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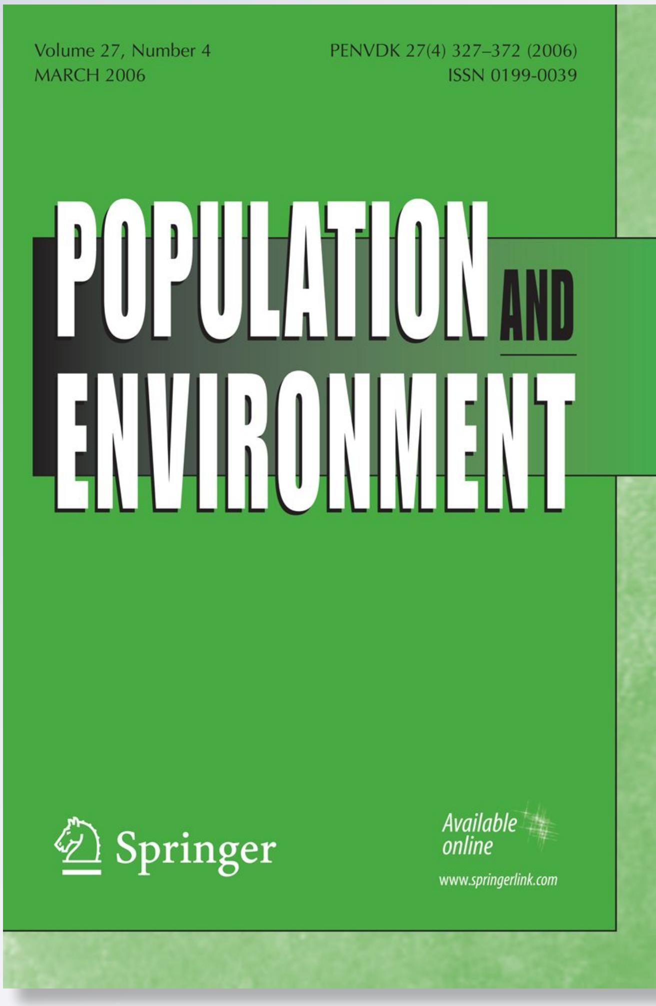

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ORIGINAL PAPER

Level-dependent deforestation trajectories in the Brazilian Amazon from 1970 to 2001

Eduardo S. Brondizio · Emilio F. Moran

Abstract This article demonstrates the importance of examining level-dependent deforestation trajectories that may be undetected within regional analyses. We examine Amazon-wide, sub-regional, settlement, and farm-level deforestation trajectories in the Brazilian Amazon and suggest factors that underlie level-dependent differences in spatial patterns and temporal magnitudes of deforestation from 1970 to 2001. At a sub-regional level, we find significant variation in frequency, magnitude, and intensity of deforestation associated with context-specific processes, including areas that have stopped deforesting, are rapidly reforesting, while at the same time increasing economic value of forest-based production. We use remote-sensing data from 1970 to 2001. For Amazon-wide and state-level analyses, we use data available from Brazil's National Institute for Space Research. For sub-regional, settlement, and farm-lot levels, time-series Landsat images and aerial photographs and detailed field-based research are used to reconstruct the history of deforestation. Our analysis empirically demonstrates that understanding deforestation trajectories requires differentiating underlying causes at different levels of analysis and to be wary of overarching explanations and solutions that ignore differences in scale.

Keywords Amazon · Deforestation trajectories · Complexity · Level dependence · Forest transitions · Scale · Remote sensing · Land use · LUCC

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Introduction

A pioneer of population and environment research

In 1996 the National Institute of Child Health and Human Development invited scholars to do research on population and environment, and from this initiative it is possible to see the steady growth of this area. One demographer who saw this as a promising direction, and who did everything in his power to provide leadership and direction to this field in Brazil was Daniel Hogan (e.g. Hogan 2007, particularly his first chapter that reviews the development of population and environment as a new field of study; Hogan et al. 2002, particularly Hogan's introductory chapter, to name but a few). He provided a crucial linkage between the international community's concern with this subject, and its development in Brazil. He eagerly embraced the need for spatially-explicit analyses in demography and developed a lab at NEPO, the center he led for many years, to advance the spatial analysis of population, and to include environmental data in demographic analyses. One can also point to his participation in other works that at a very early date already showed considerable maturity on population and environment (e.g. Torres and Costa 2000). Over the years Daniel provided stimulation and a home for scholars going to Brazil to study these issues. We are grateful for his collaboration over the years that made our work in Brazil part of the local scholarly community. One of the regions of the world which he encouraged analyses in, and in which he took part, was work on population and environment in Amazonia. As in the case of the paper we have developed here, he appreciated the importance of multi-scale, interdisciplinary, multi-temporal, spatially-explicit analyses that did not blame the victim, but that treated this interaction with the complexity that is inherent to it. We dedicate this paper to his memory.

