Introduction


One contribution of 18 to a Theme Issue ‘Ecology, economy and management of an agroindustrial frontier landscape in the southeast Amazon’.

Subject Areas:
environmental science, ecology

Keywords:
deforestation, land-use change, Amazon forests, cattle ranching, stream, Mato Grosso

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The papers in this special issue address a major challenge facing our society: feeding a population that is simultaneously growing and increasing its per capita food consumption, while preventing widespread ecological and social impoverishment in the tropics. By focusing mostly on the Amazon’s most dynamic agricultural frontier, Mato Grosso, they collectively clarify some key elements of achieving more sustainable agriculture. First, stakeholders in commodity-driven agricultural Amazonian frontiers respond rapidly to multiple forces, including global markets, international pressures for sustainably produced commodities and national-, state- and municipality-level policies. These forces can encourage or discourage deforestation rate changes within a short time-period. Second, agricultural frontiers are linked systems, land-use change is linked with regional climate, forest fires, water quality and stream discharge, which in turn are linked with the well-being of human populations. Thus, land-use practices at the farm level have ecological and social repercussions far removed from it. Third, policies need to consider the full socio-economic system to identify the efficacy and consequences of possible land management strategies. Monitoring to devise suitable management approaches depends not only on tracking land-use change, but also on monitoring the regional ecological and social consequences. Mato Grosso’s achievements in reducing deforestation are impressive, yet they are also fragile. The ecological and social consequences and the successes and failures of management in this region can serve as an example of possible trajectories for other commodity-driven tropical agricultural frontiers.

1. Introduction

This theme issue on the development of an Amazon agroindustrial frontier emerged from two scientific workshops held in Brazil, one at Tanguro Ranch (Mato Grosso) in early 2011 and another one in Bonito (Mato Grosso do Sul) during the Association of Tropical Biology and Conservation (ATBC) meeting in mid-2012. The 18 papers in this special issue focus on a major challenge facing our society: feeding a rapidly growing population that is increasing its per capita food consumption, while preventing widespread forest degradation, loss of natural ecosystems and the subsequent environmental and social consequences. These contributors address some of the key questions about the future of tropical ecosystems (figure 1): what are the consequences of land-use change for freshwater and terrestrial ecosystems? What are the large-scale conservation opportunities that could reverse or mitigate the negative ecological, social and economic consequences of crop and cattle production? What are the key forest governance lessons to be learned from Brazil’s Amazonian agricultural frontier?

This special issue focuses mostly on the Brazilian state of Mato Grosso (MT; figure 2), the Amazon’s biggest and most dynamic agricultural frontier [2–4]. Home to a wide range of stakeholders (e.g. large and small farmers, indigenous peoples, etc.) over the past two decades, MT has experienced both the highest rates of deforestation (mostly for pasture and soya bean expansion) and the greatest reductions in deforestation rates (associated with policies and macroeconomic
factors) in the Amazon. Originally, Amazon forests, cerrado biome (savannah vegetation) and pantanal vegetation accounted for 53 per cent, 40 per cent and 7 per cent of the state’s natural terrestrial ecosystems, respectively. Conversion for cattle ranching and agriculture expansion reduced these areas to 34 per cent, 20 per cent and 5 per cent (as of 2009). Although these three ecosystems are under pressure from land-use change, the contributions in this special issue are primarily centred on Amazon forests (moist, wet and transitional).

The regional focus of this special issue allows for a deep assessment of the complex ecological and social changes related to agricultural transformation of a tropical forest environment (figure 1). At the same time, the regional focus does not diminish the global relevance of topics addressed in this theme issue because deforestation and agricultural expansion are occurring rapidly in many other tropical agricultural frontiers. In this introduction, we summarize topics that are explored further in the papers within this issue: the temporal trends in land-use change in MT; the ecological and social consequences of land-use change; and the landscape management strategies that can reduce environmental degradation in agricultural frontiers.

2. Land-use change in Mato Grosso

Until recently, MT’s development was based on economic activities that resulted in deforestation, forest degradation and associated socio-ecological consequences [4]. From 1990 to 2005, for example, approximately 70,000 km² of forests in MT were converted to low-productivity pasturelands [5,6], which degraded streams [7], increased disturbance (e.g. escaped forest fires) [8,9] and altered the regional climate [10]. At the same time, socio-economic tensions emerged owing to land speculation and conflicts among loggers, indigenous peoples and farmers [11].

