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Deforestation and climate feedbacks threaten the ecological integrity of south–southeastern Amazonia

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A mosaic of protected areas, including indigenous lands, sustainable-use production forests and reserves and strictly protected forests is the cornerstone of conservation in the Amazon, with almost 50 per cent of the region now protected. However, recent research indicates that isolation from direct deforestation or degradation may not be sufficient to maintain the ecological integrity of Amazon forests over the next several decades. Large-scale changes in fire and drought regimes occurring as a result of deforestation and greenhouse gas increases may result in forest degradation, regardless of protected status. How severe or widespread these feedbacks will be is uncertain, but the arc of deforestation in south–southeastern Amazonia appears to be particularly vulnerable owing to high current deforestation rates and ecological sensitivity to climate change. Maintaining forest ecosystem integrity may require significant strengthening of forest conservation on private property, which can in part be accomplished by leveraging existing policy mechanisms.

1. Introduction

The forests of the Amazon Basin (figure 1) are part of the world's largest block of humid tropical forests. These forests provide important ecosystem services such as high biodiversity, climate regulation, carbon storage [3,4], a livelihood for millions of people [5] and, increasingly, agricultural products. The possibility of large-scale disruption of Amazonian ecosystems has received much scientific and policy attention in the past 30 years [6–8]. National and international efforts aimed at conserving Amazon forests and their ecosystem services have depended heavily but not solely on the development and expansion of protected areas (e.g. the Áreas Protegidas da Amazônia programme: http://www.mma.gov.br/port/sca/arpa/). These protected areas, in combination with federal actions to strengthen and enforce laws governing local deforestation and forest-degradation processes on private lands, have effectively conserved a significant portion of the Amazon's forests [2,9] (figure 1).

It is becoming clear that the long-term integrity of Amazon forests, including those currently under protection, depends on factors other than our ability