Since 2000, articles in scientific, policy, and other academic fora have given considerable attention to modeling and explaining the underlying causes and consequences of Amazonian deforestation (Foley et al. 2007; Soares-Filho et al. 2006; Morton et al. 2006; Curran and Trigg 2006; Asner et al. 2006; Câmara et al. 2005; Laurance et al. 2001a, b, 2004; Eva et al. 2003; Achard et al. 2002; Carvalho et al. 2001). These efforts share one feature: treatment of the Amazon as a unit—an area comparable to the contiguous USA. The state level analysis of Morton et al. (2006) among others dedicated to particular analytical units such as protected areas and indigenous reserves (e.g., Ricketts et al. 2010) are exceptions. Many important insights have come from this broad geographical scope, such as the connection between an expanding road network and deforestation (Asner et al. 2006; Laurance et al. 2001b; Alves 2002), but Amazon-wide analyses obscure important inter- and intra-regional processes and interactions, such as the differential impact of development policies and commodity markets, and to identify where successful efforts to stop or reverse deforestation have taken place. In this article, we show how different the temporal and spatial dynamics of deforestation are, and how one can miss distinct deforestation and reforestation trajectories if one does not pay attention to sub-regional processes. Results from sub-regional studies may aid the formulation of policies seeking land-use solutions that benefit people and their lands across different regions. We can learn why reforestation is gaining ground in some regions, invisible in Amazon-wide analyses, while deforestation is rampant in other areas—and why. While we focus on the 1970–2001 period in order to maintain comparative data consistent across units and levels of analysis, and with related fieldwork, we believe that the findings from this period are entirely relevant today.

When we analyze in the aggregate or Brazilian Amazon level, we get the sum of the decisions of individuals at local level, but the aggregation process can statistically swamp what happens in one part of the region. This macroscopic view can be useful, because it eliminates the "noise" from so many decision-making units and sub-regions while contributing to the understanding of the impact of macro-level policies and markets upon regional land-use change. However, it does not capture the differentiated ways that sub-regional units, communities, and individuals respond to macro-scale policies in the context of local conditions, nor are the alternative land-use solutions visible at this level of analysis. To date, macro-regional analyses do not incorporate the spatially and temporally discontinuous nature of human activities across the regions that result from cultural-institutional, socio-demographic, environmental, and economic variations and how they affect land use and deforestation trajectories (Perz 2002; Wood and Porro 2002). Taking a closer look at these processes at a sub-regional level may be essential in finding ways to reverse deforestation trajectories. In other words, we should seek understanding of solutions crafted at the local level that successfully respond to macro-scale policies and global market forces (Ostrom and Nagendra 2006).

We focus in this paper on trajectories of deforestation, which we define as the accumulated deforestation relative to a given area (unit of analysis) distributed over time. Deforestation trajectories should not be compared in absolute terms (area), but in the distribution of deforestation relative to each unit of analysis (i.e., the relative percentage contribution of each time period to the accumulated deforestation) observed during the 30 years preceding 2001, as we do in the analyses to follow. Rates of deforestation vary in time and across space. We analyze the Brazilian Legal Amazon-wide, macro-scale patterns, as most authors have done, but we go further, by also examining state level, sub-regional level (i.e., represented by three study sites), settlement level (i.e., represented by different types of communities and cohorts of farm occupation), and farm-level (i.e., represented by a sample of farm lots within each study area) deforestation trajectories and suggest what factors underlie differences in spatial patterns and temporal magnitudes of deforestation (Fig. 1). We use a combination of multi-temporal remote-sensing data from the onset of deforestation in the early 1970s and published analyses of census data, cross-sectional and longitudinal household and community surveys, and long-term ethnographic research to provide this multi-level analysis (Brondizio et al. 2002, 2009a; Brondizio 2004, 2006, 2008; VanWey et al. 2007; Moran et al. 1994, 2005; Futemma and Brondizio 2003; Walker et al. 2000; McCracken et al. 1999; Moran 1981).

