase the effectiveness of research. A learning network (also termed portfolio) is a varyingly formalized structure for facilitating collaborative learning and action (Brown & Salafsky, 2004), and ensures that the latest ideas, practical and technical expertise and research findings can be readily exchanged and benefited from. Within a scientific context, the delivery of robust and socially relevant knowledge would be enhanced if research communities with diverse skills and interests are: (1) able to share new information and knowledge efficiently and rapidly; (2) aware of the major scientific challenges that characterize both their own and other disciplines; and (3) able to draw on this knowledge and awareness to exploit economies of scale in resources and expertise, as well as to contribute towards interdisciplinary research challenges.

Here, we present findings from a symposium held in London in 2008 which formed an initial stage in the development of a learning network for a group of researchers based within one nation (the United Kingdom) who have a common interest in the Amazon. This region makes a suitable case study because it: (1) is of enormous global importance; (2) faces a highly uncertain future, threatened by both development pressures and climate change (Lenton *et al.*, 2008; Malhi *et al.*, 2008; Phillips *et al.*, 2009); and (3) is large and complex, so that effective and sustainable management and development of the region depends upon the success of effective and collaborative research efforts. Moreover, by focusing on a relatively small research community such as that based in the UK, it was comparatively easy to bring together representatives from disparate disciplines. An obvious next step would be to expand this by including the many Amazon researchers based elsewhere. However, the UK-based research community provides an excellent test-case for this exercise as they target similar funding sources, are likely to share similar challenges, and there are few logistical barriers to prevent interaction and communication among participants.

The 14 mini-reviews presented herein cover a variety of scientific disciplines and areas of research, ranging from climatology and ecology to economics and social science. Each review highlights the current state of our knowledge, and then briefly identifies key gaps in understanding and major research challenges. While our coverage of individual disciplines is necessarily concise, the value of this exercise lies in the juxtaposition of information from a diverse array of scientific disciplines within a single forum, allowing an up-to-date appraisal of current understanding and inter-connections within and among disciplines. In the discussion we draw on the groundwork provided by these syntheses to examine potentially rewarding opportunities and mechanisms to facilitate collaborative investigation. This review and analysis is a first and important step in the development of a more interactive research and learning environment.

II. STATE OF EXISTING KNOWLEDGE AND RESEARCH CHALLENGES IN AMAZONIAN RESEARCH

(1) Climate and earth-atmosphere interactions

Temperature has increased by approximately 0.25 °C per decade over the Amazon basin during the last 30 years, CO_2 levels have risen by approximately 35% compared to pre-industrial times and surface solar radiation has varied (Leuenberger, Siegenthaler & Langway, 1992; Wild *et al.*, 2005). While there has been no significant trend in annual precipitation (Malhi & Wright, 2004), there were widespread droughts in 1998 and 2005 (Marengo *et al.*, 2008; Phillips *et al.*, 2009) and dry season intensity may have increased in southern Amazonia (Li, Fu & Dickinson, 2006).

Correlative evidence suggests soil water balance and its seasonality to be a main control of vegetation type and the extent of forests (Woodward, 1987; Malhi *et al.*, 2009*a*). Vegetation distribution and extent may also be affected by temperature-induced changes in plant functioning as well as by changes in atmospheric CO_2 level (Lloyd & Farquhar, 2008) and radiation.

There are important vegetation-climate feedbacks, with early water isotope analyses estimating that approximately 50% of water is recirculated to the atmosphere through Amazon forest canopies (Salati & Vose, 1984; Shukla, Nobre & Sellers, 1990). Cox *et al.* (2000) published results from the first fully coupled climate land vegetation model and suggested a high likelihood of Amazonian rainforests converting to savanna under 21st Century global warming. However climate models underlying these results underestimate today's Amazon precipitation. Malhi *et al.* (2009*a*) used a heuristic approach to correct for the model precipitation biases, and suggested that a tendency to seasonal forest was more likely than a full transition to savanna, although the latter remained a possibility.

The current main limitations on future Amazon vegetation predictions include a simplistic representation of vegetation dynamics, insufficient model resolution (Malhi *et al.*, 2009*a*), poor cloud physics representation (D. Parker, personal communication) and uncertainties in the prediction of large-scale warming patterns of the tropical Pacific and Atlantic Oceans (Held *et al.*, 2005).

(2) Deforestation dynamics and land-use change

The Amazon basin is the most active frontier of land cover change in the world. Historically, government-sponsored colonisation schemes initiated widespread deforestation in the Amazon as nations rushed to secure ownership of their territory and gain access to natural resources (Rudel, 2005). Although there is significant intra-regional variability in the drivers of land-use change, the majority of deforestation is currently explained by: (1) the expansion of extensive cattle ranching and industrial-scale agriculture for an increasingly global food market, and the associated development of infrastructure (Pan *et al.*, 2004; Armenteras *et al.*, 2006;

Morton *et al.*, 2006); (2) the small clearings of subsistence farmers migrating to new forest frontiers (Etter *et al.*, 2006; Carr, 2009); and (3) logging which can act as a precursor to outright deforestation (e.g. Asner *et al.*, 2006). The location of most deforestation is determined by the construction of new and paving of existing roads, combined with a lack of strong governance (Soares-Filho *et al.*, 2004; Fearnside & de Alencastro, 2006). Protected areas, sustainable use reserves and indigenous lands set spatial limits to deforestation and largely perform an effective job at slowing the spread of deforestation across the basin (Nepstad *et al.*, 2006; Oliveira *et al.*, 2007). In fact, deforestation rates in the Brazilian Amazon have been decreasing since the last peak in 2004 (Nepstad *et al.*, 2009) and the Brazilian government recently set a target of 80% reduction in the deforestation rates by 2020 (COP-15 in December 2009, http://www.abin.gov.br).

Developing better predictive models of deforestation will require: (1) understanding the drivers of deforestation and subsequent land cover change at appropriate spatial scales; and (2) predicting the patterns of future road networks based on social, economic and political drivers. Detecting deforestation and its drivers in such a diverse region is challenging, although some methodologies have been successfully tested for areas with large-scale deforestation patterns (Anderson *et al.*, 2005; Morton *et al.*, 2006). Attempts to predict road expansion have improved in recent years (Arima *et al.*, 2008) although these are yet to be validated and have suffered from a lack of data on unofficial road networks (Brandão Jr & Souza Jr, 2006).

(3) Amazonian wildfires

Forest degradation (logging, fragmentation) and severe droughts combine to increase the frequency of fire in Amazonian forests, which acts as a powerful agent of tropical forest degradation. Low-intensity fires often lead to very high levels of tree mortality (up to 50% of trees $\geq$10 cm diameter) and a significant loss of faunal diversity (including disturbance sensitive forest vertebrates) (Barlow & Peres, 2004). Fires can also lead to ecosystem instability and destabilising feedback cycles, as forests that have burned once are more likely to burn again, with greater effects on vegetation and biodiversity (Cochrane *et al.*, 1999; but see Balch *et al.*, 2008 from experimental burns). Recent research has demonstrated the critical role of rare drought events led by El Nino Southern Oscillation (ENSO) and Atlantic Multidecadal Oscilation (AMO) events with related changes in the Pacific and Atlantic Oceans sea surface temperature (SST), which increase fire occurrence when combined with fire-dependent human activities (Alencar, Nepstad & Diaz, 2006; Aragão *et al.*, 2007, 2008). Fire is considered to be one of the key processes through which a climate-mediated forest dieback could occur (Barlow & Peres, 2008; Malhi *et al.*, 2009*a*).

We still have a relatively poor understanding of the spatial and temporal variation in the causes and consequences of fire, and how fires interact with other forms of forest degradation and across different spatial scales. This information is vital to predict better the local and global implications of fires, identify vulnerability, and define and highlight potential tipping points where humid tropical forests may no longer recover. Although some attempts have been made to quantify fire-mediated changes in vegetation cover (e.g. Thonicke *et al.*, 2001; Bond, Woodward & Midgley, 2005) and carbon emissions (DeFries *et al.*, 2008), we are still unable to make accurate predictions about long-term changes in vegetation and carbon dynamics in fire-disturbed forests. Key areas of uncertainty include tree mortality, biodiversity loss, forest regeneration, the above- and below-ground carbon budget, feedback cycles, and the socio-economic context of fire use and management. Remote sensing plays a critical role in any scaling-up exercises, and accuracy would be vastly improved through a temporal analysis of fire scars that takes into account fire intensity, land cover, and the type of fire.

(4) Water resources and hydrology

Estimations of the discharge of the Amazon range from 200,000 to 220,000 $m^3 s^{-1}$ (Korzun, 1978; Richey, Nobre & Deser, 1989) up to 280,000 $m^3 s^{-1}$ (ESPA-AA, 2008), representing some 15–16% of all fresh water delivered to the oceans globally. The river carries less sediment than other comparable rivers, most of which (80–90%) derives from the Andean parts of the basin (Goulding, Barthem & Ferreira, 2003). At least five large dams exist within the basin with a further nine proposed.

Forest cover is widely assumed to facilitate the maintenance of high rainfall, flood control, dry season, environmental flows and water quality (Kaimowitz, 2004). Loss of forest cover over large spatial scales is thought to decrease rainfall, though studies have shown rainfall to decrease in some areas and increase in others and the impacts to be rather small (Kaimowitz, 2004; ESPA-AA, 2008). Forests are also expected to reduce flooding frequency but appear to have little impact on the largest and most destructive events (Bradshaw *et al.*, 2007). The picture is less clear for the maintenance of dry season flows, where the outcome depends on the balance between evaporation-induced flow loss under forests and enhanced baseflows through increased infiltration. There is also an important distinction to be made between lowland and tropical montane cloud forests in this regard (Bruijnzeel, 2004).

Though a wealth of hydrological and hydro-climatic studies have been carried out at the plot scale in the Amazon (e.g. the Large-Scale Biosphere Atmosphere programme LBA), much less effort has been given to sub-basin and basin-scale hydrological remote sensing and modelling (but see Marengo *et al.*, 2001). This is critical to understand the basin-wide response to land use and climate change. Early basin-wide studies indicate that the hydrological impact of climate change may be much greater than that of land-use change (ESPA-AA, 2008). Similarly there is a dearth of long-term monitoring sufficient to capture important variability, including droughts and extreme events, with the notable exception of initiatives from ANA (http://www.ana.gov.br/ingles/indexingles.asp), the

GRDC (http://www.bafg.de/GRDC) and GEMS (http://www.gemswater.org/). Studies so far have tended to focus on how hydrological processes respond to large-scale clear-cut whereas much land-use change is less dramatic and the hydrological response is likely to be conditioned by the nature and growth dynamics of the replacement cover.

(5) Vegetation dynamics

Recent comparative studies have revealed that patterns of carbon storage and dynamics vary strongly among different upland forests in Amazonia, overturning previous ideas that different tropical forests function in broadly similar ways. Western Amazon upland forests have greater above-ground productivity (Malhi *et al*., 2004), and tree turnover (Phillips *et al*., 2004) but lower above-ground biomass (Baker *et al*., 2004*b*) than forests in central and eastern Amazonia (Aragão *et al*., 2009; Baker *et al*., 2009; Patiño *et al*., 2009). Edaphic factors, rather than mean climate, determine these patterns within forests; both soil chemical properties, particularly phosphorous concentrations, and physical properties, such as soil depth, have important roles (Quesada *et al*., 2009). In addition, variation in species composition modifies how soil conditions affect ecosystem properties such as stand-level biomass estimates (Baker *et al*., 2004*b*; Honorio Coronado *et al*., 2009) and mortality rates (Chao *et al*., 2008).

Rates of tree recruitment and mortality, and the stock of biomass, have increased widely in Amazonian forests in recent decades (Baker *et al*., 2004*a*; Lewis *et al*., 2004; Phillips *et al*., 2004) probably as a result of global environmental change (Phillips *et al*., 2008). Understanding the underlying spatial variation in forest dynamics has been important for interpreting these changes: increases in tree turnover and biomass have been largest where tree turnover rates and productivity were already high, in western Amazonia (Baker *et al*., 2004*a*; Lewis *et al*., 2004).

Understanding the context of individual sites and regions is crucial for a correct evaluation of the actual spatial patterns (Anderson *et al*., 2009) and will remain important for interpreting change in Amazonian forests. Such shifts may be driven by the observed increase in tree turnover rates or increased drought frequency, predicted by some models of future climate. For example, a change to a system where patterns of forest dynamics are more strongly constrained by water availability would cause abrupt increases in drought-related tree mortality (Nepstad *et al*., 2007; Phillips *et al*., 2009), decreased tree growth (Baker, Burslem & Swaine, 2003) and could alter the distribution of different forest types over longer timescales (Malhi *et al*., 2009*a*). However, the many drivers of change and significant heterogeneity of the Amazonian forest make the exact nature of ecological responses difficult to predict. Long-term monitoring in multiple sites, studies of the short- and long-term impacts of disturbance and drought, and close coupling of field data and modelling efforts are the key priorities for understanding the future vegetation dynamics of Amazonian forests.

(6) Ecosystem processes

While an extensive network of forest inventories had revealed regional patterns and temporal trends in the functioning and dynamics of old-growth tropical forests [e.g. the RAINFOR network (Malhi *et al*., 2002)], other studies have intensified research on the ecosystem ecology of particular sites. One result has been improved understanding of how the more obvious facets of a tropical forest stand (biomass, structure, tree growth and death) relate to the overall carbon cycle of that stand.