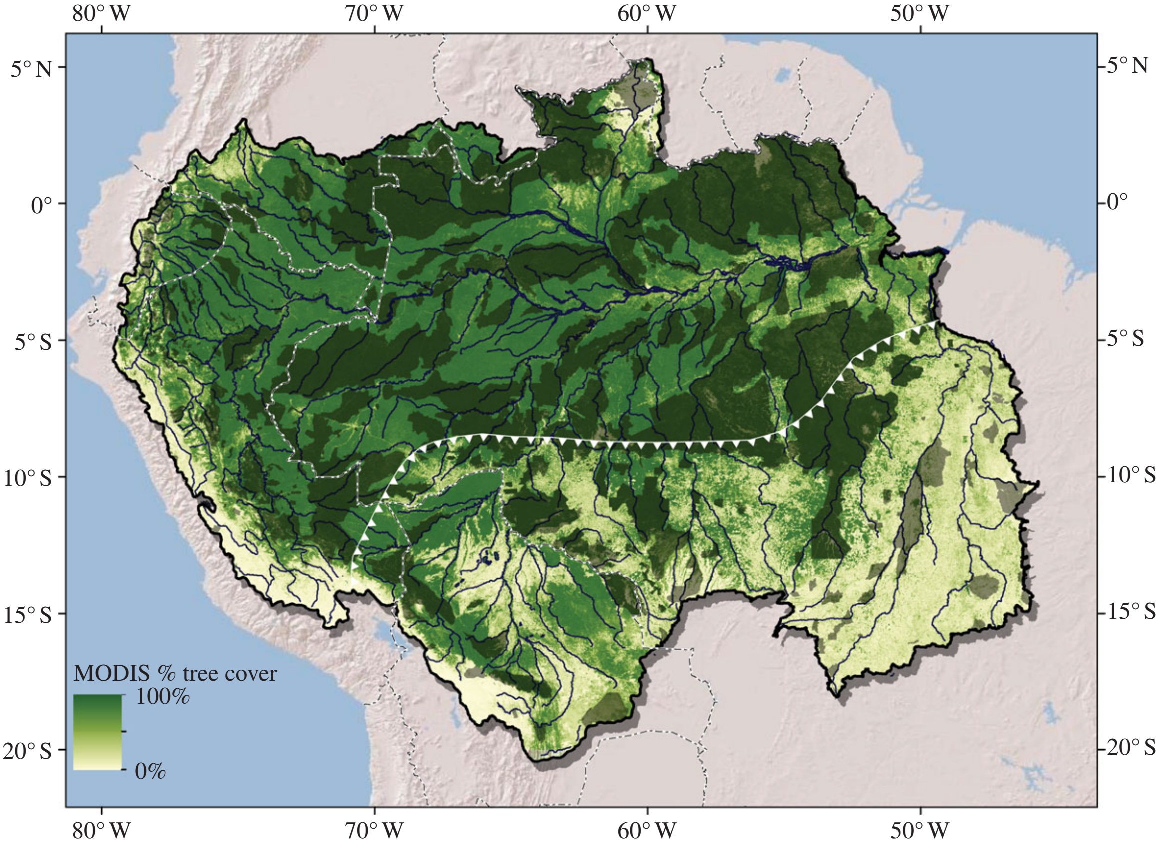

Figure 1. Amazon Basin land cover. Fractional tree cover for the year 2010 [1] is shown in shades from light green (least) to medium green (most). Protected areas are shown in dark green (adapted from Soares-Filho *et al.* [2]). Areas of the basin south and east of the white-toothed line are in the arc of deforestation and are referred to in the text as south–southeastern (SSE) Amazon.

to influence and mitigate the direct impacts of deforestation, forest degradation and resource exploitation. Externally derived climate changes and regionally driven feedbacks between deforestation and climate may disrupt ecosystem integrity in the coming decades, regardless of protected status. The south–southeastern (SSE) Amazon region appears to be particularly sensitive to these forces because of the combination of large-scale historical deforestation and its geographical position in a climatological and ecological transition zone.

In this article, we (i) review the current status of scientific understanding concerning the likely impact of deforestation and global warming on the future climate of SSE Amazonia and the associated impacts on vegetation, (ii) provide an overview of the policy instruments currently available for conservation of SSE Amazonian forests and (iii) make recommendations for research priorities to support better environmental understanding and inform conservation and mitigation strategies.

2. Current status of scientific understanding

(a) Forest–climate feedbacks

Human-induced changes in land cover and greenhouse gas (GHG) and aerosol concentrations are likely to have a strong influence on the climate of the Amazon Basin. Although there are significant unknowns regarding the spatial and temporal scales of the climatic responses to external and internal forcing, there are several key elements that are relatively well known.

(i) Deforestation has a significant influence on regional climate

Deforestation causes important changes in the energy and water balance of the Amazon. Pasturelands and croplands (e.g. soya beans and corn) have a higher albedo and decreased water demand, evapotranspiration, canopy interception and atmospheric turbulence [10,11] compared with the forests they replace. Lathuillière *et al.* [10] found that forests in the state of Mato Grosso contributed about 50 km^3 per year of evapotranspiration to the atmosphere in the year 2000 (equivalent to 50% of the statewide total). Deforestation reduced that forest flux rate by approximately 1 km^3 per year throughout the decade. As a result, by 2009, forests were contributing about 40 km^3 per year of evapotranspiration in Mato Grosso. Differences such as these can affect atmospheric circulation and rainfall in proportion to the scale of deforestation [12–14]. Recent evidence in the SSE Amazon shows that land cover heterogeneity creates centres of strong atmospheric divergence and decreased precipitation, which vary in shape and size depending on the area deforested and prevailing wind direction [15–20]. This is clearest in Rondônia, Brazil, where analysis of daily rainfall data suggests that deforestation since the 1970s has caused an 18 day delay in the onset of the rainy season [18]. This phenomenon of later onset of the rainy season since the 1970s may be occurring across much of SSE Amazonia [21].

Fires, which are closely associated with deforestation, forest fragmentation and drought intensity, are most common in the SSE Amazon [22]. The increased atmospheric aerosol loads produced by fires have been shown to decrease droplet size, increase cloud height and cloud lifetime and inhibit rainfall, particularly in the dry season in the SSE