Amazonian deforestation trajectories can be easily thought of, and are often misunderstood, as hierarchically and linearly organized, i.e., conditions set at the macro-scale result in predictable responses at lower levels. Conversely, our analysis of multi-level deforestation trajectories indicates that they operate more as a

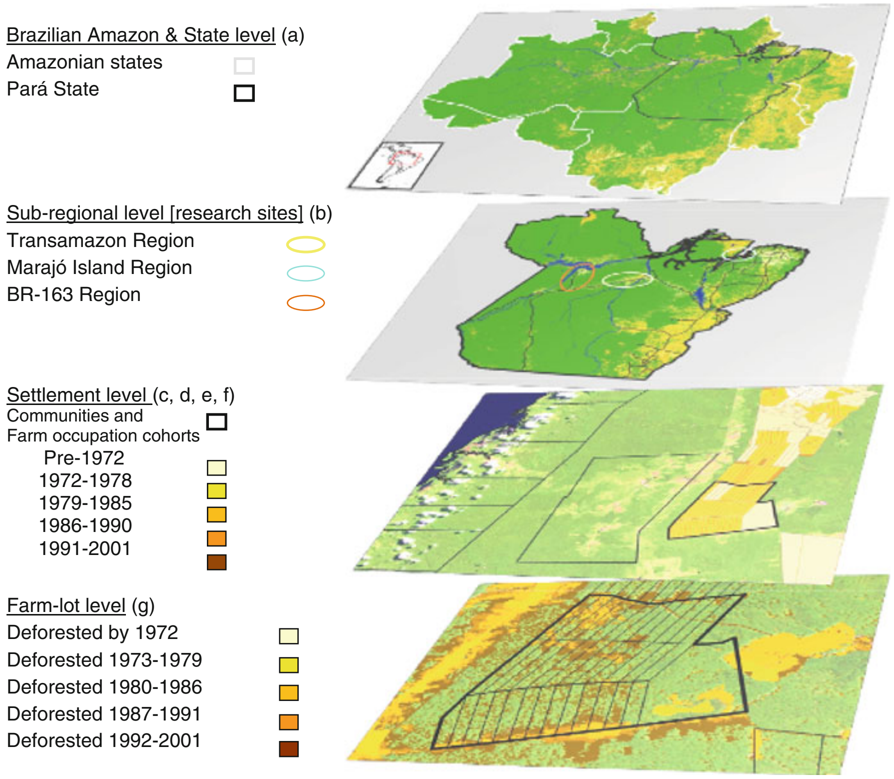


Fig. 1 Research sites, levels of analysis, and deforestation trajectories, 1972–2001 (Parenthesis indicates link to Fig. 3)

complex system interlinked across levels but resulting in nonlinear interactions and outcomes. Although variations in sub-regional trajectories are influenced by the relationship between structural conditions created at macro-scale (e.g., road and colonization networks, credit policies), its outcomes result from adaptive responses to change occurring at lower levels in different temporal frequencies. Whereas macro-scale processes, such as national policies and commodity market demands, set the conditions within which lower levels operate, the latter show considerable independence and observed responses are not predictable from knowing the macro-policies. In other words, divergent trajectories of deforestation at the local level occur against the backdrop of macro-scale structural conditions, but are products of place-specific, historical, institutional, and environmental arrangements and context-based economic decisions. Our analysis empirically demonstrates that understanding deforestation trajectories, as suggested by global comparative studies (Rudel 2005), requires differentiating underlying causes working at different levels of analysis and requires untangling those factors defining spatial pattern and temporal intensity of deforestation at each level. Our analysis questions and informs the foundations of modeling scenarios applied to regions undergoing transformation into a mosaic of social and economic groups, and types of landscapes. We suggest that macroscopic analysis and prognostic models are instrumental in guiding discussions about national and regional development policies and long-term priorities but need to account for intra-regional diversity and the nonlinear nature of factors working at different levels. As such, we show the critical importance of differentiating factors affecting sub-regional processes, a meso-scopic view, such as understanding how the impacts of development policies and programs, infrastructure, and global markets are mediated by different land tenure arrangements, type of social group, and other conditions influencing land-use decisions at lower levels.

