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Export-oriented deforestation in Mato Grosso: harbinger or exception for other tropical forests?

Ruth DeFries[1], Martin Herold[2], Louis Verchot[3], Marcia N. Macedo[4,5] and Yosio Shimabukuro[6]

[1]Ecology, Evolution and Environmental Biology, Columbia University, New York, NY 10027, USA
[2]Centre of Geo-Information, Wageningen University, Wageningen, The Netherlands
[3]Center for International Forestry Research, Bogor, Indonesia
[4]Woods Hole Research Center, Woods Hole, Falmouth, MA 02540, USA
[5]Instituto de Pesquisa Ambiental da Amazônia, Brasília 71503-505, Brazil
[6]Instituto Nacional de Pesquisas Espaciais, São José dos Campos, São Paulo 12227-010, Brazil

The Brazilian state of Mato Grosso was a global deforestation hotspot in the early 2000s. Deforested land is used predominantly to produce meat for distal consumption either through cattle ranching or soya bean for livestock feed. Deforestation declined dramatically in the latter part of the decade through a combination of market forces, policies, enforcement and improved monitoring. This study assesses how representative the national-level drivers underlying Mato Grosso's export-oriented deforestation are in other tropical forest countries based on agricultural exports, commercial agriculture and urbanization. We also assess how pervasive the governance and technical monitoring capacity that enabled Mato Grosso's decline in deforestation is in other countries. We find that between 41 and 54 per cent of 2000–2005 deforestation in tropical forest countries (other than Brazil) occurred in countries with drivers similar to Brazil. Very few countries had national-level governance and capacity similar to Brazil. Results suggest that the ecological, hydrological and social consequences of land-use change for export-oriented agriculture as discussed in this Theme Issue were applicable in about one-third of all tropical forest countries in 2000–2005. However, the feasibility of replicating Mato Grosso's success with controlling deforestation is more limited. Production landscapes to support distal consumption similar to Mato Grosso are likely to become more prevalent and are unlikely to follow a land-use transition model with increasing forest cover.

1. Introduction

Other papers in this Theme Issue focus on the causes and consequences of land-use change in the Brazilian state of Mato Grosso [1–6]. This article addresses an alternative question. Are the lessons learned from Mato Grosso's land-use transitions in the decade of the 2000s applicable to other tropical forest regions? Or, conversely, are the conclusions from the papers in this Theme Issue context-specific to Mato Grosso with limited relevance for tropical forests elsewhere? To explore this question, we examine whether the national-level drivers that affected deforestation rates in Mato Grosso over the past decade are similar in other tropical forest countries. We examine the drivers and their similarities in other countries with respect to two distinct trends that occurred in Mato Grosso in the 2000s: a rapid increase in deforestation rates in the first half of the decade and a dramatic decline in the second half.

Mato Grosso has been a focal region for Brazil's dramatic ascent as a major producer and exporter of agricultural commodities in the past several decades. The state is Brazil's largest producer of soya bean and cattle and a major producer of corn and other agricultural commodities [7]. Brazil's agricultural production and exports have grown rapidly in the past several decades. For example, production of soya beans increased in Brazil from 15 to 69 million

tonnes between 1980 and 2010. With rising international demand for soya bean as livestock for feed, exports grew from about 10 per cent to almost 38 per cent of production during the three decades [8]. Mato Grosso contributed approximately 27 per cent of national soya bean production in 2010 [7]. Heads of cattle in Brazil increased from 120 million to almost 210 million between 1980 and 2010 [8], with 14 per cent of the national herd occurring in Mato Grosso in 2010.

Beginning in the 1970s, development of new crop varieties, improved soil management, government policies and investments in infrastructure enabled agricultural expansion into Mato Grosso's savannah and Amazon forest [9,10]. More than half of Brazil's savannah (of which 19% lies in Mato Grosso) was transformed into pasture planted with African grasses and cash-crop agriculture by the mid-2000s [11,12]. With highways built in the 1970s to provide access to other parts of the country, Amazon forest in northern Mato Grosso opened to expansion and land speculation. Policies promoting large-scale cattle ranching were the primary drivers of deforestation in the 1970s and 1980s [9].