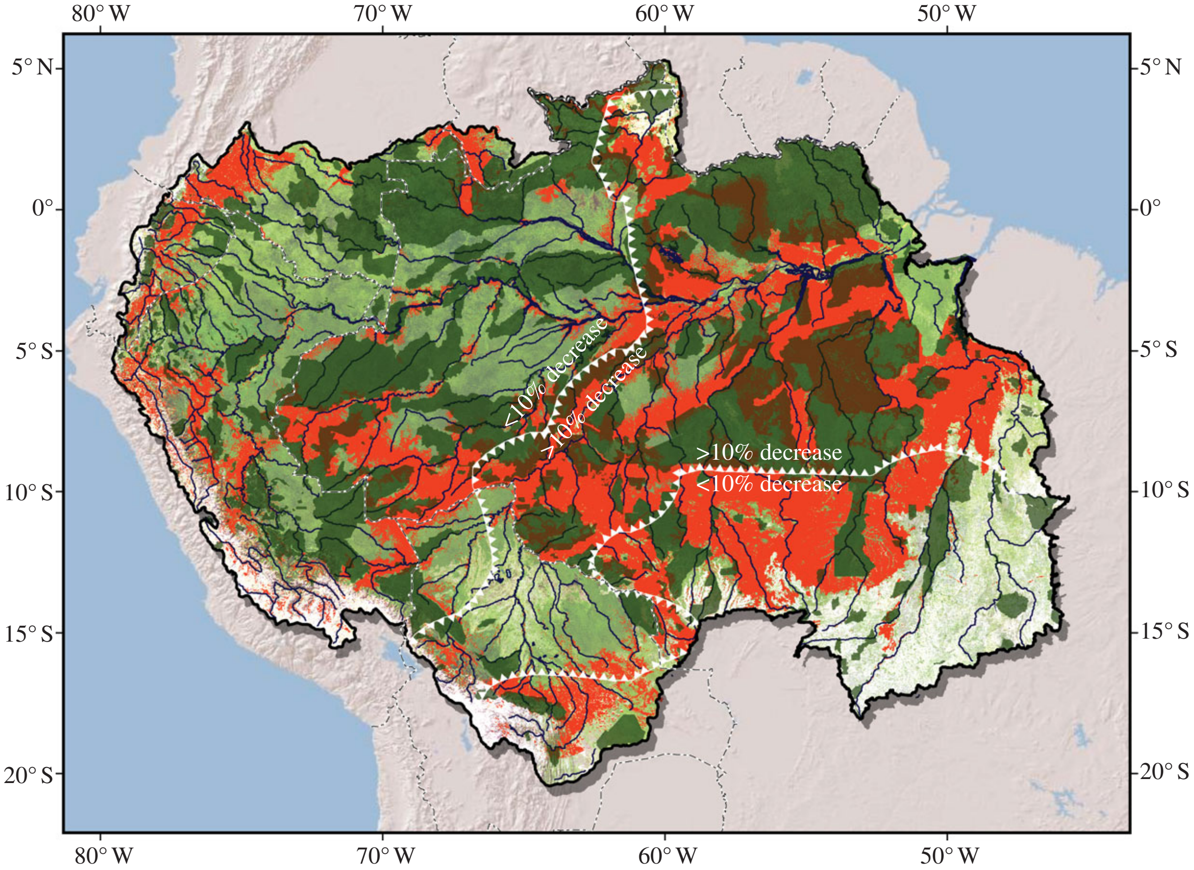

Figure 2. Change in precipitation as a result of a scenario of deforestation. In a coupled land surface and climate model simulation in which 50% of the Amazon Basin is deforested (red areas), all areas contained within the white-toothed lines experience a greater than 10% reduction in rainfall. Protected areas are shown in dark green. Areas simulated to be deforested are derived from one scenario of several presented by Soares-Filho *et al.* [25]. The simulated precipitation change values are from Coe *et al.* [26] and Costa and Pires [19]. The uncertainty of these results is large and individual global climate models give differing results but the outcome is generally similar; large-scale deforestation decreases rainfall over broad portions of the Amazon, regardless of a particular region's protected status.

Amazon [23,24]. Thus, fires and drought may create a positive feedback in the SSE Amazon such that drought is more severe with continued deforestation and climate change.

Although currently observed rainfall reductions owing to land cover change and aerosol loading appear to be limited to relatively local deforestation events, numerical model studies suggest that the reductions driven by large-scale deforestation will not necessarily be limited to deforested regions. Atmospheric circulation changes that are likely to accompany large-scale deforestation may reduce rainfall over large areas, regardless of whether the underlying land is protected forest or agriculture (figure 2) [26]. Furthermore, deforestation occurring outside the Amazon Basin can have a detrimental effect on forests within the basin. For example, deforestation in the 2 million km^2 savannah environment in southcentral Brazil, which is mostly outside of the Amazon Basin, may already be reducing rainfall hundreds of kilometres downwind in SSE Amazonia, particularly at the beginning and end of the dry season [19,26,27].