One intensive approach has been micrometeorological, through the use of eddy covariance measurements of the turbulent transfer of carbon dioxide and water, and detailed automatic weather station data. The pioneering measurements in Amazonia were in the late 1980s and early 1990s, but the scale of such measurements greatly expanded under the Brazil-led LBA experiment in Amazonia (Keller *et al*., 2004) to around ten research sites in Brazil on forests, cerrado savannas and agri-pastoral landscapes. These studies have revealed new insights into how forests respond to daily and seasonal variation in light and water, and enabled quantification of water fluxes (J.B. Fisher *et al*., 2009) and gross photosynthesis (Hutyra *et al*., 2008). However, they have proved disappointing for addressing the key question of the net carbon balance of old-growth forests because of difficulties in accurately quantifying the night-time release of carbon dioxide in the calm, turbulence-free sub-canopy space that prevails in tropical forests.

A second intensive approach has examined the carbon cycle in greater detail at a few key sites, explicitly quantifying the components of net primary productivity (NPP) and autotrophic and heterotrophic respiration. These studies have been conducted by numerous investigators, in particular through the LBA programme, and were recently compiled into a single synthesis which showed they were consistent with independent flux tower and soil gas flux data (Malhi *et al*., 2009*b*). More recently, this approach has been applied to lowland forest sites in Peru and Colombia, to a fertile *terra preta do indio* site (Aragão *et al*., 2009), and to an elevational transect in the Andes (Girardin *et al*., in press). These studies have revealed that increases in above-ground productivity are generally mirrored by increases in below-ground NPP, and that both are positively related to the soil phosphorus status.

(7) Landscape ecology

Landscape ecology studies in the Amazon have been dominated by the long-running Biological Dynamics of Forest Fragmentation Project (BDFFP; Laurance *et al*., 2002). The long-term study of a single site has allowed the detection of many temporal effects of forest fragmentation that have rarely been described, such as the progression from crowding effects in birds immediately post-fragmentation (Stouffer & Bierregaard, 1995) to local extinction events in small remnants (Ferraz *et al*., 2003). Time-series data from the BDFFP have also allowed the quantification of fragmentation-induced changes to ecological processes such as tree mortality and recruitment rates (Laurance *et al.*, 2006), leading to a better understanding of the temporal development of edge effects and the drivers of spatio-temporal variability in fragmented landscapes (Laurance *et al.*, 2007).

The uneven spatial distribution of landscape ecology research and the strong focus on the BDFFP landscape necessarily means that our understanding of the context-dependence of landscape patterns and species dynamics is very limited (Gardner *et al.*, 2009). Consequently, there is only a limited understanding of the cumulative and synergistic effects of multiple disturbances that are known to exacerbate fragmentation impacts in heavily settled parts of the Amazon (Peres, 2001; Peres & Michalski, 2006).

Landscape ecology in the Amazon suffers shortcomings that are common to the whole discipline. Although the biological integrity of forest fragments is heavily dependent on the structural characteristics of the habitat matrix surrounding those fragments (Nascimento *et al.*, 2006; Stouffer, Strong & Naka, 2009), there is a persistent reluctance to collect biological data in that matrix despite the overwhelming importance of understanding species' abilities to tolerate, disperse through, or survive in the modified habitats that replace old-growth forest. Recent studies have begun to address these questions by sampling multiple taxa in multiple habitat types (e.g. Barlow *et al.*, 2007). A second and related issue is that carefully designed studies with multiple landscapes are completely absent, yet the biophysical, socio-economic and historical context of landscapes can exert a strong influence on long-term biodiversity persistence (Gardner *et al.*, 2009).

(8) Sampling biodiversity

The Amazon basin is one of the world's most species-rich biomes and contains some of the highest known levels of biological diversity including >50,000 terrestrial vascular plant species (e.g. Hubbell *et al.*, 2008) and with some single localities of SW Amazonia sustaining the highest levels of alpha-diversity ever documented on Earth, including woody plants (Gentry, 1988), butterflies (Emmel & Austin, 1990), lizards (Dixon & Soini, 1986) and non-volant mammals (Peres, 1999). Yet the distribution of Amazonian forest biodiversity is highly heterogeneous (ter Steege *et al.*, 2006; Pitman *et al.*, 2008), particularly when comparing between seasonally flooded and unflooded forests [e.g. large forest vertebrates (Haugaasen & Peres, 2005) and small mammals (Malcolm, Patton & Da Silva, 2005)].

Because of the region's vast size, poor infrastructure and lack of research investment, our understanding of Amazonian biodiversity remains very poor with most species lists representing gross underestimates. For example, individual fish-collecting expeditions in the last two decades have consistently yielded 5% new species, while an average of 2.3 new bird species have been described each year since 1996 (Peres, 2005). Additionally, the distribution of biodiversity sampling across Amazonia is highly patchy and often limited to areas immediately around research stations (e.g. Schulman *et al.*, 2007).

Improvements in the cost-effectiveness of biodiversity research in Amazonia are urgently needed to overcome these challenges (Higgins & Ruokolainen, 2004; Gardner *et al.*, 2008; Magnusson *et al.*, 2008), and could be achieved through a number of complementary approaches, including: (1) better use of existing, unpublished datasets; (2) use of eco-regional analyses to help identify areas that are most likely to contain new species; (3) development of standardised sampling methods for species groups that rely on passive trapping techniques (e.g. many invertebrates), or which require a high level of field expertise (e.g. birds); (4) exploitation of economies of scale in field and laboratory research when conducting multi-taxa surveys; and (5) increased investment in training and education—not only of expert taxonomists and dissemination of guides and keys (including web-based identification tools), but also local field teams and laboratory technicians who are an essential part of any research program. Recent large-scale sampling programs such as the Brazilian PPBIO project (http://ppbio.inpa.gov.br/Eng) have made some progress in these areas but it is vital that the momentum is maintained.

(9) Plant taxonomy and databases

Taxonomic understanding of Amazonian plants is very limited. For example, 20–40% of tree species described in recent taxonomic monographs were new (e.g. Pennington, 1997). Additionally, the distribution of plant collections across Amazonia is highly patchy (Schulman, Toivonen & Ruokolainen, 2008). Integrating reliable species identifications into non-taxonomic studies can make a major contribution towards improving data quality, but this is challenging in a diverse, poorly documented flora. A number of botanical organisations are helping by developing user-friendly identification tools (e.g. Neotropikey; http://www.kew.org/science/tropamerica/neotropikey.htm), databases integrating distribution data (e.g. Global Biodiversity Information Facility, GBIF), and checklists to unravel complex synonymy (e.g. Govaerts, Frodin & Pennington, 2001).

Voucher specimens are needed to verify identifications and as a taxonomic resource, but specimens from ecological studies—particularly sterile ones in the case of plants—may never be incorporated into collections and herbaria, and their identifications remain unverifiable. To capitalise on data from ecological studies, there is scope for a standard mechanism for sharing and annotating location records and specimen images online. The *Atrium* system used by many herbaria (http://www.atrium-biodiversity.org/index.html) may provide an appropriate model.

DNA sequences will have an important future role in facilitating identification and taxonomy. DNA "barcodes", short sequences from a standardized genome position, are promising for identification, particularly of non-reproductive specimens (e.g. juvenile insects and seedlings). If the same barcodes were sequenced for sampling locations across the

Amazon, the data accumulated would be of enormous use in taxonomy, biogeography and conservation. The DNA sequences could be used: (1) as a new dataset alongside morphology in species delimitation; (2) in beta diversity studies using approaches of community phylogenetic structure (e.g. Webb *et al.*, 2002); (3) in analyses to identify areas that contain most lineage diversity (e.g. Forest *et al.*, 2007). The cost of DNA sequencing is decreasing, and the limiting factor to implementing such "biodiversity genomics" will be in collecting leaf samples for DNA extraction and voucher specimens. We urge field workers to make the effort and resource allocation required to collect voucher specimens and digital images. Such effort allied to emerging tools promises to deliver a huge improvement of biodiversity knowledge in the world's most species-rich biome.

(10) Speciation and biogeography

Biodiversity can be viewed as existing patterns or underlying processes, and both perspectives should play a role in conservation strategies (Moritz, 2002). This is particularly true in Amazonia, which is one of the most species-rich regions of the world for many terrestrial taxa (Bush, 1994; Haffer, 1997; Colinvaux, De Oliveira & Bush, 2000). Most explanations for these exceptional levels of biodiversity rely on populations being historically isolated (Haffer, 1969; Lovejoy, Bermingham & Martin, 1998), yet various hypotheses based on forest refugia, riverine barriers and marine incursions receive mixed support at best (e.g. Gascon *et al.*, 2000; Hall & Harvey, 2002; Aleixo, 2004; Funk *et al.*, 2007). On one hand, recent genetic studies reveal that Amazonian taxa tend to be derived from older lineages in neighbouring upland regions, which may have acted as 'species pumps' (Aleixo & Rossetti, 2007; Santos *et al.*, 2009). On the other hand, they show that dispersal from Amazonia may also generate species through divergence in peripheral populations (Brumfield & Edwards, 2007; Seddon & Tobias, 2007).

Modern molecular techniques are opening up new challenges and opportunities. Recent research shows that Amazonian species have complex evolutionary history, and that current species limits often conceal highly divergent intraspecific lineages (Marks, Hackett & Capparella, 2002; Whinnett *et al.*, 2005). In many cases, these lineages appear to represent young or cryptic species, suggesting that we may have underestimated the region's biodiversity and its propensity to generate new species. More molecular and taxonomic studies are needed to explore this issue, and to provide a phylogeographic dataset with which to investigate the roles of geography, ecology and evolutionary history in structuring biological communities across the basin. The answers will not only help us to understand Amazonian biodiversity, but to predict its response to environmental change, and to pinpoint the best strategies for its protection. One of the key points emerging is that Amazonia is a dynamic ecosystem sustained by ongoing broad-scale eco-evolutionary processes which can best be preserved by maximizing connectivity between protected areas.

(11) Amazonian hunting research

Hunting of forest mammals and birds for food is widespread across Amazonia (Peres & Lake, 2003) and the larger species preferred by hunters are often over-exploited (Peres, 2000). This is exacerbated by habitat loss in deforested areas (Peres, 2001) and possibly exacerbated when colonisation and forest clearance centre on roads instead of productive rivers. Away from the deforestation frontier, the decline of extractive industries and process of rapid urbanization in recent decades (Browder & Godfrey, 1997) may have alleviated hunting pressure on some animal populations. However, in some cases abandoned areas are already heavily degraded, and although secondary regrowth on cleared lands can support some large vertebrates and provide food to rural people (Smith, 2005), it is unlikely that such areas can provide a sustainable supply of game meat (Parry, Barlow & Peres, 2009*b*).

Hunting research needs to address two major areas of uncertainty. First, the scale of urban consumption of hunted wildlife is poorly understood yet is likely to be increasing due to urbanization and increases in urban wealth. There has been only limited use of economics and social science in Amazonian hunting research, unlike in Africa where interdisciplinary approaches to understanding demand are well advanced (e.g. Wilkie *et al.*, 2005). Second, although the extent of sustainable-use reserves has increased exponentially in recent years it is unclear how hunting in inhabited reserves will affect exploited populations and ecosystem functioning through cascading effects. Encouraging the extraction of non-timber forest products may exacerbate hunting by increasing human activity in the forest (Parry, Barlow & Peres, 2009*a*). The widespread adoption of community management of hunting through no-take areas and catch-per-unit-effort monitoring (Puertas & Bodmer, 2004) remains a distant promise. We also need to understand better the interactions between hunting and other forms of forest disturbance (Peres, 2001), fishing, and the importance of keystone resources for some game species (Fragoso, 1998).

(12) Conservation planning

Despite significant recent progress in augmenting the Amazonian network of protected areas (e.g. 148 reserves with a total area of 640,000 km^2 were created between 2003 and 2007 in Brazil alone), there are ample opportunities for further expansion of the number and total acreage of forest reserves in lowland Amazonia. However, capitalizing on this opportunity has so far been a largely *ad hoc* process. A practical approach to designing and siting reserves cannot rely on detailed biodiversity distribution data, which are unavailable for all Amazonian countries (Peres, 2005). Instead, reserve design criteria including the size, habitat composition, denomination and level of protection have been decided haphazardly depending on the local expediency of sociopolitical circumstances, with little attention heeded to lessons learned from policy debates on these topics (Peres & Zimmerman, 2001; Nepstad *et al.*, 2006) or the science of reserve allocation and implementation (Fearnside & Ferraz, 1995; Peres & Terborgh, 1995; Ferreira *et al.*, 2001).

Given our current disconcerting level of ignorance of the patterns of biodiversity distribution across Amazonia, vegetation types probably offer the best available coarse-filter surrogate of species turnover for plant and animal assemblages (Scott *et al.*, 1993). Natural vegetation types in tropical forest regions reflect baseline environmental gradients that affect species distributions. In lowland Amazonia, large rivers also form important geographic barriers (e.g. Ayres & Clutton-Brock, 1992). A set of biogeographic units defined by the overlay of major river barriers and vegetation types could therefore be used as a basis for evaluating the representation of both existing and future conservation areas (Peres, 2002).