In the 1990s, the Amazon region began to export beef to satisfy demands of the growing national, urban market. The cattle industry in Mato Grosso was not initially linked with the international beef market owing to restrictions related to foot-and-mouth disease (FMD). Many factors contributed to extension from the national to international beef market, including progress in eradicating the disease, FMD-free status conferred on the southern Amazon region in 2003, devaluation of the national currency, improvements in beef production systems, and bovine spongiform encephalopathy ('mad cow' disease) in the European Union that created demand for non-EU beef [13,14].

In addition to pasture to supply the beef market, cropland to produce soya bean began to expand into the Amazon in the early 2000s with new varieties of soya bean and infrastructure for processing and transport. While pasture remained the predominant land use following deforestation, clearing forest for soya bean contributed about 12 per cent of Mato Grosso's deforestation for large clearings (more than 25 ha) in 2000–2005 [7,15]. Indirect deforestation, or 'leakage', pushed clearing for pasture further into the agricultural frontier as soya bean expanded into pasture, accounting for additional deforestation attributable to the soya bean boom [16,17].

Deforestation rates in Mato Grosso peaked in the early 2000s driven by demands for international exports of beef and soya bean. Rates declined precipitously in the latter half of the decade. The decline occurred throughout the Amazon but most notably in the state of Mato Grosso. Area deforested in 2010 was only 11 per cent of the 1996–2005 historical average, although in 2011 deforestation in Mato Grosso ticked back upwards [18]. The drop in deforestation coincided with reduced meat and soya bean demand owing to the global economic recession; proactive efforts by national, state and local governments to control deforestation; and the soya bean industry's 2006 self-imposed moratorium on soya bean produced from deforested areas [19–21]. Monitoring capabilities to identify deforestation in near-real-time [22] and high-profile interventions in illegal activities contributed to the ability to control deforestation. Double cropping [23,24] and increased heads per hectare [7] intensified production in both croplands and pasture while deforestation declined. In sum, in Mato Grosso, the decades from the 1970s to the present represent a shift from deforestation for low-productivity pasture producing beef for local and national consumption to high-input, industrial-scale agriculture for international export. This shift occurred within the context of national- and international-level drivers.

Mato Grosso followed a generalized trajectory of forest clearing from wild lands (high forest cover, low deforestation) to a transition period (declining forest cover, high deforestation) towards intensified agriculture (low forest cover, low deforestation) [25–28]. Forest transition theory suggests that forest cover can increase with agricultural abandonment or plantations in a post-transition period as has been the case in many countries, including the USA, many European countries, China, India and Vietnam [29,30]. Determining whether and where a forest transition occurs depends on large-scale analyses of which regions become production landscapes to provide commodities for distal consumption and which regions become consumption landscapes. For example, Walker [31], Pfaff & Walker [32], Meyfroidt & Lambin [33] and Yackulic et al. [34] explain forest transitions in Brazil's Atlantic Forest, northeastern USA, Vietnam and Puerto Rico, respectively, through each location's distal connections with production landscapes.

The production landscapes of Mato Grosso's large-scale, capital-intensive agriculture are more likely to follow a pattern similar to North America's Midwestern agriculture. Such landscapes would not be expected to undergo large-scale abandonment and regrowth of forest cover over time. The Midwest became a production landscape to provide food and timber to the urbanizing eastern cities in the late 1800s as new railroads were able to transport goods eastward and small-scale farmers abandoned less productive landscapes in the northeast [32]. Understanding whether other tropical forest landscapes are likely to follow the Mato Grosso model of production landscapes for distal consumption is a critical question for identifying management and policy options that balance provisioning services such as food with other ecosystem services such as climate storage, hydrological cycling and biodiversity in tropical forest regions.

Production of commodities for international export and distal, urban consumption have become dominant drivers of deforestation in the 2000s in many tropical countries [35,36]. Land-use dynamics in Mato Grosso clearly fit this emerging pattern. The dramatic decline in deforestation, despite ample remaining forest, occurred with international market demand for deforestation-free commodities and capability of the Brazilian government to implement policies to control deforestation. To identify the prevalence of Mato Grosso's export-oriented mode of land transition across the tropics, and the applicability of lessons learned from Mato Grosso's experience with reducing deforestation, this study addresses the following questions.