Beginning in the early 2000s, soya beans emerged as another driver of Amazon deforestation [12], directly causing 17 per cent of MT’s forest clearing [3]. The soya bean expansion may also have contributed indirectly to additional deforestation as it pushed the cattle ranching frontier into previously undisturbed forests [13]. Although management practices associated with soya bean production reduced many of the negative environmental impacts of poorly managed pasturelands (e.g. the use of fire to remove weeds), they introduced others (figure 3). Compared with pasturelands, for example, soya bean fields require more pesticides and herbicides [14], cause greater alterations in the regional energy balance (e.g. higher albedo) [15] and demand more fertilizers [16].

To avoid the negative ecological and political consequences of widespread deforestation for pasture and cropland expansion, Brazil began in 2004 to set an ambitious goal under President Luis Inácio ‘Lula’ da Silva’s administration, to drastically curb Amazon forest losses. The federal government created several policies, including the National Plan for Deforestation Reduction (PPCDAM in Portuguese) in 2004, and the National Policy on Climate Change (NPCC) in 2010, which aim to reduce Amazon deforestation by 80 per cent by 2020. In 2010, MT created its own targets and proposed to cut 87 per cent of the state’s deforestation by 2020 (see table 1 for more examples).

Figure 1. Schematic diagram showing the interconnections among the processes that affect land cover and land-use change (LCLUC) and the social and biophysical outcomes of LCLUC in the Brazilian Amazon. Each contribution in this special issue is associated with at least one of the processes and outcomes. Although the contributions do not address the roles of infrastructure directly, this is an important driver of change in Amazonia.
The process of slowing deforestation and forest degradation in MT was complicated by a number of factors, including economic incentives designed to expand pasture-lands and agricultural fields [17]; weak capacity for real-time monitoring and enforcement to reduce deforestation in the early 2000s [6]; jurisdictional instability, which created disincentives to comply with some of the Brazilian environmental laws (e.g. Forest Code) [18]; increased global demand for commodities, which stimulated the expansion of cattle ranching and soya bean planting at the cost of illegal Amazon deforestation [5]; and finally, corruption that was embedded in several of the federal and state agencies responsible for reducing deforestation [19].

Despite the many challenges, MT achieved a remarkable result in the late 2000s. It reduced deforestation from 6800 (1990–2006) to 1650 km$^2$ yr$^{-1}$ (2007–2012), whereas crop and cattle production continued to grow [2]. Other Amazonian states followed a similar path [20], providing one of the most

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**Figure 2.** (a) The Amazon river basin with the percentage canopy cover derived from MODIS for the year 2010 [1]. The state of Mato Grosso is shown with the dashed-dotted line, the Upper Xingu River in blue. (b) Map of land cover classes and change in Mato Grosso as of 2010. Forests are in dark green, cerrado in beige, and crops that existed prior to 2000 in yellow. Land-use changes (LUC) that occurred from 2000 to 2010 are shown as: pasture/cerrado to crop in orange and forest to crop in red [2]. Protected areas are in medium green. The Upper Xingu is delimited with the blue line, whereas the bright green line is the boundary of the Xingu Indigenous Park, the largest single reserve.
interesting and important examples of frontier governance for tropical nations. Although the specific reasons for these reductions have yet to be fully understood, they were the result of complex interactions between policies and macroeconomic factors [21]. On the policy side, the federal and state government imposed drastic sanctions on producers in municipalities that deforested illegally, increased enforcement of environmental laws, improved deforestation monitoring, established new protected areas and indigenous reserves [22] and created new incentives to increase food production without new deforestation. MT also developed an environmental registry system of rural properties, which enabled the state to enforce environmental laws (i.e. Forest Code) more transparently and efficiently. Regarding some of the macroeconomic factors, the profitability of global commodities declined during the mid–late 2000s, Brazil’s exchange rates decreased, and the private sector created its own mechanisms to exclude deforesters from the food supply chain [21]. The active participation of multiple stakeholders was an important force to reduce deforestation. In 2003, for example, the Greenpeace campaign influenced the private sector to reject soya bean produced in recently deforested areas, resulting in an agreement called the ‘soya moratorium’.

3. Socio-ecological consequences of land-use change

Declines in MT’s deforestation may help to avoid further environmental degradation and loss of freshwater and terrestrial ecosystems, and the associated negative consequences for the livelihoods of forest-dependent people. However, continued ecological problems related to land management remain, including (i) degradation of forests by the combination of human-induced fires and drought; (ii) impoverishment of aquatic ecosystems through the widespread application of agricultural chemicals and lack of riparian restoration; and (iii) loss of indigenous peoples’ livelihood options because of ecological degradation. Furthermore, forest conversion is expected to increase with increasing national and international demand for soya, beef and/or palm oil. In the following sections, we describe some of the socio-ecological consequences of land-use change that are part of this special issue. These contributions cross disciplines spanning ecology, climatology, geography, anthropology, sociology, fire ecology and remote sensing, among others. Because of the multi-disciplinary perspectives included in this issue, individual papers reflect varying approaches from different disciplines.