The untested assumption is that a relatively simple gap analysis would capture most of the region's biodiversity without the need to carry out detailed basin-wide species inventories. In the short term, this coarse-grained approach probably offers the best hope of achieving a geographically balanced and robust pan-Amazonian nature reserve network irrespective of ecoregional differences in species richness, occurrence of rare and endemic species, ecosystem vulnerability, and urgency to counteract threats (e.g. Peres *et al.*, in press). A limitation of this approach, however, is that it provides little guidance on the specifics of reserve design, including the size, shape, connectivity, geographic position within watersheds, level of protection of conservation units, land use in the intervening habitat matrix, or how individual reserves will respond to a changing climate (Malhi *et al.*, 2008).

(13) Livelihoods and governance

Amazonia smallholder livelihoods are diverse and in flux, influenced by a range of factors (Steward, 2007; de Sherbinin *et al.*, 2008; Pacheco, 2009). Traditional livelihoods can be threatened when forest areas become more accessible to markets and cattle ranching becomes preferable to the extensive harvest of non-timber forest products. For example, rubber tappers in Acre are increasingly expanding their livelihood strategies into small-scale cattle operations, which often function as effective insurance and savings strategies (Salisbury & Schmink, 2007).

Livelihood diversification is an important coping strategy for communities (Pacheco, 2009) and steady access to capital of some form is needed to ensure household resilience (Salisbury & Schmink, 2007). The potential impacts of conditional cash-transfer mechanisms on livelihoods (e.g. recent Brazilian government direct-grant programs such as Bolsa Familia, Bolsa Floresta) have increased dramatically (see Section II.14), as well as increased interactions with urban centres where payments are normally collected and spent. Expanding urban markets and urban opportunities may increase rural-urban linkages. Migrants to urban centres in Amazonia often form part of 'multi-sited households' partaking in networks across rural-urban areas and in rural land-use decisions and helping determine urban markets for food and construction materials (Padoch *et al.*, 2008).

Migration across Amazonia is an increasingly important demographic factor (Barbieri, Carr & Bilsborrow, 2009). In older frontiers the declining capacity of farms to maintain families, coupled with soil degradation and reduced agricultural yields, can stimulate the next generation to move to new settlements, with potentially significant consequences for forest conservation (Barbieri *et al.*, 2009). In more remote areas, a rural exodus may be being driven by the lack of opportunities for education (Parry *et al.*, in press). The influence of demographics is particularly important in indigenous communities, where patterns of settlement expansion are cyclical according to household age (de Sherbinin *et al.*, 2008).

The effects of future social, economic and environmental change are likely to vary along gradients of physical accessibility and increasing remoteness from urban centres and "the frontier" (Parry *et al.*, 2010). Questions about how climate change impacts local decision-making processes and risk management strategies in land-use change are beginning to gain attention (e.g. Brondizio & Moran, 2008), but little is known about the way these interplay with wider governance strategies that are emerging in Amazonia (e.g. Boyd, 2008).

(14) Market-based conservation strategies

It is now well established that the success of conservation policies for inhabited tropical forests depends on the inclusion of local populations and recognition of their needs. Government regulation and the imposition of environmental laws ('fences-and-fines') must be combined with positive incentives which encourage users to protect terrestrial and aquatic resources while strengthening their livelihoods (Fisher *et al.*, 2008). The use of market-based strategies as part of a more rounded sustainable development approach has thus become increasingly attractive. This could find expression through individual private and commercial initiatives or as part of wider integrated conservation and development projects (ICDPs) using a community-based approach.

For example, although uncontrolled logging continues to be a major source of environmental destruction in Amazonia, sustainable timber harvesting has expanded slowly but steadily to supply niche markets (Ozinga, 2004). Non-timber forest products (NTFPs) such as latex, nuts, fruits, oils, resins and medicinal plants have for centuries been exploited by indigenous and traditional populations to meet their own needs. Nowadays, domestic and international markets for such products have grown considerably in various sectors including food, cosmetics, medicines, clothing and construction and ecotourism (Plotkin & Famolare, 2004). Under the United Nations Framework Convention on Climate Change (UNFCCC) and its proposed Reducing Emissions from Deforestation and forest Degradation (REDD+) or 'avoided deforestation and forest protection mechanism,' carbon trading has the potential to generate significant income for forest peoples (Hall, 2008).

Although such solutions are often portrayed as 'win-win', NTFP and other market-based initiatives face many challenges which result in unduly high transaction costs (the ‘Amazon factor’). These include: (1) large distances from urban markets; (2) low levels of management, organisational and commercial expertise; (3) inadequate local production, transport, financial and communications infrastructure; (4) vulnerability to fluctuations in market prices and consumer demand; (5) growing competition from alternative land uses as well as other regions and countries; and (6) assymetrical power relations which may marginalise local groups (Ros-Tonen, van den Hombergh & Zoomers, 2007). Furthermore, REDD+ policies will face problems of monitoring additionality in carbon sequestration and ecosystem service provision, of leakage of carbon emissions within and across national borders, of balancing social justice with efficiency in the distribution of financial rewards, and of potential threats to the rights of forest dwellers, amongst others (Griffiths, 2007; FOE, 2008).

III. DISCUSSION

These 14 mini-reviews demonstrate the strength and depth of ongoing research efforts in the Amazon, but also highlight factors currently limiting a more complete understanding of the complex web of environmental, economic and social patterns and processes. Many of the barriers to improved research performance (i.e. the efficient production and dissemination of reliable knowledge concerning key research priorities) are common across disciplines, and stem partly from a lack of interaction within and between natural and social sciences. Here, we examine how efforts to develop a more interactive research environment could help overcome these barriers and drive research progress, linking these observations to some of the key research challenges identified by this learning network exercise. We first consider how improved interaction amongst scientists can enhance research within traditional disciplines, and then examine how interdisciplinary research programs can help scientists engage with the full complexity of the problems facing the Amazon. Finally, we draw upon the experience of our research network exercise to propose ways to build a more interactive research environment.

(1) Improving research performance by enhancing interaction within scientific disciplines

Developing interactive research and learning networks provides substantial benefits for the progress of individual scientific disciplines. We draw upon our review to illustrate how interaction amongst researchers and the development of learning networks can be valuable, if not essential, for confronting five key challenges facing science in Amazonia and elsewhere.

(*a*) *Problem formulation, research design and analysis*

There is an almost unlimited number of research questions that could be asked regarding the environmental and social patterns and processes occurring within the Amazon. Many research design choices reflect short-term funding opportunities, and time constraints experienced by relatively isolated individual researchers or research groups. However, the immediacy of most social and environmental problems means scientists need to adopt a more strategic approach to formulating research priorities and attempt to maximise the return on investment from limited resources (Bottrill *et al.*, 2008; Gardner, 2010). More careful *a priori* consultation within a wider research network would help establish priorities for new research, including: the questions and geographic regions that are likely to return the most novel and complementary findings; the extent and quality of prior research (published and unpublished); and the practical feasibility (logistics, availability of appropriate methods, etc.) of implementing new fieldwork.

(*b*) *Sharing data, research protocols and research infrastructure*

Enhanced knowledge exchange could improve use of existing data, which are often only known to a few individuals but which could help re-direct priorities and the demand for new information following summary assessments and meta-analyses. The development and use of shared research protocols and standardised sampling techniques can significantly increase the efficiency and integrity of research projects working in new areas—as demonstrated in Amazonia by the RAINFOR network (see Section II.5). The widespread adoption of standardised methods is also essential in allowing such approaches to be validated constantly and improved for different contexts. Recent developments in this area show promise, and include the online PRODES database of deforestation maps and statistics provided by the Brazilian National Institute for Space Research (INPE; www.obt.inpe.br/prodes/), the HidroWeb database of hydrological records hosted by the Agencia Nacional de Aguas (http://hidroweb.ana.gov.br), the Amazon spatial mapping tool provided by IMAZON (www.imazongeo.org.br) and the Forest Plots Database, designed to provide a permanent repository for forest inventory data (http://www.forestplots.net/). Furthermore, there is great potential in online biodiversity information systems to help bridge the gap between the ecological and taxonomic sciences (see Sections II.8–10 and below).

Sharing research infrastructure among scientists will also facilitate more cost-efficient research and therefore generate greater scientific returns from limited funds. For example, it takes considerable time and money to train field staff to do specific tasks, so making those staff trained in one project available to groups running new projects will go a long way towards increasing the efficiency of data collection. Similarly, a simple yet centralised database of field sites would allow research teams to identify locations that have prior knowledge of particular aspects of the wider social-ecological system, thereby encouraging work in new sites and enhancing the overall cost-effectiveness of research efforts across the basin. The marginal cost of collecting new information as part of an ongoing project is negligible compared to the cost of establishing a new project from scratch, but this requires a much wider sharing of research infrastructure than is currently the case.

(*c*) *Achieving an understanding of scale*

Perhaps the greatest challenge facing researchers working in the Amazon is its sheer size. Almost all the mini-reviews highlight how our understanding of patterns and processes across the Amazon basin is limited by insufficient spatial and temporal scale and resolution in sampling. Most research is strongly aggregated spatially, and in some disciplines such as landscape ecology the majority of existing information is derived from an extremely small number of well-studied sites (Gardner *et al.*, 2009, and Section II.7). This constrained sampling would matter less if Amazonian forests, rivers and peoples were homogeneous, but evidence demonstrates otherwise. Many research questions in Amazonia can only be addressed by integrating datasets from across multiple locations and contexts as it is becoming increasingly clear that different forest types function in very different ways (Section II.5), while human-environment interactions vary greatly depending on historical and regional context (Fearnside, 2008, and Section II.13).

Temporal data are also critical for unravelling many complex problems. For example, we currently have a poor understanding of the longer term ecological consequences of land-use change, as few research projects last more than a few years. However, the few ecological studies that explicitly considered disturbance history as an explanatory variable have shown it to have a dominant effect on extant biodiversity patterns (e.g. changes in biodiversity following forest disturbance or fragmentation; Sections II.3 and II.7). Many human-environment interactions are also highly dynamic over time, confounding attempts by short-term studies to be reliable in identifying drivers of change (e.g. Ewers, Laurance & Souza Jr, 2008).

Improved communication and collaboration among research groups is likely to be the most effective way to achieve improved spatial and temporal sample replication. The RAINFOR network provides an effective template for how integrated research networks can work, and what they can achieve. By linking more than 90 researchers from multiple South American and international institutions, RAINFOR has harmonized the data-collection methods of scientists working in 140 permanent plots located at 42 geographically distinct sites across Amazonia (Malhi *et al.*, 2002), producing important insights into how forests change over time and space, and how they may respond to future environmental change (Sections II.5 and II.6). It would be impossible for a single research group to develop a project with such a wide geographical and temporal base. The RAINFOR network is made up of a consortium of research groups who maintain independent lines of investigation, yet share an interest in a common set of large-scale processes influencing vegetation dynamics in Amazonia. This shared interest justifies the marginal cost of adjusting or complementing existing sampling methodologies and alleviates the need for top-down labour- and cost-intensive project management.

(*d*) *Keeping up with the cutting edge*

Progress in science is not linear. New insights, theory and technological developments can emerge very rapidly, making it difficult for individual researchers—especially those working in isolated and poorly funded institutions—to keep their science up-to-date and cost-effective. New developments frequently spawn sub-disciplines and/or centres of excellence associated with particular research groups, further sub-dividing the learning process. Examples of this are easy to find in high-technology fields such as remote-sensing, where new indices of land-cover change and degradation from increasingly high-resolution imagery are constantly out-dating previous techniques (e.g. Chambers *et al.*, 2007, and see Sections II.2 and II.7). In a similar way, the use of DNA technology and emerging techniques such as bar-coding has led to the field of systematics being divided amongst those who have access to genetic laboratories and those that do not, generating considerable controversy and confusion regarding the validity and utility of new developments (e.g. Kress & Erickson, 2008).

Promoting an effective dialogue within a research community can provide a means to allow busy or under-resourced scientists access to state of the art science, as well as to help prevent the excessive fragmentation of scientific disciplines. This is critically important in the applied sciences, as many new policy- and market-based conservation initiatives are developing so fast that there is a serious risk that science will lag behind, and will fail to inform the development of these initiatives. A clear example of this is provided by the disparate mix of REDD+ projects, a process advanced during the UNFCCC conference in Copenhagen in December 2009, which would benefit from a more coordinated approach underpinned by robust science (see Fig. 1).

(*e*) *Enhancing scientific impact and dissemination*

Most researchers disseminate their science in peer-reviewed journals, and there is often a lag period of years before even the most important results are incorporated into the design and interpretation of subsequent work. These delays can be greatly reduced through research networks, which can exploit multi-media communication channels (e.g. e-mail list-servers, online discussion forums, web-based scientific meetings, etc.) to disseminate key findings, helping the research community to avoid past mistakes and maximising the return on investment from new research initiatives. Moreover, a more interactive scientific community can increase the policy impact and societal awareness of research by working to achieve consensus findings, making joint press releases, and pooling resources to develop novel communication tools.