Study areas and methods

We examine, simultaneously, the Legal Brazilian Amazon and its states (Fig. 2), three study areas in the state of Pará, and different types of settlements and communities, and farms in those study areas (Fig. 3). Two study areas represent active colonization and agropastoral expansion; the third, in the Amazon estuary, represents a forest-based economy. We present deforestation trajectories of whole settlements and communities (Fig. 3b–d), including cohort groups of farms occupation (Fig. 3e–f), and individual farm-lots (Fig. 3g). This approach allows us to show the differences in analytical outcomes at each level of analysis and how attention to only aggregate analyses or case studies alone can distort the complexity of trajectories of deforestation and land use in the Amazon, and their implications for conservation and regional development.

The three sub-regional study areas represent contrasting realities of what is happening in the Brazilian Amazon which we believe are representative for non-indigenous areas of the region (see Ricketts et al. 2010 for a discussion of the latter) Each study area is representative in extent and diversity of land tenure, environment, and social groups of the region. The northern BR-163 highway study area, including portions of the municipalities of Placas, Aveiros, Rurópolis, Belterra, and Santarém, is located in the Lower Amazon, bounded by the Tapajós River (west) and the Amazon River (north). The area has a long and complex history of prehistoric and pre- and postcolonial settlement, soils of limited quality, relatively flat terrain on a plateau, a strong dry season, and seasonal water limitations. The Transamazon (BR-230) study area, including portions of the municipalities of Altamira, Brasil Novo, Medicilândia, and Uruará, is located on the first bend of the Xingú River and has some of the best soils in the basin, rugged terrain, a mild dry season, and well-distributed rainfall. This area became the showcase for government-directed settlement and development in the 1970s. These areas include colonists and farmers representing different times of arrival and property sizes. The Marajó Island study area, in the municipality of Ponta de Pedras, represents a place of ancient interest to human populations, with forest and savannas, flat terrain, poor and good soils, and dominated by tide fluctuations and seasonal flooding. All three areas have been subjected to development programs and strong market forces. While the estuary area has roads, local transportation and daily life still occur mostly along a vast network of rivers; in contrast, the areas along the

Transamazon and BR-163 are strongly shaped by the road network and different kinds of colonization.

We used a combination of social and environmental science approaches in this study, further supported by the use of time-series remotely sensed data, to reconstruct the deforestation history of each study area in five time intervals from 1970 to 2001. We combined aerial photographs, data from Landsat MSS, TM, and ETM + sensors, and more recent data from the high-resolution ASTER on the Terra satellite and sensors on the IKONOS satellite for selected parts of each study area.

Our research also relies on long-term field research and biophysical modeling of land cover to support image classification, including soil samples and vegetation transects at each study site (Lu et al. 2003). For temporal comparison, deforestation trajectory data (land-cover transition matrices) were aggregated into five time periods (1970, 1979, 1986, 1991, and 2001). The initial date for each site varied slightly due to availability of data: estuary in 1969, Transamazon in 1970, and BR-163 in 1972. Property boundaries, derived from settlement grids of Brazil's National Institute for Colonization and Agrarian Reform and field checked with surveys and global positioning systems, were input to a geographic information system, along with community boundaries (or boundaries of cohorts of farm occupation), and overlaid on the satellite images. For state- and Amazon-level analyses, we used inter-annual deforestation estimates provided by Brazil's National Institute for Space Research for 1979–2001 (INPE/Projeto PRODES n.d.; Tardin et al. 1980) and data from the literature for 1970 (Mahar 1989; Cunha 1989; Moran 1993). The combination of the images and boundaries was used to extract deforestation data at the farm-lot level ($n = 9{,}671$) and in communities and settlements ($n = 35$), reserves ($n = 2$), and sub-regions ($n = 3$).

Along the Transamazon, we built on work started in 1973 (Moran 1981) and have studied a population living on 3,718 farm-lots using a stratified random sample of 402 households and 399 farms during 1997 and 2005, respectively, with a sub-sample of 171 in 2001, including detailed socio-demographic and economic surveys (Moran et al. 2005). Along BR-163 and the adjacent road system, we studied 5,953 farm-lots using a stratified random sample of 244 and 401 households in 2001 and 2003 (VanWey et al. 2007), respectively, and community-level studies (Futemma and Brondizio 2003).). In Marajó Island, we conducted longitudinal ethnography and surveys of households ($n = 143$) and communities ($n = 6$) differentiated by economic and institutional histories and land tenure (Brondizio 2008).

