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

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Improving the effectiveness of science: a case study of multi-disciplinary research on the Amazon

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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 scales 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 a region of global environmental importance, and one that 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 twelve 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 our 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 human-modified ecosystems depends partly 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 improve the dissemination of scientific findings to policy makers and society at large. There is enormous scope for improved interaction within the wider research community. Enhanced communication provides an essential foundation for more in-depth coordination of research effort and collaboration between researchers. Enhancing interaction between 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 that underpin the future of our

planet. 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 can be useful for a variety of globally important scientific questions.

Keywords: learning networks, interdisciplinary research, Brazil, Venezuela, Peru, Colombia, Bolivia, Ecuador, French Guiana, Guyana, Surinam

Introduction

The global research community is incredibly prolific, but the enormous and expanding volume of information that has been accumulated presents a significant 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-disciplinary 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 and 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 experience 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 contribute towards interdisciplinary research challenges.

Here, we present findings from a symposium held in London in 2008 which forms 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 a single geographic region (the Amazon). We chose this focus because the Amazon: (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 depends upon the success of efficient 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 outside the UK. 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 in this paper cover a variety of scientific disciplines, 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 paper and analysis is a first and important step in the development of a more sustainable and interactive research and learning environment.

State of existing knowledge and research challenges in Amazonian research

1) Climate and Earth-Atmosphere interactions

Temperature has increased by $\sim 0.25^{\circ}\text{C}$ per decade over the Amazon basin over the last 30 years, CO_2 has risen by approximately 35% compared to pre-industrial times and surface solar radiation has varied (Leuenberger et al., 1992, Wild et al., 2005). In contrast there is no significant trend in precipitation (Malhi and Wright, 2004), although there were widespread droughts in 1998 and 2005.

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

There are important vegetation-climate feedbacks, with water isotope data revealing that approximately 50 % of water is recirculated to the atmosphere through Amazon forest canopies (Salati and Vose, 1984; Shukla et al., 1990). In 2000 Cox et al. (2000) published results from the first fully coupled climate land vegetation model and predicted Amazonian rainforests to convert to savanna. However the Hadley Centre model underlying these results heavily underestimates today's Amazon precipitation. Malhi et al. (in press) used a heuristic approach to correct for the model precipitation biases, and came to much more modest conclusions with some of the rainforests being replaced by seasonal forests in their analysis but not savannah-type climate conditions. The Hadley model results are also not entirely consistent with basin-wide multi-decadal trends of aboveground biomass increase across a dense forest plot census network (Phillips et al., 1998).

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

2) Deforestation dynamics & land use change

Comment [j1]: Liana Anderson: What about: Li, W., R. Fu, and R. E. Dickinson, 2006. Rainfall and its seasonality over the Amazon in the 21st century as assessed by the coupled models for the IPCC AR4, J. Geophys. Res., 111, D02111, doi:10.1029/2005JD006355.

Comment [j2]: Check apparent contradiction with statement in section 6. I think it is just a wording issue.

Comment [j3]: check

Comment [j4]: check

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 (Rudel, 2005). Although there is significant intra-regional variability in the drivers of land-use change, the majority of deforestation is currently driven 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); 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 and de Alencastro, 2006). Protected areas, sustainable use reserves and indigenous lands set spatial limits to deforestation and perform an effective job at slowing the spread of deforestation across the Basin (Nepstad et al., 2006; Oliveira et al., 2007).

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 and economic drivers. Detecting deforestation and the drivers for deforestation 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 and 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 $\geq 10\text{cm}$ diameter) and a significant loss of faunal diversity (including disturbance sensitive forest vertebrates) (Barlow and 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 much 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 ENSO events and Atlantic SST changes, which increase fire occurrence when combined with fire-dependent human activities (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 and Peres, 2008; Malhi et al., 2009).

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 be able to better predict 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 et al., 2005) and carbon emissions (DeFries et al., 2008), we are still unable to accurately predict 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 multi-temporal analysis of fire scars that takes into account fire intensity, land-cover, and the type of fire.

4) Water resources and hydrology

Recent modelling estimates the discharge of the Amazon as 280,000 m³ per second,, while other estimates are lower at 200,000 to 220,000 m³ per second (Korzun, 1978; Richey *et al.*, 1989), representing some 15-16% of all freshwater 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 *et al.*, 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 and environmental flows and water quality (Kaimowitz, 2004). Loss of forest cover over large spatial scales is considered by many 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 though most detailed studies find no such relationship and for the largest and most destructive events forests are likely to have little impact (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).