(a) Land–water interactions

Several papers in this special issue clarify and summarize how changing land cover and land management over the past few decades in MT have influenced regional hydrology and aquatic ecology. Some of the most pervasive activities affecting stream ecology are the removal of riparian forests [23] and construction of stream impoundments, most of which are installed to provide cattle with access to drinking water. These features, though concentrated in pasturals, are common in croplands owing to the legacy of previous land uses and the need for small-scale hydroelectric power. The staggering scale of human impacts in this region is illustrated by Macedo et al. [24], who document almost 10,000 impoundments in the Upper Xingu alone, with nearly every first- and second-order stream having one or more impoundments. The authors also show that deforestation and impoundments degrade aquatic environments, increase stream temperatures (by up to 4°C), and disrupt stream connectivity.
Deforestation for pasturelands and croplands also affects aquatic systems through changes in the water balance, stream flow and biochemistry. Coe et al. [25] review how deforestation increases surface air temperatures, reduces evapotranspiration and increases runoff and stream water discharge. Forest contribution to the total evapotranspiration in MT decreased by about 20 per cent between 2000 and 2009 because of deforestation [26]. Neill et al. [27] review a series of experiments testing how these changes affect stream flow in a mixed forest and soya bean landscape in MT. Catchments dominated by soya bean fields had an approximately fourfold increase in discharge compared with forested watersheds. An observed fourfold increase in N and P fluxes in the soya bean streams was consistent with the discharge increase, but no changes in N or P concentration were observed. Soya bean is a nitrogen-fixer generally requiring no chemical N fertilization during the growing process, so the lack of change in N concentration is not surprising. However, as noted by Neill et al. [27], the lack of increase in P concentrations in soya bean streams does not reflect the large amounts of P fertilizer (approx. 50 kg ha⁻¹) that was applied. One potential explanation for this result is that the P was either removed during soya bean harvesting or adsorbed in the deep Oxisol soils common to these tropical agricultural areas [28]. Another surprising result reported by Neill et al. [27] was that there was no measurable increase in sediment flux to soya bean streams owing to the high-infiltration capacity of soils in this region. Despite some soil compaction in soya bean fields, groundwater still represented more than 95 per cent of all water flux to the streams and no significant sediment flux was observed.

Land conversion in the southeastern Amazon has been massive and rapid. Outside protected areas in the Xingu, the average watershed area occupied by croplands and pastures increased from 25 per cent in 2001 to more than 40 per cent in 2010 [24]. Research to date indicates that the hydrological consequences of these changes for aquatic ecosystems have been large, whereas the biogeochemical consequences have thus far been relatively small. However, there are still a number of outstanding questions, particularly concerning biogeochemical fluxes, which must be addressed when considering the future trajectories of aquatic ecosystem health in this and other tropical agricultural areas. One of the most important is that biogeochemical fluxes may increase over time. Soya bean has been planted for only a few years in most of these study areas. It is possible that the soil capacity to adsorb excess P will be reduced after many years or decades in soya bean production and that P fluxes to streams will eventually increase. It is also likely that the rapid increase in double cropping with maize and cotton in these agricultural systems (as presented by VanWey et al. [29]) will lead to significant change. Both maize and cotton require large amounts of chemical N fertilizers and one could expect large increases in N flux from the soil in the future [30]. Similarly as reviewed by Schiesari et al. [31], all of these crops require large inputs of pesticides, herbicides and fungicides. The effects of these agrochemicals on groundwater and stream water are largely unknown but potentially significant.

(b) Terrestrial ecosystems

The total area deforested in MT from 1990 to 2012 is larger than England (totalling approx. 136 000 km²). The most evident consequence of this transformation of the landscape is the loss and fragmentation of natural habitats for wildlife. Less obvious, but equally important are the indirect ecological consequences of deforestation. The opinion piece by Coe et al. [25], for instance, suggests that changes in climate associated with forest clearing may be large enough to increase Amazon fires and reduce the capacity of forests to store and cycle carbon. These effects could be particularly severe if future deforestation rates increase in both southeast Amazonia and the cerrado, and if atmospheric [CO₂] continues to rise. In a scenario where these gloomy predictions materialize, the end of deforestation may not be sufficient to secure the current integrity of some Amazon forests.