Level dependency in trajectories of deforestation

The Brazilian Amazon view

Figure 2 shows forest changes and respective rates at the level of the Brazilian Amazon and its states. Regionally, deforestation beginning in the 1970s increased steadily to the mid-1980s, followed by substantial decline during the late 1980s and persistent increases since 1994. This trajectory reflects, first, the immigration of settlers encouraged by government road and colonization projects of 1971–1975 and

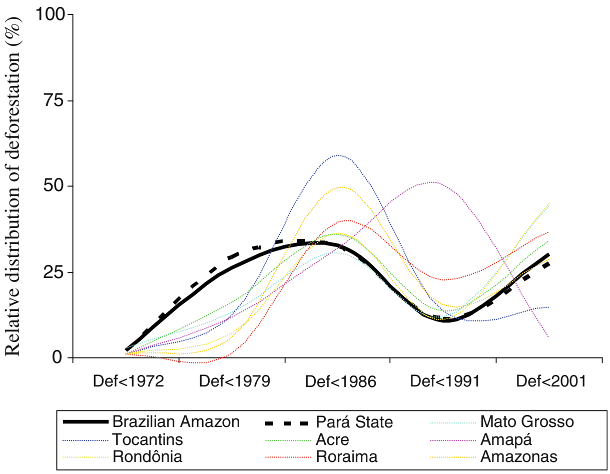


Fig. 2 Brazilian Amazon and state-level deforestation trajectories: relative distribution of deforestation 1970–2001

the subsequent in-migration, to claim land and subsidies for cattle ranching. Substantial decline in deforestation took place between the mid-1980s and mid-1990s as a result of macro-economic conditions (e.g., sustained hyperinflation and declining federal incentives) and overall deterioration of road infrastructure. New import–export policies (1990), reduced inflation and favorable economic policies to the farming sector (since 1994), and an expanding global market for land and commodities (e.g., minerals, beef, soybean, and lumber) led to the most intensive period of Amazon deforestation, which continued until 2005 (Nepstad et al. 2006). The majority of changes occurred in the state of Pará until 1995 and Mato Grosso since then, which is evident by comparing the trajectory of deforestation of the Brazilian Amazon with that of Pará and Mato Grosso before and after 1995 (see Fig. 2). Pará is the second-largest state in Brazil and is where most settlement and development schemes were located in the 1970s–1990s. Given the distribution of infrastructure and colonization during that time, what happens in Pará quantitatively shapes what happens in the Brazilian Amazon. However, the state of Mato Grosso, although undergoing extensive clearing since the 1970s, received significant infrastructural investment during the past two decades, responding strongly to international demands for soybean and beef, and backed up by political support at state and federal levels. Since the late 1990s, Mato Grosso has surpassed Pará in terms of regional contribution to total deforestation. Rondônia, Acre, Tocantins, as well as Para are expected to contribute more to the shape of aggregate analyses in the coming decade.