Comment [T5]: TAG: Check ref: Bradshaw et al's main conclusion is that deforestation leads to more flooding

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. 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. 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) Ecosystem processes

Yadvinder Malhi

6) Vegetation dynamics

Recent comparative studies have revealed that patterns of carbon storage and dynamics vary strongly between different upland forests in Amazonia, overturning previous ideas that different tropical forests function in broadly similar ways. Western

Amazon upland forests have much higher rates of aboveground productivity (Malhi et al., 2004), and tree turnover (Phillips et al., 2004) but lower aboveground biomass (Baker et al., 2004b) than forests in central and eastern Amazonia. Edaphic factors, rather than climate, determine these patterns and 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 variation in soil conditions affects certain ecosystem properties such as stand-level biomass estimates (Baker et al., 2004b) and mortality rates (Chao et al., 2008).

Comment [T6]: Check potential contradiction with section 1.

The rate of tree recruitment, mortality and biomass has increased widely in Amazonian forests in recent decades (Baker et al., 2004a; 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., 2004a; Lewis et al., 2004).

Understanding the context of individual sites and regions 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 rates (Baker *et al.*, 2003) and could alter the distribution of different forest types over longer timescales (Malhi et al., *in press*). 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 intact Amazonian forests.

Comment [RME7]: Check

7) Landscape ecology

Landscape ecology in the Amazon has 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 and Bierregaard, 1995) to local extinction events in small remnants (Ferraz et al., 2003). Time series data from the BDFFP has 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 and Michalski, 2006).

Landscape ecology in the Amazon suffers shortcomings that are common to landscape ecology in general. 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 et al., 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 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 1998), butterflies (Emmel and Austin 1990), lizards (Dixon and Soini 1986) and nonvolant mammals (Peres 1999). Yet the distribution of Amazonian forest biodiversity is highly heterogeneous (Pitman et al, 2008), particularly when comparing between seasonally flooded and unflooded forests (e.g. small mammals; Malcolm et al. 2005, and large forest vertebrates; Haugaasen & Peres 2005).

Because of its 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 and 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 ID 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 good progress in these areas and it is vital that the momentum is maintained.

9) Plant taxonomy and biodiversity databases

Taxonomic understanding of Amazonian biodiversity is very limited. For example, 20-40% of tree species described in recent taxonomic monographs were new (e.g. Pennington, 1997). Our knowledge of the diversity of invertebrates, fungi and micro-organisms is particularly rudimentary. The only published reference for more than half of all known Amazonian insects is restricted to a type locality and species description (W.L. Overal, personal communication).

Integrating reliable species identifications into non-taxonomic studies can make a major contribution towards a better data set, but this is challenging in a diverse, poorly documented flora. 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 *et al.*, 2001). Comparable work on web-based resources is underway on faunal groups, such as web archives of birdsong (www.xeno-canto.org) and butterfly images (www.neotropicalbutterflies.com)

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 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, digital images and sound recordings. Such effort allied to emerging tools promises to deliver a huge improvement of biodiversity knowledge in the world’s most species-rich forest.

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, where terrestrial biodiversity reaches its peak for reasons that remain poorly understood (Bush, 1994; Haffer, 1997; Colinvaux et al., 2000). Most explanations rely on populations being historically isolated (Haffer, 1969; Lovejoy et al., 1998), yet various hypotheses based on forest refugia, riverine barriers and marine incursions receive mixed support at best (e.g. Gascon et al., 2000; Aleixo, 2004; Hall and Harvey, 2002; 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 and 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 and Edwards, 2007, Seddon and Tobias, 2007).

Modern molecular techniques are opening up new challenges and opportunities. Recent research shows that Amazonian species tend to have complex phylogeographic structure and highly variable divergence times (e.g. Marks et al., 2002; Whinnett et al., 2005). Moreover, high levels of cryptic diversity have been uncovered in Amazonian lineages, suggesting that we may have underestimated the region’s biodiversity and its propensity to generate new species. Further work is required to explore this issue, as well as the influence of geography and ecology on range limits and speciation. In particular, more phylogeographic studies are needed to disentangle the roles of landscape, history and evolutionary process in structuring

biological communities across the basin. It seems likely that a combination of disparate factors is involved, and that genes hold the key to unraveling their interaction. The answers will not only help us to understand Amazonian biodiversity, but to predict its response to environmental change, and the best strategies for its protection.