(ii) Rising greenhouse gas concentrations will lead to increased temperature and may cause enhanced drought conditions

Numerical models agree that increasing GHG concentrations will create a warmer climate in Amazonia, with predicted mean air temperature increases ranging from 2°C to 10°C [6,28]. The range in predicted values is a function of the sources of uncertainty, including the emissions scenario assumed, the climate model used, the strength of carbon cycle feedbacks and whether anthropogenic deforestation is considered. However, changes are expected to be greatest in the dry season and where forest disturbance is greatest [6]. SSE Amazonia appears to be the region of the Amazon most susceptible to decreasing precipitation with changing climate. Fifty per cent of models taking part in the Intergovernmental Panel on Climate Change Fourth Assessment Report suggest that a severe decline in dry season rainfall and increased drought probability are likely in the SSE Amazon [6,29].

(b) Ecosystem responses

Ground-based forest inventories in the Amazon suggest that in the past several decades old-growth forests have experienced compositional shifts (e.g. increasing abundance of lianas) [30,31], increasing rates of recruitment and mortality [32] and were a net carbon sink before the 2005 drought [33]. The causes for these observed changes are not clear but may be related to changes in resource availability such as the nearly 100 ppm increase in atmospheric CO$_2$ content, increasing nutrient (N and P) deposition or increasing solar radiation [34]. An alternative view is that they may be a result of changes driven by recovery from past disturbance events [35]. Future changes in forest dynamics, particularly via changes to drought seasonality and fire frequency and intensity, could result in the SSE Amazon becoming a net carbon source [6,28,32] and thereby alter the carbon balance of a large part of Brazil.

(i) Drought significantly alters rainforest structure and function

Episodic strong droughts can be important contributors to forest degradation and tree mortality. Rainfall exclusion experiments in eastern Amazonia [36,37] showed a 20–25% loss in forest biomass over the first 5–7 years of a prescribed 50 per cent reduction in rainfall [36–38]. Because of the long dry season, the evergreen forests of the SSE Amazon have much greater seasonal variability in evapotranspiration and carbon fluxes and are generally a larger net source of carbon during drought compared with wetter regions of the Amazon [39]. Analyses of the impact of the 2005 and 2010 droughts in western and SSE Amazonia suggest a significant decrease in leaf area index occurred, and that tree mortality may have been large enough to reverse the pan-Amazonian carbon sink, although regional net primary production was not affected [33,40–42]. Forests of the SSE Amazon are already close to the climatic limits for tropical forests and they would be expected to be the most vulnerable to future climate change. Therefore, an increase in drought frequency or intensity, which could occur as a function of increasing GHGs and land cover/use changes, has the potential to significantly alter forest structure in the SSE Amazon and the regional carbon balance.

(ii) Fire significantly alters the structure and function of Amazon rainforests

Fire in Amazonia is mostly of human origin, is positively correlated with forest fragmentation and drought frequency, and leads to significant changes in the structure and function of Amazonian ecosystems [43–45]. Fires reduce above-ground live biomass [22,46,47] and cause species composition changes as a result of differential mortality rates among tree species and with changes in micro-climate [46–49]. Forest fires may create positive feedback loops whereby more litter accumulates with increased mortality and canopy thinning allows greater sunlight-induced drying of litter, making previously burned forests more fire-prone [38,50]. A thin canopy may also support the establishment of invasive C_4 grasses from neighbouring pastures, which can outcompete native vegetation and elevate forest flammability [44]. Aerosols derived from fires significantly decrease incoming solar radiation and photosynthesis over large portions of the southern Amazon during the dry season and near-surface ozone levels [51,52]. These atmospheric effects of fires may increase plant stress and contribute to degradation. The number of fires and the annual area burned has continued to increase in the SSE Amazon, despite decreasing rates of deforestation since 2005, consistent with increased forest edges and several strong droughts [22,45,53–55]. Through these mechanisms, an increase in fire frequency and intensity in the future may lead to significant changes to forest structure in the SSE Amazon.