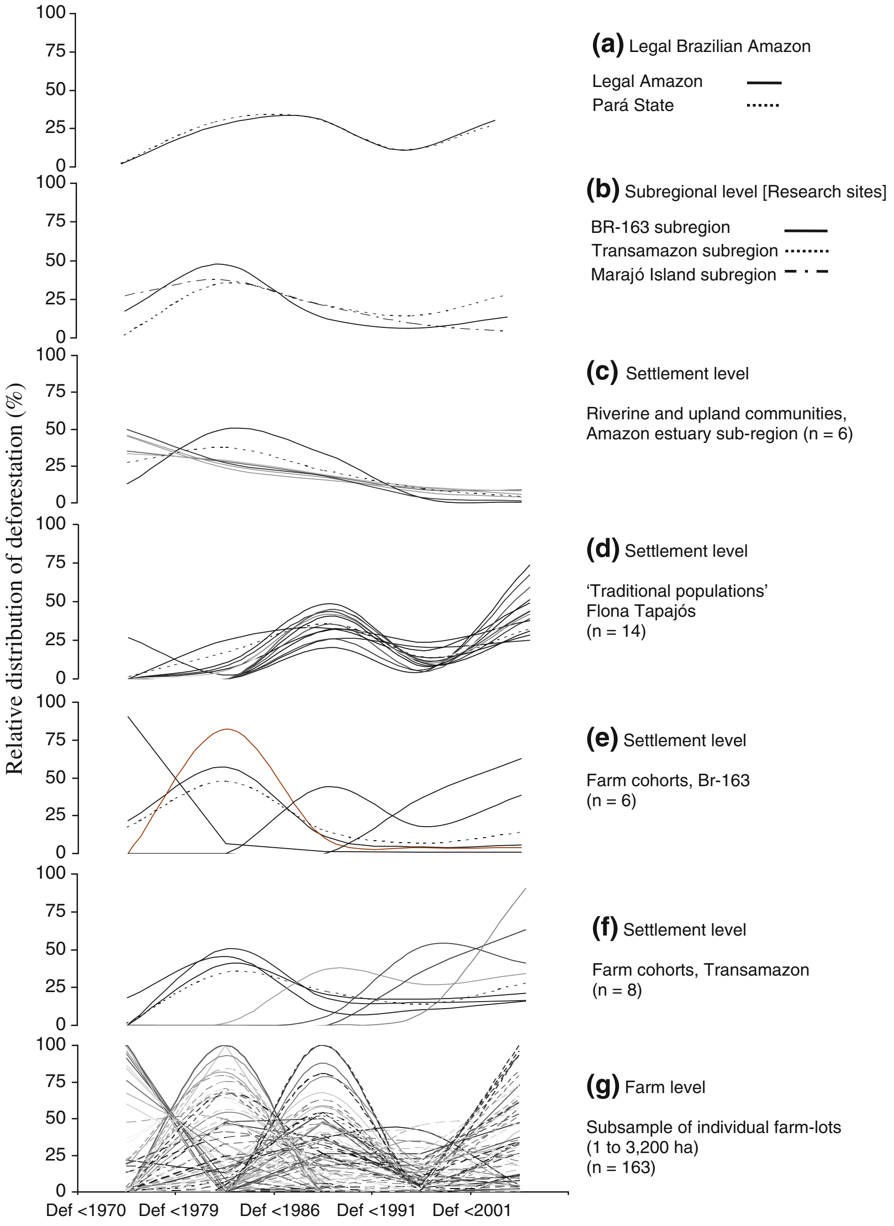
At this level, one can appreciate the long-term impact of infrastructure distribution, land tenure, and institutional arrangements shaping the spatial pattern of regional deforestation, and, on the other hand, the role of commodity prices and policy incentives in shaping fluctuations in deforestation intensity over the years. As discussed below, however, these macro-regional conditions are shaped by social, economic, institutional, and environmental conditions at lower levels.

Sub-regional dynamics

The views at a sub-regional level give a different spatial and temporal picture (Fig. 3b). At any given moment in any one of these regions, we see different aspects of their historical development and of deforestation trajectories. For example, the Marajó Island area had a dramatic increase in deforestation in the 1970s, a result of church, government, and nongovernment organizations' involvement in economic and agro-pastoral development schemes. Yet, that deforestation trajectory ended in the late 1980s with a steady decline in deforestation since then, contrary to patterns found elsewhere in the Amazon. The growth of the açaí palm (*Euterpe oleracea* Mart.) from a staple food to a national and global commodity increased economic returns to producers and brought corporate investment in large-scale agroforestry resulting in decreased deforestation and in a considerable uptick in reforestation. A historically indigenous and rural staple food, açaí fruit became a regional staple for a growing low-income urban populations after the 1970s, then a national (mid-1990s), and more recently a global "fashion" food (Brondizio 2008). This trajectory, however, represents a long-term process of land-use transition from annual crops to forest products taking place throughout municipalities in the Amazon estuary (Brondizio 2010). In addition to increasing market demand for forest products like açaí fruit and secondary wood products for low-income urban construction (Pinedo-Vasquez et al. 2001), the region experienced increasing competition from agricultural and horticultural products from other regions of the Amazon and from southern Brazil. These processes contributed to a decline in clearings for annual crops and pasture and the emergence of a regional forest-based economy. The steady decline in deforestation and the success of açaí agroforestry as a solution balancing land-use intensification and conservation of Amazonian forests, now adopted by municipalities throughout the Amazon, is hidden when we rely solely in Amazon-wide analyses, swamped by the increases in deforestation in Pará and elsewhere in the larger region.