11) Amazonian hunting research

Hunting of forest mammals and birds for food is widespread across Amazonia (Peres and 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 when colonisation and forest clearance centre on roads and away from productive rivers. Away from the deforestation frontier, the decline of extractive industries and process of rapid urbanization in recent decades (Browder and Godfrey, 1997) may have alleviated hunting pressure on some animal populations. However, many of these regions are already degraded, and although secondary regrowth on cleared lands can support some large vertebrates and provide food to rural people (Smith, 2005), supply is unlikely to sustainably support demand (Parry *et al.*, 2009).

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 inter-disciplinary approaches to understanding demand have been adopted (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, as the collection of plant products may reduce the opportunity costs of hunting wildlife (Parry *et al.*, in press-a). The widespread adoption of community management of hunting through no-take areas and catch-per-unit-effort monitoring (Puertas and Bodmer, 2004) remains a distant promise. We also need to better understand 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

There are ample opportunities for expanding the existing network of forest reserves in lowland Amazonia, but 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 2002, 2005). Instead, design criteria including the size, habitat composition, denomination and level of protection of Amazonian reserves have also been decided haphazardly depending on the local expediency of sociopolitical circumstances, with little attention heeded to lessons learned from policy debates on these topics (Nepstad et al., 2006; Peres & Zimmerman, 2001) or the science of reserve allocation and implementation (Peres & Terborgh, 1995; Fearnside & Ferraz, 1995; Ferreira et al., 1999).

Given our current disconcerting level of ignorance of the patterns of biodiversity distribution across Amazonia, vegetation types probably offers 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 existing 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. A limitation of this approach, however, is that it provides little guidance on

Comment [RME8]: My impression was that the ad hoc approach to reserve design described here is being superseded by more coherent attempts to generate mega-corridors (two running N-S and two running E-W to form a noughts-and-crosses grid). But I'm not sure I've ever read anything describing that...

the specifics of reserve design, including the size, shape, connectivity, geographic position within watersheds, level of protection of conservation units, and land use in the intervening habitat matrix.

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 function as insurance and savings strategies (Salisbury and 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 and 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 14), as well as increased interactions with urban centers where payments are normally collected and spent. 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 *et al.*, 2009). The declining capacity of farms to maintain families, coupled with soil degradation and reduced agricultural yields, stimulates the next generation to move to new settlements, with consequences for forest conservation (Barbieri *et al.*, 2009). 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”. How climate change impacts local decision-making processes and risk management strategies in land-use change are beginning to gain attention (e.g. Brondizio and 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 and Famolare, 2004). Under the UNFCCC and its proposed REDD or ‘avoided deforestation’ mechanism, carbon trading could generate significant income for forest peoples (Hall, 2008c).

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 other regions and countries; and (6) asymmetrical power relations which may marginalise local groups (Ros-Tonen *et al.*, 2007). Furthermore, REDD policies will face problems of monitoring additionality in carbon sequestration and ecosystem service provision, 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).

Discussion

These 14 mini-reviews demonstrate the strength and depth of ongoing research efforts in the Amazon, but also highlight factors limiting a more complete understanding of the complex web of ecological, 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 discuss 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.

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.

1. 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 are at least partially *ad hoc* and 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 fieldwork.

2. 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 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 6). The widespread adoption of standardised methods is also essential in allowing such approaches to be constantly validated and improved for different contexts. Recent developments in this area show promise, and include the online 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 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 steadily increase the efficiency of data collection. Similarly, a centralised database of field sites would allow research teams to rapidly identify locations that have prior knowledge of particular aspects of the social-ecological system, thereby encouraging access to new sites and greatly facilitating the 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 for researchers to take advantage of such economies requires a much wider sharing of research infrastructure than is currently the case.

3. 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 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 6, 10), while human-environment interactions vary greatly depending on historical and regional context (Fearnside, 2008, Section 13).

Temporal data is 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 3 and

7). Many human-environment interactions are also highly dynamic over time, confounding attempts by short-term studies to identify reliable drivers of change (e.g. Ewers et al. 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 130 permanent plots located at 41 geographically distinct sites across Amazonia, producing important insights into how forests change over time and space and how they may respond to future environmental change (Sections 5, 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.

4. 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 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 2, 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 & Erikson 2008).

Promoting an effective dialogue within a research community can provide a means to allow busy or under-resourced scientist's access to the state of the art science in related disciplines, as well as 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 many Reduced Emissions from Deforestation and Degradation (REDD) projects, incentivised by the UNFCCC conference in Copenhagen in December of 2009, which would benefit from a coordinated approach underpinned by robust science (see Fig. 1).

5. 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. email list-serves, 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.