— How pervasive is deforestation for expansion of export-oriented, commercial agriculture, that was typical of Mato Grosso in the early 2000s, across other tropical forest countries?
— Do other tropical forest countries have governance structures and capacity similar to those that underpinned Mato Grosso's dramatic decline in deforestation in the latter half of the 2000s?
— What modifications to the general concept of land-use transitions are needed to include the distal demands for export-oriented agriculture typified by Mato Grosso?

2. Data and methods

We first identified those tropical countries, defined as countries between the Tropic of Cancer and the Tropic of Capricorn ([37]; electronic supplementary material, table S1). To further select countries with a high proportion of land area in tropical forest biomes, we calculated the percentage of forest remaining within the forest biome. For remaining forest area in 2000, we used values from Hansen *et al.* [38] as reported in table S2 of Harris *et al.* [39]. For biome area, we used the area in biomes 1 (tropical and subtropical moist broadleaf forest), 2 (tropical and subtropical dry broadleaf forests) and 14 (mangroves) from Olson *et al.* [40]. We chose 50 per cent of area in forest biome as the threshold to consider a tropical country as a tropical forest country, based on the premise that pressure for agricultural expansion is likely to extend to forest areas in these countries. Pressures for agricultural expansion in countries with low proportion of land area in forest are more likely to be felt in non-forest than forest areas, so we excluded these countries. We used Hansen *et al.* [38] estimates of forest loss rather than data from the Food and Agriculture Organization (FAO) [41], because the former measure gross rather than net forest loss and were derived from satellite-based observations rather than country reports.

When comparing forest area with forest biome area to determine the fraction of remaining forest in 2000, the estimated fraction was unrealistically greater than 1 in Cameroon, Democratic Republic of Congo, Brunei, Bolivia and Honduras with fractions of 1.06, 1.47, 3.42, 1.05 and 1.03, respectively. As this unrealistic estimate was likely due to discrepancies between the datasets, we considered the fraction to be 1 in these countries for purposes of further analysis.

To assign countries to transitional category (pre-transition, transition with low deforestation, transition with high deforestation and post-transition), we clustered the tropical forest countries based on two variables: deforestation rate (relative to area in forest biomes) for 2000–2005 and percentage of forest remaining in forest biomes. Clustering was done with the *k*-means function in R v. 2.12.1.

To determine whether countries face similar pressures for deforestation as Mato Grosso, we used three indicators: growth in the value of agricultural exports from 1991–2001 to 2008 [42, table C1]; self-reported drivers of deforestation in national strategies and action plans for REDD+ [28]; and a combination of percentage population that was urban in 2000 and average annual rate of change of percentage urban from 2000 to 2005 [43]. We considered a country to have similar or greater pressures than Mato Grosso if any of the three indicators were within 10 per cent less or any amount greater than the indicators for Brazil. For the urbanization indicators, we considered a country to be similar to Brazil if percentage urban and change in percentage urban were similar or greater than Brazil.

We used two indicators to assess whether a country has governance and capacity to control deforestation. Governance scores are from the worldwide governance indicators [44] and range from −2.5 (weak) to 2.5 (strong). The indicator reflects the quality of governance based on a statistical compilation of responses from a large number of enterprise, citizen and expert survey respondents in industrial and developing countries. We used the 2010 value for the 'rule of law' indicator, which reflects perceptions of the extent to which agents have confidence in and abide by the rules of
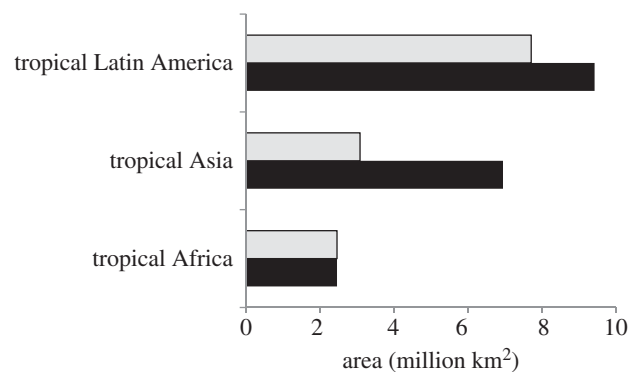

Figure 1. Area in tropical forest biomes [40] (black bars) and 2000 forest area reported in Harris *et al.* [39] (grey bars). Countries included in each continent are listed in the electronic supplementary material, table S1.

society, including property rights. Although forest governance data are provided by the FAO [45], we did not use this source because not all tropical forest countries are included in the assessment. Monitoring capacity was taken from Romijn *et al.* [46]. We considered a country to have measures similar to Brazil if it had a governance score within 10 per cent below or greater than Brazil's score and monitoring capacity equal to or greater than Brazil.