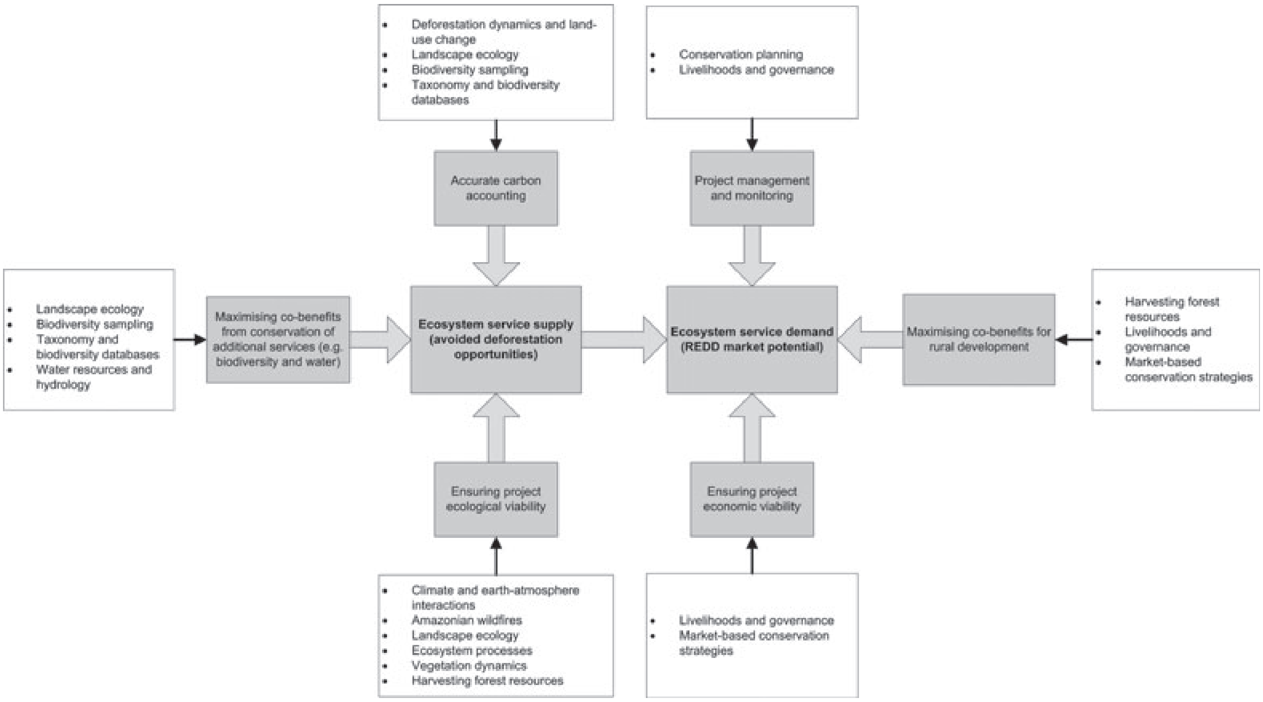

Fig. 1. A summary of interdisciplinary research needs for understanding the supply and demand of carbon sequestration services within an avoided deforestation (REDD) project, as well as long-term ecological, economic and social viability issues.

(2) Improving research performance by increasing interaction across disciplines

Calls for interdisciplinary research in environmental conservation are not new (Kinzig, 2001) but have been increasing, reflected by the rapid development of conservation science *sensu lato* as an inherently interdisciplinary field concerned with understanding complex human-environment relationships in the search for sustainability (Robinson, 2008; Cooke *et al.*, 2009; Lowe, Whitman & Phillipson, 2009). Interdisciplinarity is particularly relevant for understanding processes in human-modified tropical forests, which are both ecologically and socially complex, as well as highly dynamic. Successful interdisciplinary research will benefit from research networks in the same way as intra-disciplinary research (Section III.1), although there are obvious and substantial additional benefits that can be gained from the establishment of a more interactive research environment.

At the simplest level our research network exercise highlighted several pairwise interactions between disciplines that could generate significant reciprocal benefits. For example, the link between the taxonomic and ecological sciences could be greatly strengthened. At present many of the biodiversity specimens collected during ecological research fail to make it into museum collections or herbariums (Section II.9), while ecologists frequently rely upon outdated field guides when making identifications. Given that taxonomists (and biogeographers) require specimens from as wide a range of localities as possible and ecologists and conservation biologists require accurate species data, there is a clear benefit for these two groups to work more closely together. Once again, the increasing number of online resources could play an important role in facilitating this interaction.

Another mutually beneficial pairwise interaction exists between field ecologists and the remote sensing community. Remote sensing scientists approximate real patterns of ecological change, while fieldworkers are often interested in extrapolating direct measurements of ecological phenomena from small sampling localities to landscapes and regions. Given this apparent inter-dependence it is unclear why only a very small number of studies has attempted to link newly developed indices of canopy degradation [e.g. Normalised Vegetation Fraction Index (Souza, Roberts & Monteiro, 2005)] with field biodiversity data (Aguilar-Amuchastegui & Henebry, 2007), despite the fact that severe forest degradation currently threatens a much larger area of forest in the Amazon than deforestation (Asner *et al.*, 2005; Peres, Barlow & Laurance, 2006).

Interdisciplinary approaches are also critical when confronting environmental problems whose characteristics do not allow a clean separation of social, ecological and biogeophysical phenomena (Kinzig, 2001; Liu *et al.*, 2007). One of the strongest conclusions to emerge from our learning network exercise was the high level of interdependency that underpins many observed phenomena, both within and between the social and ecological sciences. A good example of this is the process of road building. Despite being a critical factor in the development of deforestation models (e.g. Soares-Filho *et al.*, 2006) there have been very few successful validations of road-building models against actual field data (see Section II.2). Moreover, roads are only proximate drivers of deforestation and their construction is underpinned by a complex array of biophysical and socioeconomic drivers (Perz *et al.*, 2007). It is likely that deforestation models could be greatly improved by more effectively harnessing this socioeconomic information, allowing the evaluation of the impact of more nuanced development scenarios on patterns of deforestation and changing land use (Section II.2).

Interdisciplinary studies are also essential to understand the potential for cascades and feedback effects in human-modified forest ecosystems (Gardner *et al.*, 2009). For example it is well known that the perturbation of ecological systems can precipitate cascading effects, such as those caused by over-hunting of large vertebrates on the composition of plant communities (e.g. Terborgh *et al.*, 2008), though changes to the ecological system can also have important feedbacks on the coupled social system. In another example increased fires can reduce the value of the forest for NTFPs (Sinha & Brault, 2005), encouraging a shift in livelihoods towards farming and increasing the risk of fires occurring in neighbouring areas of forest in the future. The possibility of severe climate change in the Amazon could lead to an increasing number of feedbacks between climate, and ecological and social systems (Malhi *et al.*, 2008).

Like many areas of the world, the Amazon is experiencing rapid change in its underlying governance structure, with shifts from centralised command-control systems to de-centralised governance and the emergence of public-private, voluntary and market-based conservation strategies (Boyd, 2008). A major driver of these changes is the promise offered by novel forest conservation finance through ecosystem services markets, and in particular REDD+; http://www.undp.org/mdtf/un-redd/overview.shtml. Understanding the opportunities and challenges posed by REDD+ is a quintessentially interdisciplinary problem that demands a variety of methodological approaches as well as disciplinary expertise from nearly all the areas of research analysed herein, including questions of ecological and social viability, forest management and monitoring, livelihoods and market dynamics (Fig. 1). Researchers should embrace this interdisciplinary approach from the outset if science is to make a genuine contribution to a more sustainable future for Amazonia: integration is essential to ensuring that the right variables are collected at appropriate spatial and temporal scales, and that researchers from individual disciplines are aware from an early stage of the assumptions and pervasive uncertainty confronting any interdisciplinary analysis (Kinzig, 2001; Cooke *et al.*, 2009). Research and learning networks provide a vital first step in this process of integration.

(3) Effective communication provides the basis of an interactive research environment

While successful collaborations among scientists from the same or different disciplines can bring many advantages, they can be deceptively difficult to establish. They are often driven as much by chance encounters, differences in personal interest and trust as they are by scientific priorities. Fortunately, one basic yet important lesson from our learning and research network exercise is that there are many ways of benefiting from increased interaction without entering into full collaboration, and research performance can also be improved through enhancing communication and coordination among scientists engaged in independent yet related research activities (Fig. 2).

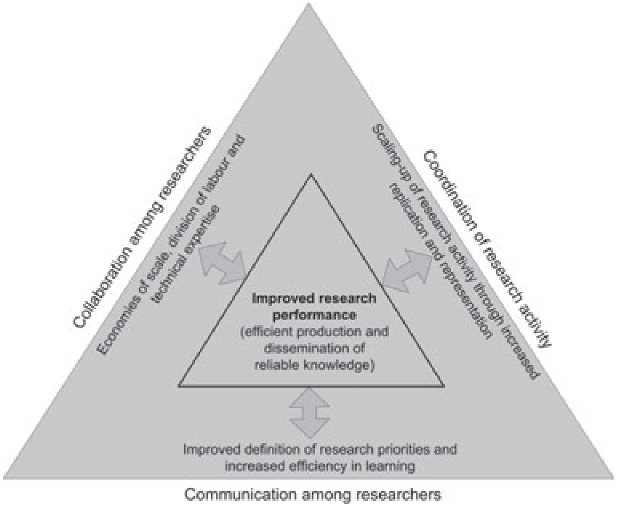

Fig. 2. A conceptual model of the three main dimensions of interaction within a research environment. Effective communication provides a basis for more formal researcher interactions including the coordination of data using comparable sampling methods and the development of active collaborations. All three forms of interaction can make valuable contributions to improving research performance. While many questions, including all interdisciplinary problems, require the establishment of collaborations with researchers working in other departments, institutions and countries, considerable progress can often first be made simply through efforts to improve communication and transparency regarding new ideas, unpublished findings and newly developed tools and technologies.

Despite being the least ambitious form of interaction, effective communication both within and among disciplines provides an essential basis for identifying high-priority research questions and helps ensure the best use of limited resources by avoiding repetitive or unfeasible work (Fig. 2). Communication of published work is often hindered by an excess of subject-specific jargon (Ewers & Rodrigues, 2006) as well as by linguistic and financial constraints which means that scientists working in developing and developed countries use very different sources of information (Pitman *et al.*, 2007). Research development could be strengthened and accelerated through the development of multi-disciplinary reviews, such as that presented here, which encourage simpler terminology, as well as the communication of a wide range of other types of information, including unpublished findings, proven field methods and analytical approaches, untested research hypotheses and ideas, published and unpublished literature, ongoing independent research projects, funding opportunities and recommendations on field logistics. Unfortunately the exchange of many of these forms of information is frequently limited by a lack of time as well as concern that sharing privileged information will compromise individual research performance and intellectual property.

(4) Overcoming barriers to interactive and interdisciplinary research

Establishing lasting networks is of course a very difficult task, and there are many potential barriers that could prevent more interactive and interdisciplinary research environments from developing. Many of these are structural, relating to the regional scope of the network, scarcity (or inequality) of funding, disciplinary institutional traditions and organisational structures, inadequate interdisciplinary training and insufficient rewards for integrative research (Kinzig, 2001; B. Fisher *et al.*, 2009). We examine some of the steps that are being taken to overcome these barriers in more detail.

(*a*) *Expanding the regional scope*

The narrow UK regional focus of the present learning network helped bring together representatives from disparate disciplines. However, this synthesis is obviously only a first step towards a more inclusive network, or set of networks, which should involve researchers from many countries, and most importantly those based within the Amazonian basin itself. Amazonian universities, research institutions and regulatory agencies are at the front line of Amazonian research, and obviously represent the most important component of effective collaborative research projects. They are also best placed to coordinate and disseminate the results of research to the most relevant decision makers, land-use planners and land managers.

Significant progress can be made through the development of additional regional networks - bringing together researchers who work in relative proximity to each other and interact through applications to common funding sources (e.g. as would be the case for networks based in each of the nine countries that comprise the Amazon). Within Brazil, initiatives such as the Center for Integrated Studies of Biodiversity in the Amazon (CENBAM) provide a good example of this, and are helping support and train field assistants, parataxonomists and scientists beyond the major regional centres of scientific research in Belém and Manaus. Similar initiatives in the other Amazonian countries would be beneficial. Ultimately a more ambitious task is to find ways to connect members of the global research community who work on tropical forests, irrespective of where they are based. While this may seem impractical, a superb precedent has been set by coral reef researchers (http://coral.aoml.noaa.gov/mailman/listinfo/coral-list/) bringing together more than 6000 researchers from across the world, effectively sharing ideas, data and opportunities for research and education.

(*b*) *Funding barriers*

There are reassuring signs that structural barriers to interdisciplinary research are being weakened by novel funding programs, and a focus towards assessing the actual impact of research programs (see the proposed arrangements for the assessment and funding of research in UK higher education institutions; http://www.hefce.ac.uk/pubs/hefce/2009/09_38/). However, networks also depend on targeted resources that can provide the physical, technological and human resources necessary to maintain a coherent, responsive and up-to-date network support structure, as well as to help overcome the enormous barriers associated with data access and sharing. Although much work remains to be done, there is promising evidence for moves in this direction within the Amazon region, such as through the Brazilian National Institutes of Science and Technology in 2008 which received R$600 million in federal government support to create regional centres of excellence and better integrate existing institutions and research groups. Decentralization of funds towards institutions and individuals who are responsible for developing research networks in distinct regions (while also maintaining the integrity of shared goals and national or global levels through coordinated selection, monitoring and evaluation procedures) is essential for capacity building and providing a dependable basis for future work. The regional Executive Hubs created to support the Brazilian national PPBio program (http://ppbio.inpa.gov.br/Eng) provides a good example of this.