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 as an inherently interdisciplinary field concerned with understanding complex human-environment relationships in the search for sustainability (Robinson 2008; Lowe et al. 2009; Cooke et al. 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 (points 1-5 above), although there are obvious and substantial additional benefits that can be gained from the establishment of an 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, while ecologists frequently rely upon outdated guide books when making identifications (Section 9). 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 plays 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 have attempted to link newly developed indices of canopy degradation (e.g. Normalised Vegetation Fraction Index, Souza et al. 2005) with field biodiversity data (e.g. 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 et al. 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. One example 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 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 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 non-timber forest products (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, ecological and social systems (Malhi et al. 2008).

Like many areas of the world, the Amazon is experiencing rapid and unpredictable changes 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 Reduced Emissions from Deforestation and Degradation (REDD; <http://www.undp.org/mdtf/un-redd/overview.shtml>). Understanding the opportunities and challenges posed by REDD is a quintessentially interdisciplinary problem that requires a variety of methodological approaches as well as disciplinary expertise from nearly all the areas of research analysed in this paper, including questions of ecological and social viability, forest management and monitoring, livelihoods and market dynamics (Fig. 1). Researchers must actively 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.

Effective communication provides the basis of an interactive research environment

While successful collaborations between scientists from the same or different disciplines can bring many advantages, they can be deceptively difficult to establish. Frequently, they are driven by chance encounters and differences in personal interest and trust amongst individuals as much as 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).

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 and 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 multi-disciplinary reviews, such as the one developed 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.

Barriers preventing interactive and interdisciplinary research

There are many potential barriers that could prevent a more interactive and interdisciplinary research environment from developing. Many of these are structural, relating to the scarcity (or inequality) of funding, disciplinary institutional traditions and organizational structures, inadequate interdisciplinary training and insufficient rewards for integrative research (Kinzig 2001; Fisher et al. 2009). However, there is growing evidence that these structural barriers are being weakened by new interdisciplinary 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/).

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 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 frustratingly difficult 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 and seek 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 in this paper is an important first step towards achieving these aims.

Conclusions and recommendations

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 manuscript indicates there is an impressive willingness from researchers across different disciplines to work together to achieve this. 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 inter-disciplinary perspective-type pieces that are often led by a small and potentially biased group of researchers. Learning networks can then 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.

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Figure 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.

Figure 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.