3. Results

(a) Identification of tropical forest countries

Of 80 tropical countries, 36 contain more than a half of their land areas within forest biomes (for list of countries, see the electronic supplementary material, table S1). Hereafter, we consider these 36 countries as 'tropical forest countries'. The 36 tropical forest countries collectively contain 91 per cent of all area in tropical forest biomes and 79 per cent of 2000 forest area according to Hansen *et al.* [38], with the remaining area distributed in the other 44 countries.

The amount of forest remaining within the forest biomes is a key characteristic for determining a country's situation with respect to the forest transition curve. Forest area remaining within forest biomes in the tropical forest countries is expectedly lowest in tropical Asia and highest in tropical Africa (figure 1).

(b) Determination of forest transition category

Clustering of the tropical forest countries according to fraction of forest remaining in forest biomes and deforestation rate (relative to forest biome area) grouped the tropical forest countries into four categories: pre-transition countries with relatively low deforestation and high remaining forest; transition countries with high deforestation and medium remaining forest; transition countries with relatively low deforestation and medium remaining forest; and post-transition countries with low deforestation and low remaining forest (table 1 and figure 2).

Thirteen of the 36 countries were clustered in the pre-transition group. These countries contain 34 per cent of remaining forest area, indicating the potential for future deforestation, as well as efforts to control deforestation, to influence a substantial amount of tropical forest. Approximately half of the countries in Africa and Latin America

Table 1. Result of *k*-means cluster of proportion of forest remaining in biome calculated from 2000 forest area in Harris *et al.* [39] and biome area from Olson *et al.* [40], and deforestation rate calculated from median estimate of 2000–2005 gross forest loss in Harris *et al.* [39]. Note that deforestation rate is relative to forest biome area. Numbers for the error range around the means are ± 1 s.d. Numbers in parentheses are fraction of forest remaining relative to total remaining forest area in all tropical forest countries.

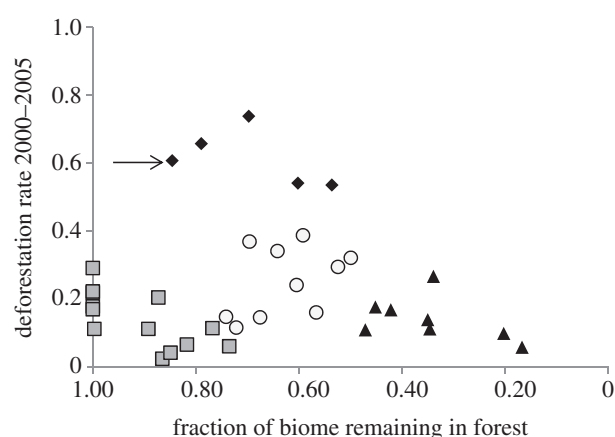| cluster	mean proportion of forest remaining in biome	mean annual deforestation rate 2000–2005	countries (*n*)	remaining forest area (1000 km^2)	fraction of forest biome
pre-transition	0.94 $\pm$ 0.10	0.14 $\pm$ 0.08	13	4580 (0.34)	0.23
transition (high deforestation)	0.69 $\pm$ 0.13	0.61 $\pm$ 0.18	5	4920 (0.37)	0.31
transition (low deforestation)	0.63 $\pm$ 0.08	0.25 $\pm$ 0.10	10	2850 (0.21)	0.25
post-transition	0.34 $\pm$ 0.11	0.14 $\pm$ 0.06	8	1070 (0.08)	0.21
all countries	0.69 $\pm$ 0.28	0.24 $\pm$ 1.44	36	13 420 (1.0)	1.00