Morton et al. [32] provide a glimpse of fire regimes in a drier and warmer future Amazon. The authors quantified the spatial–temporal patterns of forest fires in MT and other states to show that dry and warm climatic conditions in 2007 and 2010 triggered widespread fires that affected approximately 15 000–26 000 km² of Amazonian forests. This is particularly interesting because these widespread fires occurred during a period of low deforestation, suggesting that climate overwhelmed the likely reduction in sources of fire ignition. Fires that occur during these climatic conditions are expected not only to affect large forests areas, but also to be more intense [33]. Schwartzman et al. [34], for example, report that several indigenous groups of the Xingu Indigenous Park (XIP) consider that fires which occur during drought events are more intense and affect larger forested areas than they did in previous decades. They also report that fires, which were commonly used as a management tool for agriculture in the past, are now more likely to escape into forests.

Two other contributions to this special issue provide more detailed description of fire effects on vegetation dynamics. Balch et al. [35] make the important point that repeated forest fires can shape forest structure and diversity by altering forest trajectories and regeneration mode (from seeds to resprouting), whereas Silverio et al. [36] provide support for the hypothesis that fire-induced tree mortality can mediate the transition from forest to grassy ecosystems along forest edges, which are abundant in the region [37]. Based on the results from these contributions and from other studies [9,37,38], it is reasonable to infer that forest fires could become one of the most important drivers of forest degradation in the near future. To avoid this process of forest impoverishment by fire, management strategies should be implemented to reduce (i) sources of fire ignition associated with pastures/agricultural activities and (ii) the formation of forest edges. Interesting and important initiatives are already in place (table 1), whereas others are under development (see [39]). Logging is another important driver of forest degradation, but is not included in this special issue (see [40] for more details).

(c) Socio-economic systems

The process of land-use transitions from forests to intensively managed agricultural landscapes has several potential consequences for social systems in Amazonia. In this special issue, three contributions present examples of these effects. VanWey et al. [29] found that the increase in double cropping in central MT was associated with improvements in socio-economic indicators, such as income and investments in education. The authors use these and other results to argue that agriculture intensification often co-occurs with the development of institutions and economic activities, as well
as with investments in public goods, which ultimately improve the livelihood of some societal groups. But for other groups—particularly those that depend directly on natural resources for their subsistence—the environmental consequences of land-use change can have complex and contrasting effects (details in Le Tourneau et al. [41]). For example, it is clear that recent deforestation outside the XIP reduced resources that are important for the livelihood of indigenous peoples [34]. The degradation of the Xingu headwaters, for instance, promoted the impoverishment of fish communities which are the main source of protein for XIP inhabitants.

Two other contributions propose innovative methodologies to assess the complex effects of land-use change on socio-economic and ecological systems in Amazonia. Le Tourneau et al. [41] developed a multi-dimensional indicator system (DURAMAZ) that integrates many aspects of sustainable development. The authors used this methodology across twelve Amazon regions to show that social, economic and ecological characteristics varied widely depending on cultural factors, sense of place and, to a lesser extent, economic factors. The authors concluded that the same development policy could have different outcomes depending on the cultural, regional, sub-regional and economic context where it is implemented. In the second contribution, Gardner et al. [42] present the Sustainable Amazon Network (Rede Amazônia Sustentável), a multi-disciplinary research initiative involving more than 30 partners and organizations. The goal of this initiative is to assess both social and ecological dimensions of land-use sustainability in the eastern Brazilian Amazon. To do so, the authors combine different disciplines and spatial and temporal scales, while connecting local actors and institutions to create better conditions for local policy and management decisions. These two initiatives are particularly important because they attempt to integrate the complexities related to land-use change and its effects on diverse socio-economic and ecological systems.

4. Managing agricultural frontiers

A major challenge for sustainable management of tropical agricultural landscapes is to transform low-yield, high-deforestation production systems into high-yield, low-deforestation ones [43,44]. Extensive tracts of land in the tropics could undergo these transformations, especially in Brazil’s cattle ranching frontier, where approximately 200 million ha of pastures sustain notoriously low cattle densities [45,46]. The recent declines in MT’s deforestation, coupled with increases in crop and cattle productivity, suggest that agriculture intensification could indeed spare large tracts of land for tropical forest conservation [2] so long as deforestation is not pushed further beyond the
frontier [13]. But, without strong governance and incentives to keep native forests standing, MT’s achievements in reducing deforestation could be transient [47] or even reversed due to increasing demand for food and biofuel production [48]. At the same time, the negative ecological consequences associated with excessive pesticide and fertilizer use—required by highly intensive production systems—could eclipse some of the environmental benefits of declining deforestation [31].