3. South–southeastern Amazon is a priority region

At least six factors presented above suggest that the coupled climate and ecology of SSE Amazon are particularly vulnerable: (i) total deforested area and current rates of deforestation are higher here than in any other region of the Amazon Basin [56]; (ii) SSE Amazonia spans a transition zone between rainforest and savannah environments, making remaining forests susceptible to relatively small changes in climate [19,57]; (iii) evapotranspiration has decreased significantly over deforested regions [10] and the onset of the rainy season may be delayed by deforestation [16,18,19]; (iv) total rainfall depends, in part, on the savannah region upwind [19,27], which is already highly deforested, is undergoing rapid agricultural expansion, and has fewer policy controls on deforestation [58]; (v) global climate model simulations suggest that it is the most sensitive region in the Amazon to global climate change [6]; and (vi) fires and drought are more frequent and intense in the SSE Amazon [22] and may increase with changing climate and land use [28,29,45]. There are potential mitigating factors, such as increased plant water-use efficiency that could reduce some drought impacts (discussed in §6). However, the combination of factors suggests that additional disturbances to land surface and climate could increase the probability of significant tree mortality through drought and fire in SSE Amazon.

Conservation of the remaining ecological integrity of SSE Amazonia will likely require mitigating some of the current and future human negative influences to avoid potentially detrimental feedbacks on climate and ecosystem functioning. This needs to be accomplished both via global reductions of GHG emissions (which we do not address here) and through reductions in deforestation and fires at regional and continental scales.

4. Policy mechanisms to encourage forest conservation

As a result of concerted efforts by policy-makers and non-governmental organizations at both state and federal levels, nearly 50 per cent of the remaining Amazon rainforest has been included in formal protected areas such as indigenous lands, sustainable-use production forests and reserves, strictly protected forests, military lands and Private Natural Heritage Reserves (figure 1) [2]. It is clear that large protected areas are effective and that expansion of the protected network is an important conservation strategy for the Amazon Basin [44]. In the case of the SSE Amazon, most of the large forest blocks are already in some form of protection. Therefore, in addition to maintaining protected areas, future efforts to reduce deforestation or increase forest cover in SSE Amazon would need to be heavily weighted towards policies and actions focused on relatively small forest fragments on private property.

There currently exist several policy mechanisms that have the potential to complement protected areas and land management strategies, thereby increasing the effectiveness of long-term forest conservation particularly on private property. Four such policy tools available for the Amazon Basin are the international Reducing Emissions from Deforestation and Forest Degradation (REDD+) mechanism, national and sub-national zoning/land-use planning efforts such as Brazil's Legal

Amazon Ecological-Economic Macro-Zoning (MacroZEE), the Brazilian Forest Code and the Brazilian National Policy on Climate Change.

The international REDD+ mechanism includes conservation, enhancement and sustainable management of forest carbon stocks, and was adopted under the United Nations Framework Convention on Climate Change in December 2010. When fully operational, REDD+ will provide positive policy and financial incentives to countries that demonstrate reductions in emissions and/or increases in the removal of carbon from the atmosphere (i.e. sequestration). Several major pilot projects are already in place in Brazil, and the Brazilian Amazon Fund has begun disbursement of funds (see [59]) in the Amazon [60]. There are limits to what may be achieved through REDD+ mechanisms [61] but they have the potential to energize existing forest conservation policies such as regional zoning and the Brazilian Forest Code.

At the national and sub-national scales, land-use planning and zoning programmes are intended to balance the demands of economic development with conservation goals. One such example is the MacroZEE (Decree 7378, 1 December 2010), which provides a policy structure for the legal Amazon designed to simultaneously maximize conservation and household and industrial scale economic production as a function of regional characteristics and needs. For the SSE Amazon, the emphasis is on fostering: (i) containment of the deforestation fronts through protected and alternate use areas; (ii) recovery and reuse of degraded areas; (iii) diversification and increased productivity where the land is occupied (both forest and non-forest); and (iv) regulation and innovation within the agro-industrial complex. Exercises involving stakeholder participation and land cover simulation in the Xingu River in Mato Grosso, Brazil suggested that sophisticated application of state and local level zoning regulations could simultaneously reduce the pressures on remaining forests, decrease landscape fragmentation and increase agricultural output [62]. Options include spatially varying application of forest code regulations based on the agricultural suitability of land coupled with policies or incentives that encourage agricultural intensification, such as double cropping and increasing cattle herd density.