Figure 2. Transition type for 36 tropical forest countries based on *k*-means cluster of the proportion of forest remaining within forest biomes in 2000 (estimated from Harris *et al.* [39] and Olson *et al.* [40]). Deforestation rate is estimated from median estimate in table S2 of Harris *et al.* [39]. Note that the deforestation is relative to forest biome area rather than remaining forest area. Arrow indicates Brazil. Grey squares, pre-transition; black diamonds, transition high deforestation; grey circles, transition low deforestation; black triangles, post-transition.

were clustered in the pre-transition group (five of eight and seven of 15, respectively; electronic supplementary material, table S1). Expectedly, most of the post-transition countries were located in tropical Asia (six of eight). Post-transition countries contain 21 per cent of land within the forest biome relative to all of the tropical forest countries, with 8 per cent of remaining forest. Most (79%) of the tropical forest biome is located in pre-transition or transitional countries, underscoring the potential for market pressures to either increase deforestation or put in place efforts to control it.

(c) Pervasiveness of deforestation drivers similar to Brazil

We used three indicators to assess whether drivers for deforestation in Brazil were similar in other tropical forest countries: growth in value of agricultural exports (figure 3*a*); self-reported proportion of deforestation driven by commercial agriculture (figure 3*b*); and urbanization (figure 4). These

indicators reduce the complexity of myriad factors that influence deforestation, including institutions, history and cultural practices but are used here as quantifiable metrics that can be assessed for all countries.

Only five of the tropical forest countries (Gabon, Sierra Leone, Indonesia, Malaysia and Peru) had growth in agricultural exports similar to or greater than Brazil. Four countries (Liberia, Gabon, Brunei and Venezuela) had percentage urban and urbanization rate similar to or greater than Brazil, although all but seven countries had urbanization rates greater than Brazil. Three countries (Costa Rica, Vietnam and Malaysia) self-reported that commercial agriculture drives a proportion of deforestation similar to or greater than Brazil. Together, these indicators suggest that 10 of the 30 tropical forest countries could be following a similar pathway as Brazil, with deforestation driven by expansion of export-oriented, commercial agriculture for urban consumption, much like the pattern observed in Mato Grosso (see the electronic supplementary material, table S1). Only one of the 10 countries following the Mato Grosso model falls within the post-transition category, supporting other analyses suggesting that export and urban consumption was a less influential driver of deforestation in the past and is emerging as a stronger driver in pre-transition and transition countries [35,36].