The high rate of deforestation in the BR-163 highway study area during the 1970s was followed by a decline in the 1980s and 1990s. This decline occurred during an era of waning support for settlements and a decaying road system, which led to high rates of lot turnover and outmigration. The regional agrarian structure was reconfigured in the late 1990s, driven by international market demands for soybean

Fig. 3 Multilevel deforestation trajectories: relative distribution of deforestation, Brazilian Amazon ▶ 1970–2001 (5 periods). Trajectories derived from overlapping layers representing unit boundaries (farm-lot, settlements, etc.) over land-cover transition matrices generated through multitemporal remote-sensing analysis and field surveys. Selection of underlying factors based on household and farm surveys, census statistics, literature, and long-term ethnographic research. **a** Legal Amazon and Pará State, 1978–2001 (25); **b** Sub-regional 1 research areas, Pará State: Transamazon (Altamira, Brasil Novo, Medicilândia), BR-163 (Santarém, Belterra, Aveiros), Amazon estuary (Ponta de Pedras); **c** Settlement level [Riverine and upland cooperative rural communities, Ponta de Pedras, Marajó Island ($n = 6$ communities, $n = 143$ households)]; **d** Settlement level [Traditional population areas ($n = 14$), national forest ($n = 1$)]; **e** Settlement level [BR-163 cohort groups of farm occupation ($n = 7$ cohorts encompassing 5,953 farm-lots), 1972–2001]; **f** Settlement level [Transamazon cohort groups of farm occupation ($n = 8$ encompassing 3,718 farm-lots), 1970s to 2001]; **g** Farm-lot level Random subsample (**e**, **f**) of 163 individual farm-lots (1–3,200 ha) of a total of 9,671 farm-lots in our study areas products and new export infrastructure facilities. This shift fueled an aggressive land market and increased deforestation rates by 2001 (Ludewigs et al. 2009). Farmers in the Santarém area of the BR-163 region began deforestation in the 1950s and 1960s, but it is hidden within Amazon-wide analyses because the areas were small. Its decline in the 1980s is also hidden, because it was the heyday of deforestation for newly settled areas in Pará, Mato Grosso, and Rondônia.



The Transamazon area, the showcase of government-induced colonization in the early 1970s, also underwent a decline in deforestation starting in 1976 as policies shifted emphasis away from small farming. This change coincided with poor macroeconomic conditions ca. 1988, declining cocoa prices (and plant disease), and limited success with pasture management. In the 1990s, the introduction of more competitive grass species and a growing demand for beef refueled forest and secondary forest vegetation clearing, and better prices led to more attention to cocoa production. In comparison with the BR-163 study area, the Transamazon area experienced more sustained deforestation. Transamazon farmers benefited from better soils and water availability, perennial crops (cocoa and sugar cane), and higher rates of risk-minimizing cattle ranching to balance the farm portfolio (Moran et al. 1994, 2002; Walker et al. 2000).

The assumption tends to be that these regions maintained a steady rate of deforestation like Pará as a whole and thus shape the analysis of the rest of the Amazon. This closer look shows different trajectories and underlying processes that are too important to overlook. According to INPE data (INPE various dates), Rondônia, Acre, and other parts of the region show similar trajectories to those discussed above, although at different times. In other words, infrastructure expansion, colonization settlements, and migration flows have shaped the distribution and driven the temporal intensity of deforestation during the 1970s and 1980s, then followed by the impact of market demand for agropastoral and forest products. In parallel, aggressive creation of indigenous, protected areas, and agro-extractivist reserves has mediated the rate and spatial pattern of deforestation in parts of the region (Ricketts et al. 2010).

Settlement and farm-level dynamics

As we move from sub-regional to local settlements, communities, and farm-lots, one sees greater variability of responses to macro-processes. As we have seen above, impressive intensification of açaí agroforestry in response to increasing market demand changed the regional economic profile of the Amazon estuary. Even more striking is the variability in rates and extent of deforestation among rural communities within this region (Fig. 3c). The settlement pattern and location of communities derive from land inheritance and sharecropping systems dating back to colonial times, as well as church-based land acquisition and distribution to communities since the 1960s. When comparing riverine and upland (cooperative) settlements, total deforested area of 5–95%, and the long-term trajectories of forest clearing differ substantially. Environmental endowments, land tenure, and external projects for mechanization, ranching, and resettlement are factors explaining these differences. At the farm level, market demand has had differential influences on land users' decisions about agroforestry intensification depending on several factors affecting production, but particularly land tenure and availability of floodplain areas, household labor, and distance and dependence on middlemen to access market centers. Whereas a decline in clearing is found in all six communities, the underlying reasons differ substantially. Upland communities have abandoned mechanization and pasture areas, and riverine communities have reduced the amount of swidden plots for manioc cultivation, in both cases proportionally to the increase in açaí agroforestry areas (Brondizio 2008).