(*c*) *Researcher behaviour*

Perhaps a more serious barrier to interdisciplinary research is behavioural, and relates to the values and attitudes held by researchers working in different disciplines (Kinzig, 2001; Lele & Norgaard, 2005). Whether intended or not, the values held by individual scientists manifest themselves during collaborative research exercises in the form of implicit assumptions regarding the relative utility of other disciplines, and different methodological approaches in tackling a given problem. The personal experience of a number of authors of this paper indicates that achieving an atmosphere of mutual respect within an interdisciplinary project can be extremely challenging and requires considerable patience, acceptance of uncertainty as part of the research process, and a willingness to be constructive and withhold subjective judgement when confronted with alternative world-views. Participants in interdisciplinary projects need to be self-reflective about their own value judgements and should work to achieve a common language for discussing fundamental issues while also seeking to identify a core set of shared values as a motivation for integration (Lele & Norgaard, 2005). We believe that the collaborative development of multidisciplinary research syntheses such as that presented herein is an important first step towards achieving these aims.

IV. CONCLUSIONS

(1) Proactive efforts to build a more interactive research environment are necessary to improve the performance and efficiency of scientific research and help answer globally important scientific questions. Our experience of writing this review indicates there is an impressive willingness from researchers across different disciplines to work together to achieve this.
(2) The production of portfolios of short and critical syntheses on the status and direction of individual disciplines, such as that presented here, can provide a very useful and accessible briefing on potential interdisciplinary research opportunities, as well as an entry point for dialogue among scientists who may otherwise have little understanding of each others' work. To encourage this, journals should provide space for and actively encourage such syntheses, which are complementary to the more traditional single-discipline reviews and more subjective interdisciplinary perspective-type pieces that are often led by a small and potentially biased group of researchers.
(3) Emerging learning networks can form the basis for developing a more collaborative research environment that reaches beyond more traditional means of knowledge exchange, and provides a basis for improved research performance within and among disciplines.
(4) Within the Amazonian context, the obvious next stage in the development of a truly effective learning network is to include researchers that are based outside the UK, and in particular those based within Amazonian nations themselves.
(5) Nurturing the growth of a working and viable multidisciplinary research network will ultimately require leadership and dedication from a critical mass of participants in different disciplines, as well as a significant shift in attitudes towards research funding.
(6) Despite its experiential nature, we hope that this review provides some inspiration for developing this and other research networks.

V. ACKNOWLEDGMENTS

We would like to thank the Natural History Museum in London for hosting the symposium that facilitated the development of this manuscript. T.A.G. thanks the Natural Environmental Research Council (NE/F01614X/1) and J.B. and T.A.G. thank the Instituto Nacional de Ciência e Tecnologia - Biodiversidade e Uso da Terra na Amazônia (CNPq 574008/2008–0) for funding while this paper was written. We also thank William Foster, William Magnusson and one anonymous reviewer for comments that helped improve the manuscript.

VI. REFERENCES

Aguilar-Amuchastegui, N. & Henebry, G. M. (2007). Assessing sustainability indicators for tropical forests: spatio-temporal heterogeneity, logging intensity, and dung beetle communities. *Forest Ecology and Management* **253**, 56–67.

Aleixo, A. (2004). Historical diversification of a Terra-firme forest bird superspecies: A phylogeographic perspective on the role of different hypotheses of Amazonian diversification. *Evolution* **58**, 1303–1317.

Aleixo, A. & Rossetti, D. F. (2007). Avian gene trees, landscape evolution, and geology: towards a modern synthesis of Amazonian historical biogeography? *Journal of Ornithology* **148**, S443–S453.

Alencar, A., Nepstad, D. & Diaz, M. D. V. (2006). Forest understory fire in the Brazilian Amazon in ENSO and non-ENSO years: Area burned and committed carbon emissions. *Earth Interactions* **10**, 6.

Anderson, L. O., Shimabukuro, Y. E., DeFries, R. S. & Morton, D. C. (2005). Assessment of deforestation in near real time over the Brazilian Amazon using multitemporal fraction images derived from Terra/MODIS. *IEEE Geoscience and Remote Sensing Letters* **2**, 315–318.

Anderson, L. O., Malhi, Y., Ladle, R. J., Aragao, L. E. O. C., Shimabukuro, Y., Phillips, O. L., Baker, T., Costa, A. C. L., Espejo, J. S., Higuchi, N., Laurance, W. F., Lopez-Gonzales, G., Monteagudo, A., Nunez-Vargas, P., Peacock, J., Quesada, C. A., Almeida, S. & Vasquez, R. (2009). Influence of landscape heterogeneity on spatial patterns of wood productivity, wood specific density and above ground biomass in Amazonia. *Biogeosciences*, **6**, 1883–1902, 2009.

Aragão, L. E. O. C., Malhi, Y., Barbier, N., Lima, A., Shimabukuro, Y., Anderson, L. & Saatchi, S. (2008). Interactions between rainfall, deforestation and fires during recent years in the Brazilian Amazonia. *Philosophical Transactions of the Royal Society B: Biological Sciences* **363**, 1779–1785.

Aragão, L. E. O. C., Malhi, Y., Metcalfe, D. B., Silva-Espejo, J. E., Jiménez, E., Navarrete, D., Almeida, S., Costa, A. C. L., Salinas, N., Phillips, O. L., Anderson, L. O., Alvarez, E., Baker, T. R., Goncalvez, P. H., Huamán-Ovalle, J., Mamani-Solórzano, M., Meir, P., Monteagudo, A., Patiño, S., Peñuela, M. C., Prieto, A., Quesada, C. A., Rozas-Dávila, A., Rudas, A., Silva, Jr., J. A. & Vásquez, R. (2009). Above- and below-ground net primary productivity across ten Amazonian forests on contrasting soils. *Biogeosciences* **6**, 2759–2778.

Aragão, L. E. O. C., Malhi, Y., Roman-Cuesta, R. M., Saatchi, S., Anderson, L. O. & Shimabukuro, Y. E. (2007). Spatial patterns and fire response of recent Amazonian droughts. *Geophysical Research Letters* **34**.

Arima, E. Y., Walker, R. T., Sales, M., Souza Jr, C. M. & Perz, S. G. (2008). The fragmentation of space in the Amazon basin: emergent road networks. *Photogrammetric Engineering and Remote Sensing* **74**, 699–709.

Armenteras, D., Rudas, G., Rodriguez, N., Sua, S. & Romero, M. (2006). Patterns and causes of deforestation in the Colombian Amazon. *Ecological Indicators* **6**, 353–368.

Asner, G. P., Broadbent, E. N., Oliveira, P. J. C., Keller, M., Knapp, D. E. & Silva, J. N. M. (2006). Condition and fate of logged forests in the Brazilian Amazon. *Proceedings of the National Academy of Sciences U.S.A.* **103**, 12947–12950.

Asner, G. P., Knapp, D. E., Broadbent, E. N., Oliveira, P. J. C., Keller, M. & Silva, J. N. (2005). Selective logging in the Brazilian Amazon. *Science* **310**, 480–482.

Ayres, J. M. & Clutton-Brock, T. H. (1992). River boundaries and species range size in Amazonian primates. *American Naturalist* **140**, 531–537.

Baker, T. R., Burslem, D. & Swaine, M. D. (2003). Associations between tree growth, soil fertility and water availability at and regional scales in Ghanian tropical rain forest. *Journal of Tropical Ecology* **19**, 109–125.

Baker, T. R., Phillips, O. L., Laurance, W. F., Pitman, N. C. A., Almeida, S., Arroyo, L., DiFiore, A., Erwin, T., Higuchi, N., Killeen, T. J., Laurance, S. G., Nascimento, H., Monteagudo, A., Neill, D. A., Silva, J. N. M., Malhi, Y., López Gonzalez, G., Peacock, J., Quesada, C. A., Lewis, S. L. & Lloyd, J. (2009). Do species traits determine patterns of wood production in Amazonian forests? *Biogeosciences* **6**, 297–307.

Baker, T. R., Phillips, O. L., Malhi, Y., Almeida, S., Arroyo, L., Di Fiore, A., Erwin, T., Higuchi, N., Killeen, T. J., Laurance, S. G., Laurance, W. F., Lewis, S. L., Monteagudo, A., Neill, D. A., Vargas, P. N., Pitman, N. C. A., Silva, J. N. M. & Martinez, R. V. (2004*a*). Increasing biomass in Amazonian forest plots. *Philosophical Transactions of the Royal Society of London B: Biological Sciences* **359**, 353–365.

Baker, T. R., Phillips, O. L., Malhi, Y., Almeida, S., Arroyo, L., Di Fiore, A., Erwin, T., Killeen, T. J., Laurance, S. G., Laurance, W. F., Lewis, S. L., Lloyd, J., Monteagudo, A., Neill, D. A., Patino, S., Pitman, N. C. A., Silva, J. N. M. & Martinez, R. V. (2004*b*). Variation in wood density determines spatial patterns in Amazonian forest biomass. *Global Change Biology* **10**, 545–562.

Balch, J. K., Nepstad, D. C., Brando, P. M., Curran, L. M., Portela, O., de Carvalho, O. & Lefebvre, P. (2008). Negative fire feedback in a transitional forest of southeastern Amazonia. *Global Change Biology* **14**, 2276–2287.

Barbieri, A. F., Carr, D. L. & Bilsborrow, R. E. (2009). Migration within the frontier: the second generation colonization in the Ecuadorian Amazon. *Population Research and Policy Review* **28**, 291–320.

Barlow, J., Gardner, T. A., Araujo, I. S., Avila-Pires, T. C., Bonaldo, A. B., Costa, J. E., Esposito, M. C., Ferreira, L. V., Hawes, J., Hernandez, M. I. M., Hoogmoed, M. S., Leite, R. N., Lo-Man-Hung, N. F., Malcolm, J. R., Martins, M. B., Mestre, L. A. M., Miranda-Santos, R., Nunes-Gutjahr, A. L., Overal, W. L., Parry, L., Peters, S. L., Ribeiro-Junior, M. A., da Silva, M. N. F., da Silva Motta, C. & Peres, C. A. (2007). Quantifying the biodiversity value of tropical primary, secondary, and plantation forests. *Proceedings of the National Academy of Sciences U.S.A.* **104**, 18555–18560.

Barlow, J. & Peres, C. A. (2004). Ecological responses to El Niño-induced surface fires in central Brazilian Amazonia: management implications for flammable tropical forests. *Philosophical Transactions of the Royal Society of London B: Biological Sciences* **259**, 367–380.

Barlow, J. & Peres, C. A. (2008). Fire-mediated dieback and compositional cascade in an Amazonian forest. *Philosophical Transactions of the Royal Society of London B: Biological Sciences* **363**, 1787–1794.

Bond, W. J., Woodward, F. I. & Midgley, G. F. (2005). The global distribution of ecosystems in a world without fire. *New Phytologist* **165**, 525–537.

Bottrill, M. C., Joseph, L. N., Cawardine, J., Bode, M., Cook, C., Game, E. T., Grantham, H., Kark, S., Linke, S., McDonald-Madden, E., Pressey, R. L., Walker, S., Wilson, K. A. & Possingham, H. P. (2008). Is conservation triage just smart decision making? *Trends in Ecology & Evolution* **23**, 649–654.

Boyd, E. (2008). Navigating Amazonia under uncertainty: learning from past and present forms of environmental governance. *Philosophical Transactions of the Royal Society B: Biological Sciences* **363**, 1911–1916.

Bradshaw, C. J. A., Sodhi, N. S., Peh, K. S. H. & Brook, B. W. (2007). Global evidence that deforestation amplifies flood risk and severity in the developing world. *Global Change Biology* **13**, 2379–2395.

Brandão Jr, A. O. & Souza Jr, C. (2006). Mapping unofficial roads with Landsat images: a new tool to improve the monitoring ot the Brazilian Amazon rainforest. *International Journal of Remote Sensing* **27**, 177–189.

Brondizio, E. S. & Moran, E. F. (2008). Human dimensions of climate change: the vulnerability of small farmers in the Amazon. *Philosophical Transactions of the Royal Society B: Biological Sciences* **363**, 1803–1809.

Browder, J. D. & Godfrey, B. J. (1997). *Rainforest Cities: Urbanization, development and globalization of the Brazilian Amazon.* Columbia University Press, New York.

Brown, M. & Salafsky, N. (2004). *Learning about Learning Networks: Results from a cross-disciplinary study*. Foundations of Success, Bethseda, MD.

Bruijnzeel, L. A. (2004). Tropical montane cloud forest: a unique hydrological case. In *Forest, Water and People in the Humid Tropics: Past, Present and Future Hydrological Research for Integrated Land and Water Management* (eds. M. Bonell and L. A. Bruijnzeel), pp. 462–484. Cambridge University Press, Cambridge, UK.

Brumfield, R. T. & Edwards, S. V. (2007). Evolution into and out of the Andes: A Bayesian analysis of historical diversification in Thamnophilus antshrikes. *Evolution* **61**, 346–367.

Bush, M. B. (1994). Amazonian speciation - a necessarily complex model. *Journal of Biogeography* **21**, 5–17.

Carr, D. (2009). Population and deforestation: why rural migration matters. *Progress in Physical Geography* doi:10.1177/0309132508096031.