The 10 countries with indicators of export-oriented and urban drivers of deforestation similar to Brazil accounted for 44 per cent (range of 41–54%) of forest loss within tropical forest countries other than Brazil from 2000 to 2005 (table 2). Including Brazil in the calculation, the deforestation in countries with drivers similar to Brazil was 74 per cent (range 72–77%) of total deforestation in these countries in 2000–2005. As expected, the percentage of deforestation that occurred in countries with drivers similar to Brazil's was the highest in high deforestation transition countries (68%, ranging from 66 to 72%, of deforestation in high deforestation transition countries) and low deforestation transition countries (52%, ranging from 42 to 70%, of deforestation in low deforestation transition countries). The substantial percentage in pre-transition countries (38% ranging from 22 to 48%) indicates the prevalence of drivers likely to generate pressures for expansion of export-oriented agricultural expansion into forests in the absence of control measures.
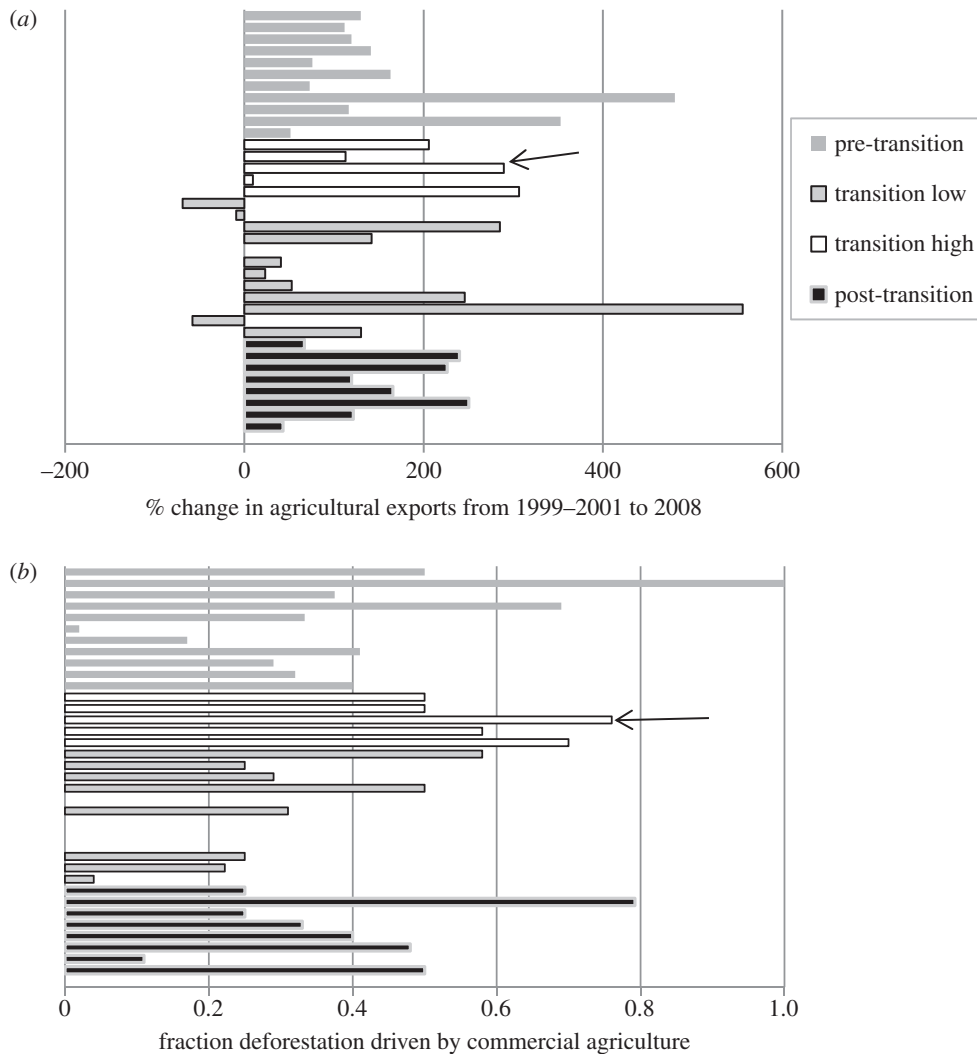
Figure 3. (*a*) Growth in value of agricultural exports from 1999–2001 to 2008 [42] and (*b*) self-reported fraction of deforestation driven by commercial agriculture [28] for tropical forest countries. Arrows indicate Brazil.
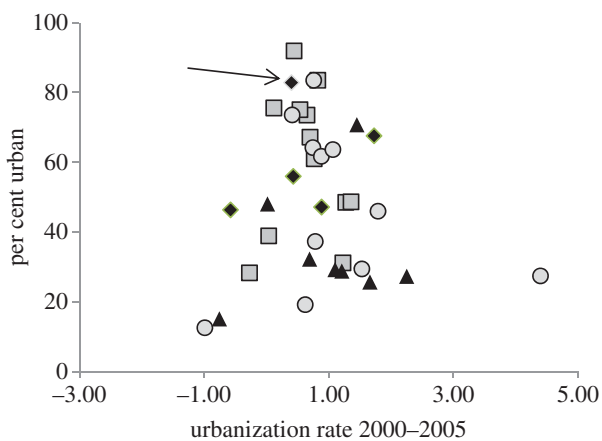

Figure 4. Average annual rate of urbanization (per cent change) from 2000 to 2005 versus per cent of total population in urban areas in 2000 [43] for tropical forest countries. The arrow indicates the data point for Brazil. Squares, pre-transition; diamonds, transition high; circles, transition low; triangles, post-transition. (Online version in colour.)