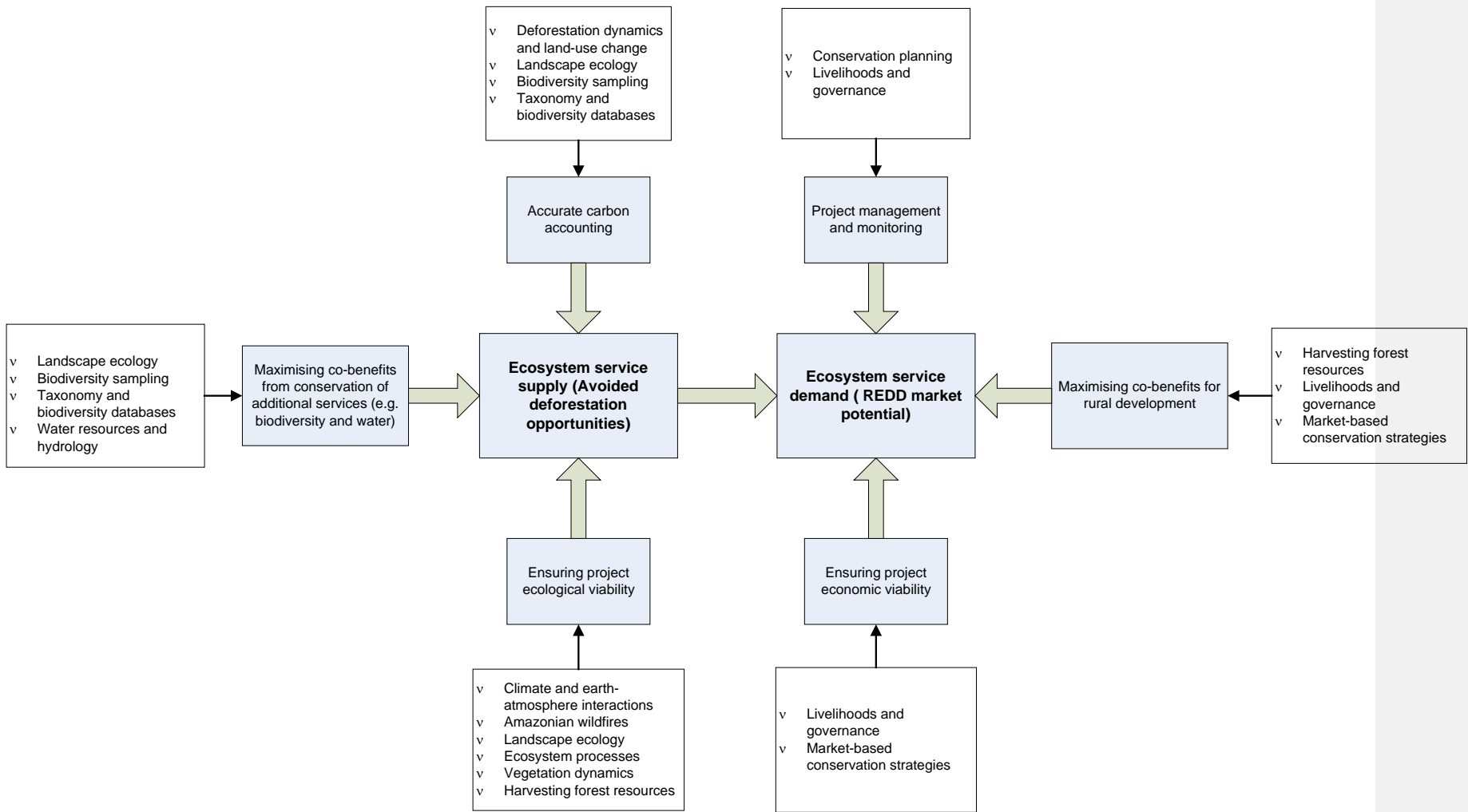


Figure 1.

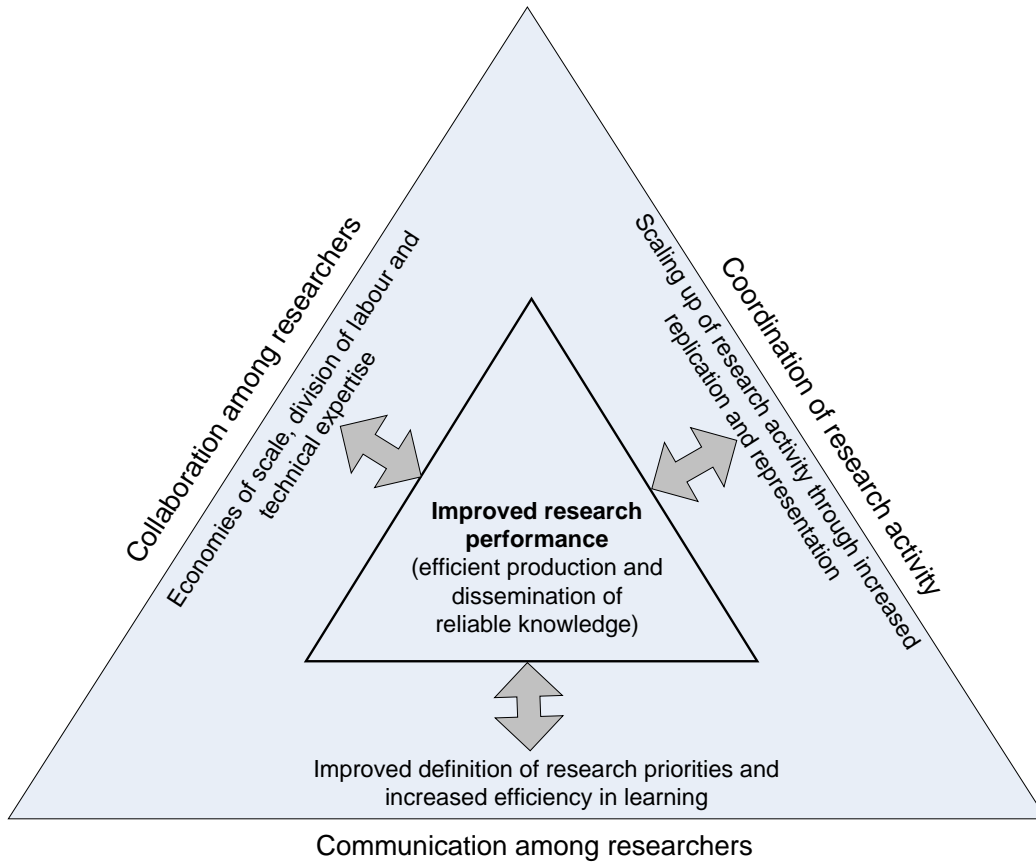


Figure 2.