Chambers, J. Q., Asner, G. P., Morton, D. C., Anderson, L. O., Saatchi, S. S., Espirito-Santo, F. D. B., Palace, M. & Souza Jr, C. (2007). Regional ecosystem structure and function: ecological insights from remote sensing of tropical forests. *Trends in Ecology & Evolution* **22**, 414–423.

Chao, K. J., Phillips, O. L., Gloor, E., Monteagudo, A., Torres-Lezama, A. & Martinez, R. V. (2008). Growth and wood density predict tree mortality in Amazon forests. *Journal of Ecology* **96**, 281–292.

Cochrane, M. A., Alencar, A., Schulze, M. D., Souza, C. M., Jr., Nepstad, D. C., Lefebvre, P. & Davidson, E. A. (1999). Positive feedbacks in the fire dynamic of closed canopy tropical forests. *Science* **284**, 1832–1835.

Colinvaux, P. A., De Oliveira, P. E. & Bush, M. B. (2000). Amazonian and neotropical plant communities on glacial time-scales: The failure of the aridity and refuge hypotheses. *Quaternary Science Reviews* **19**, 141–169.

Cooke, I. R., Queenborough, S. A., Mattison, E. H. A., Bailey, A. P., Sandars, D. L., Graves, A. R., Morris, J., Atkinson, J., Trawick, P., Freckleton, R. P., Watkinson, A. R. & Sutherland, W. J. (2009). Integrating socio-economics and ecology: a taxonomy of quantitative methods and a review of their use in agro-ecology. *Journal of Applied Ecology* **46**, 269–277.

Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A. & Totterdell, I. J. (2000). Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature* **408**, 750–750.

de Sherbinin, A., VanWey, L. K., McSweeney, K., Aggarwal, R., Barbieri, A., Henry, S., Hunter, L. M., Twine, W. & Walker, R. (2008). Rural household demographics, livelihoods and the environment. *Global Environmental Change-Human and Policy Dimensions* **18**, 38–53.

DeFries, R. S., Morton, D. C., van der Werf, G. R., Giglio, L., Collatz, G. J., Randerson, J. T., Houghton, R. A., Kasibhatla, P. K. & Shimabukuro, Y. (2008). Fire-related carbon emissions from land use transitions in southern Amazonia. *Geophysical Research Letters* **35**.

Dixon, J. R. & Soini, P. (1986). *The reptiles of the Upper Amazon Basin, Iquitos Region Peru.* Milwaukee Public Museum, Milwaukee.

Emmel, T. C. & Austin, G. T. (1990). The tropical rainforest butterfly fauna of Rondonia, Brazil: species diversity and conservation. *Tropical Lepidoptera* **1**, 1–12.

ESPA-AA (2008). *Challenges to Managing Ecosystems Sustainably for Povery Alleviation: Securing Well-Being in the Andes/Amazon. Situation analysis prepared for the ESPA Program.* Amazon Initiative Consortium, Belém, Brazil.

Etter, A., McAlpine, C. A., Phinn, S., Pullar, D. & Possingham, H. P. (2006). Characterizing a tropical deforestation wave: a dynamic spatial analysis of a deforestation hotspot in the Colombian Amazon. *Global Change Biology* **12**, 1409–1420.

Ewers, R. M., Laurance, W. F. & Souza Jr, C. M. (2008). Temporal fluctuations in Amazonian deforestation rates. *Environmental Conservation* **35**, 303–310.

Ewers, R. M. & Rodrigues, A. S. L. (2006). Speaking different languages on biodiversity. *Nature* **443**, 506.

Fearnside, P. M. (2008). The roles and movements of actors in the deforestation of Brazilian Amazonia. *Ecology and Society* **13**, 23. [online] URL: http://www.ecologyandsociety.org/vol13/iss21/art23/.

Fearnside, P. M. & de Alencastro, G. P. (2006). BR-319: Brazil's Manaus-Porto Velho highway and the potential impact of linking the arc of deforestation to central Amazonia. *Environmental Management* **38**, 705–716.

Fearnside, P. M. & Ferraz, J. (1995). A conservation gap analysis of Brazil Amazonian vegetation. *Conservation Biology* **9**, 1134–1147.

Ferraz, G., Russell, G. J., Stouffer, P. C., Bierregaard, R. O., Jr., Pimm, S. L. & Lovejoy, T. E. (2003). Rates of species loss from Amazonian forest fragments. *Proceedings of the National Academy of Sciences U.S.A.* **100**, 14069–14073.

Ferreira, L. V., de Sá, R. L., Buschbacher, R., Batmanian, G., da Silva, J. M. C., Arruda, M. B., Moretti, E., de Sá, L. F. S. N., Falcomer, J. & Bampi, M. I. (2001). Identificação de áreas prioritárias para a conservação de biodiversidade por meio da representatividade das unidades de conservação e tipos de vegetação nas ecorregiões da Amazônia Brasileira. In *Biodiversidade na Amazônia Brasileira: Avaliação e Ações Prioritárias para a Conservação, Uso Sustentável e Repartição de Benefícios* (eds. A. Veríssimo, A. Moreira, D. Sawyer, I. dos Santos, L. P. Pinto, and J. P. R. Capobianco), pp. 268–286. Instituto Socioambiental & Estação Liberdade, São Paulo.

Fisher, B., Balmford, A., Green, R. E. & Trevelyan, R. J. (2009). Conservation science training: the need for an extra dimension. *Oryx* **43**, 361–363.

Fisher, J. B., Yadvinder, M., Bonal, D., Rocha, H. R. d., Araujo, A. C. d., Gamo, M., Goulden, M. L., Hirano, T., Huete, A. R., Kondo, H., Kumagai, T., Loescher, H. W., Miller, S., Nobre, A. D., Nouvellon, Y., Oberbauer, S. F., Panuthai, S., Roupsard, O., Saleska, S., Tanaka, K., Tanaka, N., Tu, K. P. & Randow, C. v. (2009). The land-atmosphere water flux in the tropics. *Global Change Biology* **15**, 2694–2714.

Fisher, R., Maginnis, S., Jackson, W., Barrow, E. & Jeanrenaud, S., editors. (2008). *Linking Conservation and Poverty Reduction: Landscapes, people and power.* Earthscan, London.

FOE (2008). *REDD Myths: a critical review of proposed mechanisms to reduce emissions from deforestation and degradation in developing countries.* Friends of the Earth International.

Forest, F., Grenyer, R., Rouget, M., Davies, T. J., Cowling, R. M., Faith, D. P., Balmford, A., Manning, J. C., Proches, S., van der Bank, M., Reeves, G., Hedderson, T. A. J. & Savolainen, V. (2007). Preserving the evolutionary potential of floras in biodiversity hotspots. *Nature* **445**, 757–760.

Fragoso, J. M. V. (1998). Home range and movement patterns of white-lipped peccary (*Tayassu pecari*) herds in the northern Brazilian Amazon. *Biotropica* **30**, 458–469.

Funk, W. C., Caldwell, J. P., Peden, C. E., Padial, J. M., De la Riva, I. & Cannatella, D. C. (2007). Tests of biogeographic hypotheses for diversification in the Amazonian forest frog, Physalaemus petersi. *Molecular Phylogenetics and Evolution* **44**, 825–837.

Gardner, T. A. (2010). *Monitoring Forest Biodiversity: Improving Conservation Through Ecologically Responsible Management.* Earthscan, London.

Gardner, T. A., Barlow, J., Araujo, I. S., Avila-Pires, T. C., Bonaldo, A. B., Costa, J. E., Esposito, M. C., Ferreira, L. V., Hawes, J., Hernandez, M. I. M., Hoogmoed, M. S., Leite, R. N., Lo-Man-Hung, N. F., Malcolm, J. R., Martins, M. B., Mestre, L. A. M., Miranda-Santos, R., Overal, W. L., Parry, L., Peters, S. L., Ribeiro-Junior, M. A., da Silva, M. N. F., da Silva

Motta, C. & Peres, C. A. (2008). The cost-effectiveness of biodiversity surveys in tropical forests. *Ecology Letters* **11**, 139–150.

Gardner, T. A., Barlow, J., Chazdon, R. L., Ewers, R. M., Harvey, C. A., Peres, C. A. & Sodhi, N. S. (2009). Prospects for tropical forest biodiversity in a human-modified world. *Ecology Letters* **12**, 561–582.

Gascon, C., Malcolm, J. R., Patton, J. L., da Silva, M. N. F., Bogart, J. P., Lougheed, S. C., Peres, C. A., Neckel, S. & Boag, P. T. (2000). Riverine barriers and the geographic distribution of Amazonian species. *Proceedings of the National Academy of Sciences U.S.A.* **97**, 13672–13677.

Gentry, A. H. (1988). Changes in plant community diversity and floristic composition on environmental and geographical gradients. *Annals of the Missouri Botanical Garden* **75**, 1–34.

Girardin, C. A. G., Malhi, Y., Aragão, L. E. O. C., Mamani, M., Huaraca Huasco, W., Durand, L., Feeley, K. J., Rapp, J., Silva-Espejo, J. E., Silman, M., Salinas, N. & Whittaker, R. J. (in press). Net primary productivity and its allocation along a tropical forest elevational transect in the Peruvian Andes. *Global Change Biology*.

Goulding, M., Barthem, R. & Ferreira, E. (2003). *The Smithsonian Atlas of the Amazon*. Smithsonian Institution, Washington.

Govaerts, R., Frodin, D. G. & Pennington, T. D. (2001). *World Checklist and Bibliography of Sapotaceae*. Royal Botanic Gardens Kew, London.

Griffiths, T. (2007). *Seeing 'RED'? 'Avoided deforestation' and the rights of indigenous peoples and local communities*. Forest People's Programme.

Haffer, J. (1969). Speciation in Amazonian forest birds. *Science* **165**, 131–137.

Haffer, J. (1997). Alternative models of vertebrate speciation in Amazonia: An overview. *Biodiversity and Conservation* **6**, 451–476.

Hall, A. (2008). Payments for environmental services: the case of Brazilian Amazonia. *Journal of International Development* **20**, 965–981.

Hall, J. P. W. & Harvey, D. J. (2002). The phylogeography of Amazonia revisited: New evidence from riodinid butterflies. *Evolution* **56**, 1489–1497.

Haugaasen, T. & Peres, C. A. (2005). Mammal assemblage structure in Amazonian flooded and unflooded forests. *Journal of Tropical Ecology* **21**, 133–145.

Held, I. M., Delworth, T. L., Lu, J., Findell, K. L. & Knutson, T. R. (2005). Simulation of Sahel drought in the 20th and 21st centuries. *Proceedings of the National Academy of Sciences U.S.A.* **102**, 17891–17896.

Higgins, M. A. & Ruokolainen, K. (2004). Rapid tropical forest inventory: a comparison of techniques based on inventory data from western Amazonia. *Conservation Biology* **18**, 799–811.

Honorio Coronado, E. N., Baker, T. R., Phillips, O. L., Pitman, N. C. A., Pennington, R. T., Vásquez Martínez, R., Monteagudo, A., Mogollón, H., Dávila Cardozo, N., Ríos, M., García-Villacorta, R., Valderrama, E., Ahuite, M., Huamantupa, I., Neill, D. A., Laurance, W. F., Nascimento, H. E. M., Soares de Almeida, S., Killeen, T. J., Arroyo, L., Núñez, P. & Freitas Alvarado, L. (2009). Multi-scale comparisons of tree composition in Amazonian terra firme forests. *Biogeosciences* **6**, 2719–2731.

Hubbell, S. P., He, F., Condit, R., Borda-de-Água, L., Kellner, J. & ter Steege, H. (2008). How many tree species are there in the Amazon and how many of them will go extinct? *Proceedings of the National Academy of Sciences U.S.A.* **105**, 11498–11504.

Hutyra, L. R., Munger, J. W., Hammond-Pyle, E., Saleska, S. R., Restrepo-Coupe, N., Daube, B. C., de Camargo, P. B. & Wofsy, S. C. (2008). Resolving systematic errors in estimates of net ecosystem exchange of CO$_2$ and ecosystem respiration in a tropical forest biome. *Agricultural and Forest Meteorology* **148**, 1266–1279.

Kaimowitz, D. (2004). Useful myths and intractable truths: the politics of the link between forests and water in central America. In *Forest, Water and People in the Humid Tropics: Past, Present and Future Hydrological Research for Integrated Land and Water Management* (eds. M. Bonell and L. A. Bruijnzeel), pp. 86–98. Cambridge University Press, Cambridge, UK.

Keller, M., Alencar, A., Asner, G. P., Braswell, B., Bustamante, M., Davidson, E., Feldpausch, T., Fernandes, E., Goulden, M., Kabat, P., Kruijt, B., Luizão, F., Miller, S., Markewitz, D., Nobre, A. D., Nobre, C. A., Priante Filho, N., da Rocha, H., Silva Dias, P., von Randow, C. & Vourlitis, G. L. (2004). Ecological research in the large-scale biosphere-atmosphere experiment in Amazonia: early results. *Ecological Applications* **14**, S3–S16.

Kinzig, A. P. (2001). Bridging disciplinary divides to address environmental and intellectual challenges. *Ecosystems* **4**, 709–715.

Korzun, V. I. (1978). *World water balance and water resources of the Earth*. UNESCO, Paris.

Kress, W. J. & Erickson, D. L. (2008). DNA Barcoding - a windfall for tropical biology? *Biotropica* **40**, 405–408.