(d) Pervasiveness of governance to control deforestation

Of the 36 tropical forest countries, only two (Costa Rica and Malaysia) had both governance scores [44] and monitoring capacity [46] similar to or greater than Brazil (figure 5 and table 3). These two countries contain only 3 per cent of

remaining forest and 9 per cent (7–12%) of 2000–2005 forest loss in tropical forest countries excluding Brazil. All except one pre-transition country had governance scores lower than Brazil. All governance scores in post-transition countries were substantially lower than Brazil. Monitoring capacity was more widespread, with 38 per cent of tropical forest countries having capacity rated in the highest 'very good' category equal to Brazil's rating (table 3). Most pre-transition countries had limited or low monitoring capacity.

4. Discussion and conclusions

Results suggest that pressures on tropical forests from market forces for international export and urban consumption are prevalent, though by no means ubiquitous, across tropical forest countries. Ten of 35 tropical forest countries other than Brazil had deforestation drivers similar to Brazil. Deforestation in these countries accounted for 44 per cent (ranging from 41 to 54%) of non-Brazilian deforestation in 2000–2005. Only one of eight post-transition countries (low deforestation, low remaining forest) had indicators of pressure to expand export-oriented agriculture into forests, as opposed to nine of 27 countries in pre-transition (low deforestation, high remaining forest) or transition (higher deforestation, medium remaining forest cover) countries. This difference suggests that export-oriented
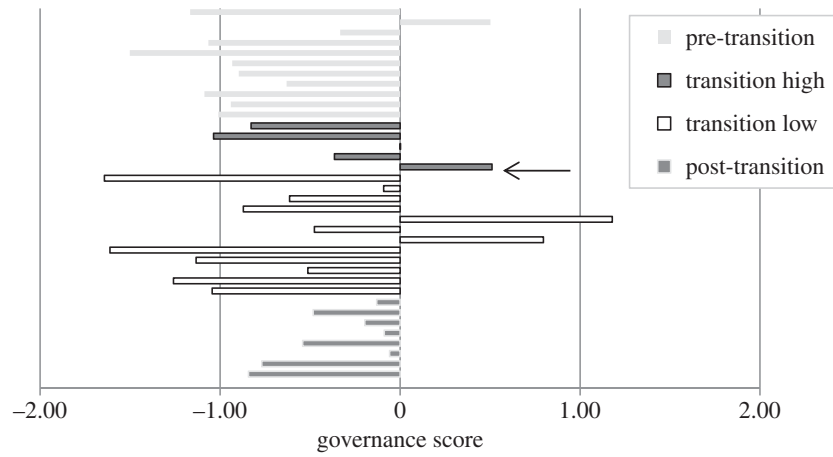
Figure 5. Governance scores for tropical forest countries [44]. Scores range between −2.5 and 2.5. The arrow indicates the data point for Brazil.

Table 2. Deforestation for 2000–2005 in tropical forest countries (excluding Brazil) according to transition category. Range is from medium, low and high estimates of gross forest loss in Harris *et al.* [39]. Transition includes high and low deforestation transition countries, excluding Brazil.

	forest loss in countries with drivers similar to Brazil (km^2 yr^{-1})	number of countries with drivers similar to Brazil (total countries in parentheses)	total forest loss (km^2 yr^{-1})	per cent of total forest loss in countries with drivers similar to Brazil
pre-transition	1970 (480–4730)	4 (12)	5210 (2160–9810)	38 (22–48)
transition	9760 (7410–12 130)	5 (15)	17 670 (10 480–26 320)	55 (46–71)
post-transition	550 (0–1330)	1 (8)	5130 (1940–8880)	11 (0–15)
all tropical forest countries (excluding Brazil)	12 280 (7890–18 190)	10 (35)	28 010 (14 580–44 840)	44 (41–54)
all tropical forest countries (including Brazil)	45 200 (22 840–69 080)	11 (36)	60 930 (29 530–95 730)	74 (72–77)

Table 3. Monitoring capacity for tropical forest countries as reported in Romijn *et al.* [46]. Categories are limited, low, intermediate, good and very good. Brazil's monitoring capacity is 'very good.' Two countries are excluded because they were not reported.

	limited and low	intermediate and good	very good
pre-transition	6	2	2
transition (high deforestation)	0	2	3
transition (low deforestation)	1	4	6
post-transition	2	4	2
all tropical forest countries	9	12	13

agriculture was a less common driver of deforestation prior to the 2000s when forests in post-transition countries were cleared. With the current trajectory of increasing trade, higher demands for agricultural commodities from urban populations and competition of land for biofuels [47,48], it is reasonable to expect that pressures on forests for expansion of export-oriented agriculture for distal consumption will increase. As the papers in this Theme Issue illustrate for Mato Grosso, large-scale intensive agriculture in the tropics involves trade-offs of high yields with ecological, hydrological and social repercussions.