The Brazilian Forest Code has been an enormously influential form of legislation, and although there have been long-standing difficulties with enforcement, it has defined a path forward for including private property in Amazon forest conservation policy. Despite the recent successful efforts to weaken the forest code, it is still an important tool for controlling deforestation and encouraging reforestation outside of protected areas. The efficacy of the Brazilian Forest Code for the future of SSE Amazonia could be greatly strengthened, if the policies and regulations guiding land use in savannahs were harmonized with those for Amazon rainforests. The current forest codes require significantly less preservation on private land in the savannah regions than in the rainforest regions (i.e. 20% on savannah outside of the legal Amazon and 35% for savannah within the legal Amazon versus 80% for rainforest in the Amazon) [58]. As discussed previously, the climates of these two regions are linked. As a result, the current forest code requirements in the savannah regions may be too low to preserve the precipitation benefits the SSE Amazon receives from the savannah.

Finally, the Brazilian National Policy on Climate Change (Law 12187, 29 December, 2009) broadly defines the goal of reducing, by 2020, the Amazon deforestation levels by 80 per cent and cerrado deforestation levels by 40 per cent, both compared with the 1996–2005 baseline. This legislation seeks to contribute to the reduction in global GHG emissions under the United Nations Framework Convention on Climate Change guidelines. However, it fails to recognize the biophysical effects of Amazon and cerrado deforestation on climate regulation [63] and ecological stability of the preserved areas. A revision of this policy, which is due by 2020, to include vegetation–climate feedbacks could help establish mechanisms to: (i) avoid deforestation in specific regions; (ii) improve the resilience of the conserved forests to climate change; and (iii) minimize forest degradation and subsequent GHG emissions.

5. Actions supporting forest conservation

Given the possibility of increasing dry season length and drought frequency, practices that control fire may be the highest priority for forest conservation in the SSE Amazon. The increase in fires in the past decade, despite declining deforestation rates, indicates the opportunities for expansion of fire management in this fragmented landscape. Fire-reducing land management techniques, strict controls on fire permitting, strong enforcement of fire restrictions and firefighting efforts championed by governmental (e.g. IBAMA, http://www.ibama.gov.br/) and non-governmental (e.g. Aliança da Terra, http://www.aliancadaterra.org.br/) organizations in Brazil have been shown to reduce fire frequency, particularly in Mato Grosso [64,65]. These activities should be encouraged and expanded in order to partially offset the effects of increasing landscape fragmentation and drought frequency [44,45].

Widespread adoption of reduced impact logging (RIL) is another potentially important practice for maintaining forest integrity. Relative to conventional logging practices, RIL significantly decreases GHG emissions [66] and forest canopy damage [67]. Avoiding canopy damage reduces fire risk, because a degraded canopy increases the solar radiation reaching the forest floor, thereby increasing air temperature, reducing relative humidity and decreasing litter moisture content [68].

6. Opportunities for future research

There are gaps in our physical and socio-political sciences knowledge that if addressed have the potential to greatly increase confidence in our projections of the future ecosystem trajectories. We recommend the following priority areas for future research.

(a) Regional climate linkages

The savannah environment appears to be important to the climate of the SSE Amazon but it remains unknown how sensitive other portions of the basin are to large-scale interdependencies. The relative importance of particular forests for maintaining the climatic and hydrologic cycles of the basin needs to be more systematically investigated. Could a progressive degradation of forests in the SSE adversely affect the environment of western Amazonia? What is the likelihood of a threshold response, whereby large portions of the Amazon change to drought-tolerant vegetation as a result of global climate change and deforestation [28,69]? These questions need to be addressed with more sophisticated coupled numerical model applications that include interactive aspects such as: crops, secondary regrowth, fires, logging and a changing climate.

(b) Climate–fire interactions and large-scale forest composition and functioning

A major concern for the coming decades is that fire frequency and subsequent forest degradation will greatly increase [6,28]. As we have discussed, research suggests that fire frequency and intensity may increase across much of the SSE Amazon in the future owing to more frequent drought and landscape fragmentation [44,45], but our available data and numerical tools are still limiting. For example, research clearly shows the importance of fire as a mechanism of tree mortality and indicates that mortality increases exponentially with landscape fragmentation and drought [45]. Unfortunately, our understanding of fire-induced tree mortality is based on a very limited number of studies in seasonally dry forests, whereas the response of tree species in what is currently the wetter, mostly fire-free portions of the Amazon is still unclear. Additionally, fire and the subsequent tree mortality are treated only crudely in most numerical models, generally in a statistical manner without direct representation of the underlying physical processes [45]. Focused research, simultaneously addressing both the field data and numerical model gaps, is required for progress on this issue.