Laurance, W. F., Lovejoy, T. E., Vasconcelos, H. L., Bruna, E. M., Didham, R. K., Stouffer, P. C., Gascon, C., Bierregaard, R. O., Laurance, S. G. & Sampaio, E. (2002). Ecosystem decay of Amazonian forest fragments: a 22-year investigation. *Conservation Biology* **16**, 605–618.

Laurance, W. F., Nascimento, H. E. M., Laurance, S. G., Andrade, A., Ewers, R. M., Harms, K. E. & Ribeiro, J. E. (2007). Habitat fragmentation, variable edge effects, and the landscape-divergence hypothesis. *PLoS ONE* **2**, e1017. doi:1010.1371/journal.pone.0001017.

Laurance, W. F., Nascimento, H. E. M., Laurance, S. G., Andrade, A., Ribeiro, J. E. L. S., Giraldo, J. P., Lovejoy, T. E., Condit, R., Chave, J., Harms, K. E. & D'Angelo, S. (2006). Rapid decay of tree-community composition in Amazonian forest fragments. *Proceedings of the National Academy of Sciences U.S.A.* **103**, 19010–19014.

Lele, S. & Norgaard, R. B. (2005). Practicing interdisciplinarity. *BioScience* **55**, 967–975.

Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S. & Schellnhuber, H. J. (2008). Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences U.S.A.* **105**, 1786–1793.

Leuenberger, M., Siegenthaler, U. & Langway, C. C. (1992). Carbon isotope composition of atmospheric Co$_2$ during the last Ice-Age from an Antarctic ice core. *Nature* **357**, 488–490.

Lewis, S. L., Phillips, O. L., Baker, T. R., Lloyd, J., Malhi, Y., Almeida, S., Higuchi, N., Laurance, W. F., Neill, D. A., Silva, J. N. M., Terborgh, J., Lezama, A. T., Martinez, R. V., Brown, S., Chave, J., Kuebler, C., Vargas, P. N. & Vinceti, B. (2004). Concerted changes in tropical forest structure and dynamics: evidence from 50 South American long-term plots. *Philosophical Transactions of the Royal Society of London B: Biological Sciences* **359**, 421–436.

Li, W., Fu, R. & Dickinson, R. E. (2006). Rainfall and its seasonality over the Amazon in the 21st century as assessed by the coupled models for the IPCC AR4. *Journal of Geophysical Research* **111**, D02111, doi:02110.01029/02005JD006355.

Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E., Pell, A. N., Deadman, P., Kratz, T., Lubchenko, J., Ostrom, E., Ouyang, Z., Provencher, L., Redman, C. L., Schneider, S. H. & Taylor, W. W. (2007). Complexity of coupled human and natural systems. *Science* **317**, 1513–1516.

Lloyd, J. & Farquhar, G. D. (2008). Effects of rising temperatures and [CO2] on the physiology of tropical forest trees. *Philosophical Transactions of the Royal Society B: Biological Sciences* **363**, 1811–1817.

Lovejoy, N. R., Bermingham, E. & Martin, A. P. (1998). Marine incursion into South America. *Nature* **396**, 421–422.

Lowe, P., Whitman, G. & Phillipson, J. (2009). Ecology and the social sciences. *Journal of Applied Ecology* **46**, 297–305.

Magnusson, W. E., Costa, F., Lima, A., Baccaro, F., Braga-Neto, R., Romero, R. L., Menin, M., Penha, J., Hero, J. M. & Lawson, B. E. (2008). A program for monitoring biological diversity in the Amazon: An alternative perspective to threat-based monitoring. *Biotropica* **40**, 409–411.

Malcolm, J. R., Patton, J. L. & Da Silva, M. N. F. (2005). Small mammal communities in upland and floodplain forests along an Amazonian white-water river. In *Mammalian Diversification: From Chromosomes to Phylogeography* (eds. E. Lacey and P. Myers), pp. 335–380. University of California Publication in Zoology, Berkeley.

Malhi, Y., Aragão, L. E. O. C., Galbraith, D., Huntingford, C., Fisher, R., Zelazowski, P., Sitch, S., McSweeney, C. & Meir, P. (2009*a*). Exploring the likelihood and mechanisms of a climate-change induced dieback of the Amazon rainforest. *Proceedings of the National Academy of Sciences U.S.A.* doi: 10.1073/pnas.0804619106.

Malhi, Y., Aragao, L. E. O. C., Metcalfe, D. B., Paiva, R., Quesada, C. A., Almeida, S., Anderson, L., Brando, P., Chambers, J. Q., da Costa, A. C. L., Hutyra, L. R., Oliveira, P., Patino, S., Pyle, E. H. & Robertson, A. L. (2009*b*). Comprehensive assessment of carbon productivity, allocation and storage in three Amazonian forests. *Global Change Biology* **15**, 1255–1274.

Malhi, Y., Baker, T. R., Phillips, O. L., Almeida, S., Alvarez, E., Arroyo, L., Chave, J., Czimczik, C. I., Di Fiore, A., Higuchi, N., Killeen, T. J., Laurance, S. G., Laurance, W. F., Lewis, S. L., Montoya, L. M. M., Monteagudo, A., Neill, D. A., Vargas, P. N., Patino, S., Pitman, N. C. A., Quesada, C. A., Salomao, R., Silva, J. N. M., Lezama, A. T., Martinez, R. V., Terborgh, J., Vinceti, B. & Lloyd, J. (2004). The above-ground coarse wood productivity of 104 Neotropical forest plots. *Global Change Biology* **10**, 563–591.

Malhi, Y., Phillips, O. L., Lloyd, J., Baker, T., Wright, J., Almeida, S., Arroyo, L., Frederiksen, T., Grace, J., Higuchi, N., Killeen, T., Laurance, W. F., Leano, C., Lewis, S., Meir, P., Monteagudo, A., Neill, D., Vargas, P. N., Panfil, S. N., Patino, S., Pitman, N., Quesada, C. A., Rudas-Ll, A., Salomao, R., Saleska, S., Silva, N., Silveira, M., Sombroek, W. G., Valencia, R., Martinez, R. V., Vieira, I. C. G. & Vinceti, B. (2002). An international network to monitor the structure, composition and dynamics of Amazonian forests (RAINFOR). *Journal of Vegetation Science* **13**, 439–450.

Malhi, Y., Roberts, J. T., Betts, R. A., Killeen, T. J., Li, W. & Nobre, C. A. (2008). Climate change, deforestation, and the fate of the Amazon. *Science* **319**, 169–172.

Malhi, Y. & Wright, J. (2004). Spatial patterns and recent trends in the climate of tropical rainforest regions. *Philosophical Transactions of the Royal Society of London Series B: Biological Sciences* **359**, 311–329.

Marengo, J. A., Leibmann, B., Kousky, V. E., Filizola, N. P. & Wainer, I. C. (2001). Onset and end of the rainy season in the Brazilian Amazon Basin. *Journal of Climate* **14**, 833–852.

Marengo, J. A., Nobre, C. A., Tomasella, J., Oyama, M. D., Sampaio de Oliveira, G., de Oliveira, R., Camargo, H., Alves, L. M. & Brown, I. F. (2008). The drought of Amazonia in 2005. *Journal of Climate* **21**, 495–516.

Marks, B. D., Hackett, S. J. & Capparella, A. P. (2002). Historical relationships among Neotropical lowland forest areas of endemism as determined by mitochondrial DNA sequence variation within the Wedge-billed Woodcreeper (Aves: Dendrocolaptidae : Glyphorynchus spirurus). *Molecular Phylogenetics and Evolution* **24**, 153–167.

Moritz, C. (2002). Strategies to protect biological diversity and the evolutionary processes that sustain it. *Systematic Biology* **51**, 238–254.

Morton, D. C., DeFries, R., Shimabukuro, Y. E., Anderson, L. O., Arai, E., Espirito-Santo, F. d. B., Freitas, R. & Morisette, J. (2006). Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. *Proceedings of the National Academy of Sciences U.S.A.* **103**, 14637–14641.

Nascimento, H. E. M., Andrade, A. C. S., Camargo, J. L. C., Laurance, W. F., Laurance, S. G. & Ribeiro, J. E. (2006). Effects of the surrounding matrix on tree recruitment in Amazonian forest fragments. *Conservation Biology* **20**, 853–860.

Nepstad, D., Soares-Filho, B. S., Merry, F., Lima, A., Moutinho, P., Carter, J., Bowman, M., Cattaneo, A., Rodrigues, H., Schwartzman, S., McGrath, D. G., Stickler, C. M., Lubowski, R., Piris-Cabezas, P., Rivero, S., Alencar, A., Almeida, O. & Stella, O. (2009). The end of deforestation in the Brazilian Amazon. *Science* **326**, 1350–1351.

Nepstad, D. C., Schwartzman, S., Bamberger, B., Santilli, M., Ray, D., Schlesinger, P., Lefebvre, P., Alencar, A., Prinz, E., Fiske, G. & Rolla, A. (2006). Inhibition of Amazon deforestation and fire by parks and indigenous lands. *Conservation Biology* **20**, 65–73.

Nepstad, D. C., Tohver, I. M., Ray, D., Moutinho, P. & Cardinot, G. (2007). Mortality of large trees and lianas following experimental drought in an Amazon forest. *Ecology* **88**, 2259–2269.

Oliveira, P. J. C., Asner, G. P., Knapp, D. E., Almeyda, A., Galvan-Gildemeister, R., Keene, S., Raybin, R. F. & Smith, R. C. (2007). Land-use allocation protects the Peruvian Amazon. *Science* **317**, 1233–1236.

Ozinga, S. (2004). *Footprints in the Forest: Current practices and future challenges in forest certification*. FERN.

Pacheco, P. (2009). Smallholder livelihoods, wealth and deforestation in the eastern Amazon. *Human Ecology* **37**, 27–41.

Padoch, C., Brondizio, E., Costa, S., Pinedo-Vasquez, M., Sears, R. R. & Siqueira, A. (2008). Urban forest and rural cities: multi-sited households, consumption patterns, and forest resources in Amazonia. *Ecology and Society* **13**, 2. [online] URL: http://www.ecologyandsociety.org/vol13/iss12/art12/.

Pan, W. K. Y., Walsh, S. J., Bilsborrow, R. E., Frizzelle, B. G., Erlien, C. M. & Baquero, F. (2004). Farm-level models of spatial patterns of land use and land cover dynamics in the Euadorian Amazon. *Agriculture, Ecosystems and Environment* **101**, 117–134.

Parry, L., Barlow, J. & Peres, C. A. (2009*a*). Allocation of hunting effort by Amazonian smallholders: implications for conserving wildlife in mixed-use landscapes. *Biological Conservation* **142**, 1777–1786.

Parry, L., Barlow, J. & Peres, C. A. (2009*b*). Hunting for sustainability in tropical secondary forests. *Conservation Biology* **23**(5), 1270–1280.

Parry, L., Peres, C.A., Day, B., & Amaral, S. (2010). Rural–urban migration brings conservation threats and opportunities to Amazonian watersheds. *Conservation Letters* **3**, 251–259.

Parry, L., Day, B., Amaral, S. & Peres, C. A. (in press). Drivers of rural exodus from Amazonian headwaters. *Population and Environment*.

Patiño, S., Lloyd, J., Paiva, R., Baker, T. R., Quesada, C. A., Mercado, L. M., Schmerler, J., Schwarz, M., Santos, A. J. B., Aguilar, A., Czimczik, C. I., Gallo, J., Horna, V., Hoyos, E. J., Jimenez, E. M., Palomino, W., Peacock, J., Peña-Cruz, A., Sarmiento, C., Sota, A., Turriago, J. D., Villanueva, B., Vitzthum, P., Alvarez, E., Arroyo, L., Baraloto, C., Bonal, D., Chave, J., Costa, A. C. L., Herrera, R., Higuchi, N., Killeen, T., Leal, E., Luizão, F., Meir, P., Monteagudo, A., Neil, D., Núñez-Vargas, P., Peñuela, M. C., Pitman, N., Priante Filho, N., Prieto, A., Panfil, S. N., Rudas, A., Salomão, R., Silva, N., Silveira, M., Soares deAlmeida, S., Torres-Lezama, A., Vásquez-Martínez, R., Vieira, I., Malhi, Y. & Phillips, O. L. (2009). Branch xylem density variations across the Amazon Basin. *Biogeosciences* **6**, 545–568.

Pennington, T. D. (1997). *The genus Inga*. Royal Botanic Gardens Kew, London.

Peres, C. A. (1999). Nonvolant mammal community structure in different Amazonian forest types. In *Mammals of the Neotropics: the Central Neotropics* (eds. J. F. Eisenberg and K. H. Redford), pp. 564–581. University of Chicago Press, Chicago.

Peres, C. A. (2000). Evaluating the impact and sustainability of subsistence hunting at multiple Amazonian forest sites. In *Hunting for Sustainability in Tropical Forests* (eds. J. G. Robinson and E. L. Bennett), pp. 31–56. Columbia University Press, New York.

Peres, C. A. (2001). Synergistic effects of subsistence hunting and habitat fragmentation on Amazonian forest vertebrates. *Conservation Biology* **15**, 1490–1505.