The effectiveness of measures to control deforestation differs according to the drivers. Deforestation driven by expansion of export-oriented agriculture may respond to international market demands for sustainably produced products, but requires governance to develop, implement and enforce control measures, such as the soya bean and beef moratoria and government programmes introduced in Mato Grosso in the late 2000s. The paucity of governance and capacity in most tropical forests countries raises concerns about the replicability of Mato Grosso's success with controlling deforestation.

Each country and each region within a country has a particular set of drivers, ecological conditions, history and land-use dynamics. However, the general pattern of export-driven agricultural expansion suggests an alternative pathway to a land-use transition model that emphasizes small-scale agriculture and increasing forest cover following abandonment [25,26]. Rather, as the Mato Grosso experience indicates, clearing for large-scale agriculture destined for distal consumption
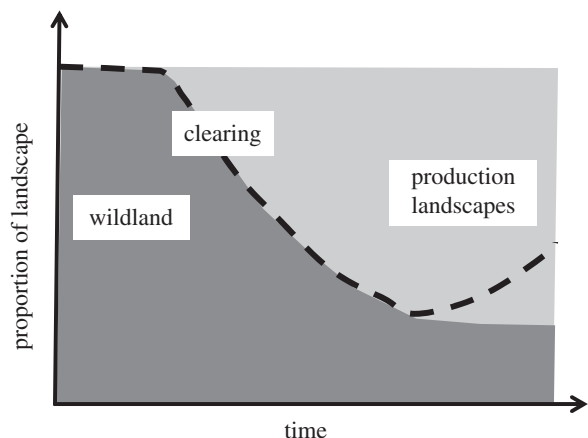
Figure 6. Schematic of land-use transitions in production landscapes characteristic of Mato Grosso. Dark grey represents forest or other wild lands and light grey represented lands converted to produce commodities consumed in distal locations. Dashed line is trajectory of forest cover following traditional forest transition theory.

can lead to rapid deforestation, potential to control deforestation through market signals and low likelihood of abandonment for forest regrowth (figure 6). The heterogeneity of circumstances, market connections and drivers across tropical forest countries indicates that multiple pathways are possible, with an export-oriented transition model becoming increasingly dominant. Whether forest transitions occur at national, regional or global scales depends on the dominance of production landscapes relative to less productive agricultural landscapes that are more likely to be abandoned. The increasing prevalence of export-oriented agriculture to satisfy distal demands suggests that the generalized concept of forest recovery with development requires modification to account for a future likelihood of a greater proportion of production landscapes.

This analysis of Mato Grosso and deforestation drivers in other tropical forest countries suffers from a number of limitations. Self-reported drivers and aggregated national statistics are imperfect indicators and do not capture heterogeneity within countries. Spatially explicit indicators of intensive agriculture would be more informative, including direct measures of the size of clearings [49] and use of inputs such as fertilizer and machinery, but data are limited for many countries. Pan-tropical, satellite-derived deforestation data for the time period following the early 2000s would allow analysis of more recent trends, but only estimates of net changes in forest cover are available [41]. The metric of fraction forest remaining in forest biome does not account for inaccessible forest areas such as steep slopes, protected areas and wetlands that can be a substantial portion of forest area in some countries. Ideally, comparison of deforestation rates among countries would be on the basis of forest area available for agricultural expansion although the definition can change depending on agricultural technology and crop type. Moreover, the metric is based on canopy closure and does not distinguish among old growth forest, secondary forest and tree plantations. We do not consider degradation as a process affecting tropical forests or the similarities of other tropical forest countries to Mato Grosso in terms of escaped fires during dry years [50]. The conceptual model of land-use transitions driven by distal demands for agricultural commodities is rudimentary and requires empirical analysis to assess the large and increasing pressures on tropical forest landscapes.

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