(c) Tropical forest species response to increasing temperature

Leaf-level warming studies in Amazonia suggest that a temperature increase of 2°C can substantially reduce photosynthesis [70]. While evidence from outside the tropics suggests that total ecosystem damage should be limited because of respiratory and photosynthetic acclimation to higher temperatures [71], relatively little information is available for tropical plant species. The temperature dependencies of photosynthesis and respiration are very large sources of uncertainty in current predictions of ecosystem response to future climate [36,72,73] and the extent of future global warming [74]. Forest structure (e.g. canopy height) and productivity may also respond directly to the ambient radiation environment in addition to ambient temperature and precipitation [73]. There is a great need for additional field and modelling studies in this area.

(d) Biophysical response of tropical forest species to increasing carbon dioxide

Elevated atmospheric CO_2 generally stimulates plant growth directly through increased photosynthesis and indirectly through increased water-use efficiency [75]. Global vegetation models predict large increases in Amazonian forest biomass with increasing CO_2 because this biophysical response is applied as a constant, and the simulated vegetation does not acclimate to this forcing [76]. In most climate/vegetation models, this biophysical effect compensates for any climate-change-driven loss of biomass [77,78]. These simulated responses are highly uncertain, because there are no *in situ* field-based studies on the strength and persistence of CO_2-induced changes to tropical tree growth rates. In addition, soil nutrient constraints are poorly known and may significantly affect the nature of any climate- and CO_2-driven change in biome composition [79]. As a result, predictions of how biomass may change with increasing CO_2 are still highly uncertain.

(e) Regional policy linkages

Deforestation rates within the Amazon Basin have dropped to historically low levels, in part because of the application and enforcement of new and existing conservation policies within the Amazon [9]. Conversely, annual deforestation and expansion of soya bean and pasture in the neighbouring cerrado environment is still large and now exceeds the deforestation rate of the Amazon [80]. It is unknown to what degree these two trends are linked. What are the social and political drivers of continuing deforestation in the cerrado? Is deforestation in the cerrado, in part, due to leakage from the Amazon? Could the strong enforcement of anti-deforestation policies in the Amazon be driving part of the observed deforestation in the cerrado? Among industrial growers, is the cerrado viewed more favourably as a region for expansion? Research exploring the potential links between decision-making processes and policy mechanisms in these two regions is needed.

(f) Social aspects of land cover change

Spatially explicit simulations of land cover change as a function of socioeconomic drivers have become important tools in the Amazon for illustrating the potential impact of policy interventions and describing theoretical future land-use distributions to maximize ecosystem services (e.g. Dinamica Ego, http://www.csr.ufmg.br/dinamica/) [25]. However, little is know about the feedbacks between policy applications and individual decision-making. For example, can policies that promote agricultural intensification and deforestation reduction result in significant negative feedbacks such as increasing land prices and greater demand for deforestation locally and regionally? Continued model development and application with social science data are needed in order to represent more sophisticated feedbacks between policies and land-use decisions.

7. Conclusions

In the past decade, we have developed a much clearer understanding of some of the large-scale climate changes and ecosystem responses associated with human activities in the Amazon. Evidence suggests that the ecosystem integrity of remaining forests in SSE Amazon, whether protected or unprotected, may be particularly vulnerable to environmental disturbances caused by local and regional deforestation and increasing atmospheric GHG content.

The current network of Amazonian protected areas is extensive and has thus far successfully isolated a large fraction of the Amazon from significant degradation. Most remaining large forest blocks in the SSE Amazon are already included in protected areas, and as a result any new protected areas would by necessity be small and may over-extend already-stretched resources and budgets. Key strategies for the immediate future will be to maintain the physical integrity of existing protected areas, continue and expand the strong enforcement against degradation such as fires, and strengthen forest conservation on private properties. The suite of conservation, zoning and funding mechanisms available in Brazil and the successes so far in reducing deforestation provide optimism. Paths can be found to devise strategies, provide guidance, and fund and implement significant new conservation initiatives particularly on private property throughout the Amazon and cerrado regions.

Important physical and social science unknowns remain. They include the biophysical response of forests to changing CO$_2$, temperature, drought and fire. Unknowns also include the social and political linkages between differing rates of deforestation in the cerrado and Amazon. Research focused on these topics is likely to be valuable for improving and implementing strategies that effectively protect forests, maintain climate and ecosystem function, and provide a wide array of development and livelihood opportunities across Amazonia.

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