Peres, C. A. (2002). Expanding conservation area networks in the last wilderness frontiers: The case of Brazilian Amazonia. In *Making Parks Work: Strategies for Preserving Tropical Nature* (eds. J. Terborgh, C. VanSchaik, L. Davenport, and M. Rao), pp. 137–148. Island Press, Washington DC.

Peres, C. A. (2005). Why we need megareserves in Amazonia. *Conservation Biology* **19**, 728–733.

Peres, C. A., Barlow, J. & Laurance, W. F. (2006). Detecting anthropogenic disturbance in tropical forests. *Trends in Ecology & Evolution* **21**, 227–229.

Peres, C. A., Gardner, T. A., Barlow, J., Zuanon, J., Michalski, F., Lees, A. C., Vieira, I. C. G., Moreira, F. M. S. & Feeley, K. J. (in press). Biodiversity conservation in human-modified Amazonian forest landscapes. *Biological Conservation*.

Peres, C. A. & Lake, I. R. (2003). Extent of nontimber resource extraction in tropical forests: Accessibility to game vertebrates by hunters in the Amazon basin. *Conservation Biology* **17**, 521–535.

Peres, C. A. & Michalski, F. (2006). Synergistic effects of habitat disturbance and hunting in Amazonian forest fragments. In *Emerging Threats to Tropical Forests* (eds. W. F. Laurance and C. A. Peres), pp. 105–126. University of Chicago Press, Chicago.

Peres, C. A. & Terborgh, J. W. (1995). Amazonian nature-reserves - an analysis of the defensibility status of existing conservation units and design criteria for the future. *Conservation Biology* **9**, 34–46.

Peres, C. A. & Zimmerman, B. (2001). Perils in parks or parks in peril? Reconciling conservation in Amazonian reserves with and without use. *Conservation Biology* **15**, 793–797.

Perz, S. G., Caldas, M. M., Arima, E. & Walker, R. J. (2007). Unofficial road building in the Amazon: socioeconomic and biophysical explanations. *Development and Change* **38**, 529–551.

Phillips, O. L., Aragao, L., Lewis, S. L., Fisher, J. B., Lloyd, J., Lopez-Gonzalez, G., Malhi, Y., Monteagudo, A., Peacock, J., Quesada, C. A., van der Heijden, G., Almeida, S., Amaral, I., Arroyo, L., Aymard, G., Baker, T. R., Banki, O., Blanc, L., Bonal, D., Brando, P., Chave, J., de Oliveira, A. C. A., Cardozo, N. D., Czimczik, C. I., Feldpausch, T. R., Freitas, M. A., Gloor, E., Higuchi, N., Jimenez, E., Lloyd, G., Meir, P., Mendoza, C., Morel, A., Neill, D. A., Nepstad, D., Patino, S., Penuela, M. C., Prieto, A., Ramirez, F., Schwarz, M., Silva, J., Silveira, M., Thomas, A. S., ter Steege, H., Stropp, J., Vasquez, R., Zelazowski, P., Davila, E. A., Andelman, S., Andrade, A., Chao, K. J., Erwin, T., Di Fiore, A., Honorio, E., Keeling, H., Killeen, T. J., Laurance, W. F., Cruz, A. P., Pitman, N. C. A., Vargas, P. N., Ramirez-Angulo, H., Rudas, A., Salamao, R., Silva, N., Terborgh, J. & Torres-Lezama, A. (2009). Drought sensitivity of the Amazon rainforest. *Science* **323**, 1344–1347.

Phillips, O. L., Baker, T. R., Arroyo, L., Higuchi, N., Killeen, T. J., Laurance, W. F., Lewis, S. L., Lloyd, J., Malhi, Y., Monteagudo, A., Neill, D. A., Vargas, P. N., Silva, J. N. M., Terborgh, J., Martinez, R. V., Alexiades, M., Almeida, S., Brown, S., Chave, J., Comiskey, J. A., Czimczik, C. I., Di Fiore, A., Erwin, T., Kuebler, C., Laurance, S. G., Nascimento, H. E. M., Olivier, J., Palacios, W., Patiño, S., Pitman, N. C. A., Quesada, C. A., Saldias, M., Torres Lezama, A. & Vinceti, B. (2004). Pattern and process in Amazon tree turnover, 1976–2001. *Philosophical Transactions of the Royal Society of London B: Biological Sciences* **359**, 381–407.

Phillips, O. L., Lewis, S. L., Baker, T. R., Chao, K.-J. & Higuchi, N. (2008). The changing Amazon forest. *Philosophical Transactions of the Royal Society B: Biological Sciences* **363**, 1819–1827.

Pitman, N. C. A., Azaldegui, M. D. L., Salas, K., Vigo, G. T. & Lutz, D. A. (2007). Written accounts of an Amazonian landscape over the last 450 years. *Conservation Biology* **21**, 253–262.

Pitman, N. C. A., Mogollon, H., Davila, N., Rios, M., Garcia-Villacorta, R., Guevara, J., Baker, T. R., Monteagudo, A., Phillips, O. L., Vasquez-Martinez, R., Ahuite, M., Aulestia, M., Cardenas, D., Ceron, C. E., Loizeau, P. A., Neill, D. A., Percy, N. V., Palacios, W. A., Spichiger, R. & Valderrama, E. (2008). Tree community change across 700 km of lowland Amazonian forest from the Andean foothills to Brazil. *Biotropica* **40**, 525–535.

Plotkin, M. & Famolare, L., editors. (2004). *Sustainable Harvest and Marketing of Rain Forest Products. Conservation International*, Washington DC.

Puertas, P. E. & Bodmer, R. E. (2004). Hunting effort as a tool for community-based wildlife management in Amazonia. In *People in Nature: Wildlife conservation in south and central America* (eds. K. M. Silvius, R. E. Bodmer, and J. M. Fragoso), pp. 123–138. Columbia University Press, New York.

Quesada, C. A., Lloyd, J., Schwarz, M., Baker, T. R., Phillips, O. L., Patiño, S., Czimczik, C. I., Hodnett, M., Herrera, R., Arneth, A., Lloyd, G., Malhi, Y., Dezzeo, N., Luizão, F. J., Santos, A. J. B., Schmerler, J., Arroyo, L., Silveira, M., Priante Filho, N., Jiménez, E. M., Paiva, R., Vieira, I., Neill, D. A., Silva, N. M., Peñuela, M. C., Monteagudo, A., Vásquez, R., Prieto, A., Rudas, A., Almeida, S., Higuchi, N., Lezama, A. T., López-González, G., Peacock, J., Fyllas, N. M., Alvarez Dávila, E., Erwin, T., di Fiore, A., Chao, K.-J., Honorio, E. N., Killeen, T. J., Peña Cruz, A., Pitman, N. C. A., Núñez, P., Salomão, R., Terborgh, J. & Ramírez, H. (2009). Regional and large-scale patterns in Amazon forest structure and function are mediated by variations in soil physical and chemical properties. *Biogeosciences Discussions* **6**, 3993–4057.

Richey, J. E., Nobre, C. & Deser, C. (1989). Amazon River discharge and climate variability - 1903 to 1985. *Science* **246**, 101–103.

Robinson, J. (2008). Being undisciplined: transgressions and intersections in academia and beyond. *Futures* **40**, 70–86.

Ros-Tonen, M., van den Hombergh, H. & Zoomers, A., editors. (2007). *Partnerships in Sustainable Forest Resource Management: Lessons from Latin America.* Brill, Leiden.

Rudel, T. K. (2005). *Tropical Forests: Regional paths of destruction and regeneration in the late Twentieth Century*. Columbia University Press, New York.

Salafsky, N. & Margoluis, R. (1999). Threat reduction assessment: A practical and cost-effective approach to evaluating conservation and development projects. *Conservation Biology* **13**, 830–841.

Salati, E. & Vose, P. B. (1984). Amazon Basin - a system in equilibrium. *Science* **225**, 129–138.

Salisbury, D. S. & Schmink, M. (2007). Cows versus rubber: changin livelihoods among Amazonian extractavists. *Geoforum* **38**, 1233–1249.

Santos, J. C., Coloma, L. A., Summers, K., Caldwell, J. P., Ree, R. & Cannatella, D. C. (2009). Amazonian amphibian diversity is primarily derived from late Miocene Andean lineages. *PLoS Biology* **7**, 448–461.

Schulman, L., Ruokolainen, K., Junikka, L., Sääksjärvi, I., Salo, M., Juvonen, S.-K., Salo, J. & Higgins, M. (2007). Amazonian biodiversity and protected areas: do they meet? *Biodiversity and Conservation* **16**, 3011–3051.

Schulman, L., Toivonen, T. & Ruokolainen, K. (2008). Analysing botanical collecting effort in Amazonia and correcting for it in species range estimation. *Journal of Biogeography* **34**, 1388–1399.

Scott, J. M., Davis, F., Csuti, B., Noss, R., Butterfield, B., Groves, C., Anderson, H., Caicco, S., D'Erchia, F., Edwards Jr., T. C., Ulliman, J. & Wright, R. G. (1993). Gap analysis: a geographic approach to protection of biological diversity. *Wildlife Monographs* **123**, 1–41.

Seddon, N. & Tobias, J. A. (2007). Song divergence at the edge of Amazonia: an empirical test of the peripatric speciation model. *Biological Journal of the Linnean Society* **90**, 173–188.

Shukla, J., Nobre, C. & Sellers, P. (1990). Amazon deforestation and climate change. *Science* **247**, 1322–1325.

Sinha, A. & Brault, S. (2005). Assessing sustainability of nontimber forest product extractions: how fire affects sustainability. *Biodiversity and Conservation* **14**, 3537–3563.

Smith, D. A. (2005). Garden game: Shifting cultivation, indigenous hunting and wildlife ecology in western Panama. *Human Ecology* **33**, 505–537.

Soares-Filho, B., Alencar, A., Nepstad, D. C., Cerqueira, G., Diaz, M. d. C. V., Rivero, S., Solórzano, L. & Voll, E. (2004). Simulating the response of land-cover changes to road paving and governance along a major Amazon highway: the Santarém-Cuiabá corridor. *Global Change Biology* **10**, 745–764.

Soares-Filho, B. S., Nepstad, D. C., Curran, L. M., Cerqueira, G. C., Garcia, R. A., Ramos, C. A., Voll, E., McDonald, A., Lefebvre, P. & Schlesinger, P. (2006). Modelling conservation in the Amazon basin. *Nature* **440**, 520–523.

Souza, C. M., Roberts, D. A. & Monteiro, A. L. (2005). Multitemporal analysis of degraded forests in the southern Brazilian Amazon. *Earth Interactions* **9**, 19.

Steward, A. (2007). Nobody farms here anymore: livelihood diversification in the Amazonian community of Carvao, a historical perspective. *Agriculture and Human Values* **24**, 75–92.

Stouffer, P. C. & Bierregaard, R. O., Jr. (1995). Effects of forest fragmentation on understory hummingbirds in Amazonian Brazil. *Conservation Biology* **9**, 1085–1094.

Stouffer, P. C., Strong, C. & Naka, L. N. (2009). Twenty years of understorey bird extinctions from Amazonian rain forest fragments: consistent trends and landscape-mediated dynamics. *Diversity and Distributions* **15**, 88–97.

ter Steege, H., Pitman, N. C. A., Phillips, O. L., Chave, J., Sabatier, D., Duque, A., Molino, J.-F., Prevost, M.-F., Spichiger, R., Castellanos, H., von Hildebrand, P. & Vasquez, R. (2006). Continental-scale patterns of canopy tree composition and function across Amazonia. *Nature* **443**, 444–447.

Terborgh, J., Nunez-Iturri, G., Pitman, N. C. A., Valverde, F. H. C., Alvarez, P., Swamy, V., Pringle, E. G. & Paine, C. E. T. (2008). Tree recruitment in an empty forest. *Ecology* **89**, 1757–1768.

Thonicke, K., Venevsky, S., Sitch, S. & Cramer, W. (2001). The role of fire disturbance for global vegetation dynamics: coupling fire into a Dynamic Global Vegetation Model. *Global Ecology and Biogeography* **10**, 661–677.

Uriarte, M., Ewing, H. A., Eviner, V. T. & Weathers, K. C. (2007). Constructing a broader and more inclusive value system in science. *BioScience* **57**, 71–78.

Webb, C. O., Ackerly, D. D., McPeek, M. A. & Donoghue, M. J. (2002). Phylogenies and community ecology. *Annual Review of Ecology and Systematics* **33**, 475–505.

Whinnett, A., Zimmermann, M., Willmott, K. R., Herrera, N., Mallarino, R., Simpson, F., Joron, M., Lamas, G. & Mallet, J. (2005). Strikingly variable divergence times inferred across an Amazonian butterfly 'suture zone'. *Proceedings of the Royal Society of London B* **272**, 2525–2533.

Wild, M., Gilgen, H., Roesch, A., Ohmura, A., Long, C. N., Dutton, E. G., Forgan, B., Kallis, A., Russak, V. & Tsvetkov, A. (2005). From dimming to brightening: decadal changes in solar radiation at Earth's surface. *Science* **308**, 847–850.

Wilkie, D. S., Starkey, M., Abernethy, K., Effa, E. N., Telfer, P. & Godoy, R. (2005). Role of prices and wealth in consumer demand for bushmeat in Gabon, central Africa. *Conservation Biology* **19**, 268–274.

Woodward, F. I. (1987). *Climate and Plant Distribution.* Cambridge University Press, Cambridge, UK.