To create agricultural systems that are more sustainable, Nepstad et al. [47] propose the integration of three mechanisms: (i) jurisdictional REDD+ (reductions in carbon emissions from deforestation and forest degradation), to avoid deforestation and help agriculture to transition to more intensive systems, while contributing to climate stabilization; (ii) market transformation, to exclude deforesters and producers that do not comply with socio-environmental regulations from the production supply chain; and (iii) domestic policy reforms, to reward and regulate environmental and social performance. Together, these mechanisms could foster a rural development model that promotes reductions of greenhouse gas emissions, while increasing crop and cattle production, securing land rights for indigenous peoples and restoring deforested areas.

Stickler et al. [18] analysed the role of the Brazilian Forest Code (FC), one of the primary legal mechanisms for rewarding and regulating environmental performance. The authors estimated that the costs of complying with some of the requirements of the FC can reach US$3.7–5.8 billion in net present value of the land. These high costs can create disincentives for producers to conserve forests as required by law (e.g. 80% of forests on private properties in the Amazon). Recent revisions to the FC opened the possibility of incentives for farmers to comply with environmental regulations for non-compliant deforestation that occurred prior to 2008. These incentives include the opportunity for landowners to offset their deforestation by protecting forests elsewhere, although this mechanism may create suboptimal distribution of forests from an ecological standpoint. Even with the current incentives, the opportunity costs involved in keeping forests standing remain high, so other mechanisms that facilitate the compliance of private landowners with the FC seem strategic.

Durigan et al. [23] report on the challenges of restoring riparian forests, another requirement of the Brazilian FC. The authors assessed an interdisciplinary effort to restore the Xingu headwaters (figure 1). Despite successes in developing new restoration techniques and effectively engaging social groups, the area restored by the campaign was relatively small. Among the factors that contributed to this outcome are the high costs of reforestation with native plants (when there is low potential for natural regeneration), the uncertainties of legislation and the lack of economic incentives.

Although MT’s achievements in reducing deforestation can be considered fragile [47], this region has a level of governance that is more effective in controlling deforestation than most other tropical countries. DeFries et al. [49], for example, found that very few tropical forest countries (two of 36) have national-level governance and monitoring capacity similar to Brazil, despite the fact that about one-third of these countries currently face pressures similar to Brazil for expansion of export-oriented agricultural production.

5. Challenges ahead

The papers in this issue collectively point to some key considerations for MT and other agricultural frontiers across the tropics. First, land-use changes in commodity-driven agricultural frontiers such as MT respond rapidly to multiple forces, including global markets, international pressures for sustainably produced commodities, and policies at the national-, state- and municipality-level. These forces can either encourage or discourage deforestation within a short time-period, as evidenced by the massive changes in MT that occurred in the 2000s. In addition, climate events such as drought are becoming an increasingly influential force, causing fire-induced degradation that can rapidly alter the landscape. Second, agricultural frontiers are linked socio-ecological systems. Land-use changes are linked with water quality and stream discharge, which in turn are linked with the health of indigenous populations. Land management practices at the farm level can thus have ecological and social repercussions far downstream of the farm. Policies need to consider the full socio-economic system to identify the consequences of possible land management strategies. Third, the economic, political and climatic changes affecting tropical agricultural frontiers are newly emerging. Adaptive approaches to management are needed to maintain functional ecological and social systems. Monitoring to devise suitable management approaches depends not only on tracking land-use changes, but also on monitoring the ecological and social consequences. Because few other regions in the tropics have environmental governance comparable to MT, the ecological and social consequences, as well as the successes and failures of management in MT, serve as an example of possible trajectories for other commodity-driven tropical agricultural frontiers. Finally, while global and regional policies are important tools to influence land-use trajectories towards sustainability, it is at the farm level that land managers make decisions that affect these trajectories. Science-based studies remain disconnected from these daily, local decisions. Rather, land managers’ decisions are more likely driven by pragmatic considerations such as markets, prior practices and perceived enforcement of regulations. Future efforts need to identify management practices that reduce environmental costs of production and are achievable from the farmers’ perspectives.

This special issue was improved by constructive discussions with Daniel Nepstad, Oswaldo Carvalho, Ane Alencar and Marcia Macedo as well as by comments of three anonymous reviewers. We thank Francis Putz, Giselda Durigan, Marcia Macedo and Chris Neil for helpful comments on the manuscript, Paul Lefebvre for preparing figure 2, and Divino Silvério for kindly providing figure 3d. We gratefully acknowledge financial support from NSF, and the Gordon and Betty Moore Foundation (no. 1963).

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