Within the BR-163 region, we find both farming areas and conservation reserves. The Flona-Tapajós National Forest reserve has 95% forest cover overall, but variable deforestation rates across its resident communities. Since 1974, Flona-Tapajós has been subjected to land invasions by small and large operators. The reserve encompasses 25 "traditional" rural communities, with two claiming indigenous status. Communities present little variation in total forest cover, ranging 80–90%, but important differences in terms of their relative deforestation trajectories (Fig. 3d), albeit small in extent. The riparian communities present lower rates of clearing over time than communities accessible by roads and areas with an active land market for small- and large-scale agricultural production. The northern BR-163 area has experienced successive colonization for the last 150 years, especially since 1950 (Brondizio 2006). Farm-lots settled before the 1970s, mostly <100 ha, were largely deforested by 1974, when BR-163 opened and planned settlements were initiated (Fig. 3e). Cohorts of farm-lots occupied since then show trajectories similar to the Transamazon area but with more deforestation during the 1970s and 1980s. However, the rate of land going to secondary succession shortly after clearing was higher than along the Transamazon until the arrival of soybean cultivation around 1999. The higher rate of lot turn-over was due to the decay of primary and secondary roads, lack of social services, and limited access to water, all of which led a large number of farmers to abandon or sell their lots.

If we contrast the trajectories of deforestation among settlement cohorts along the Transamazon, we observe the role of historical migration starting shortly before 1970 accelerated by government intervention (Fig. 3f). The trajectories are similar, but the magnitude of deforestation varies from one migratory group (cohort) to another depending on prevalent regional infrastructure (e.g., deterioration of the road system) and macroeconomic conditions (e.g., hyperinflation, market opportunities). Independent of cohorts, farm-lots generally show a developmental process associated with periods of establishment and expansion of land-use activities. We observe that intervals between pulses of deforestation may reflect alternating processes of intensification and extensification of land-use activities during consolidation of a farm-lot (Brondizio et al. 2002; McCracken et al. 1999), and the arrival of new owners, i.e., lot turn over explains a significant part of deforestation pulses (VanWey et al. 2007). Patterns observed at the settlement and community levels, however, can be offset by the internal variability among farmers (Fig. 3g). Decisions regarding deforestation may be made to seize a period opportunity or for long-term investment. Depending on available capital, some farmers invest in large, single-event deforestation, whereas others follow the general pattern of progressive expansion of cleared area through deforestation pulses of various magnitudes. In some cases, farmers maintain only a small land area cleared, producing for household consumption and a modest surplus for markets. Farmers respond differently to external factors, depending on the stage of farm formation, and other factors such as consumption needs, available labor and technology, access to credit, commodity prices, environmental endowments (e.g., soil fertility, water, and topography), and, not least, one's vision and goals for the farm lot. However, we observed pulses of deforestation even for farm-lots opened during periods of recession and hyperinflation (mid-1980s to mid-1990s) when regional deforestation was at its lowest levels. In other words, independent of macroeconomic conditions, these farmers had to settle, open land for cultivation, and start the process of farm formation; and they respond to local economic opportunities such as clearing land to add market value to it (Brondizio 2004). Farm size also affects deforestation strategy; it correlates inversely with relative deforestation (percentage) but positively with absolute deforestation (area). Larger properties account for most of the deforestation in the BR-163 area but not in the Transamazon area, where lot sizes are more evenly distributed (Brondizio et al. 2009a).

Untangling the spatial pattern and temporal magnitude of deforestation

The analysis of trajectories as presented above allows us to understand the nature of level-dependent processes and to untangle factors affecting spatial pattern and temporal intensity of deforestation (Table 1). At the level of the Brazilian Amazon, the spatial pattern of deforestation is explained by transportation and colonization networks, including establishing the basis for an evolving mosaic of institutional arrangements aimed at long-term development goals. The temporal intensity of deforestation has been driven by policy incentives, macroeconomic processes, including commodity markets, and rates of interregional migration. Sub-regionally, however, the spatial pattern of deforestation is explained by settlement pattern and the spatial structure of institutional arrangements, dominant land-use systems, technology, environmental endowments, topography, and the spatial distribution of resources. The intensity of deforestation is explained by the evolution and aging of settlement schemes, rates of in- and outmigration, market prices of particular commodities, and cycles of credit incentives. At settlement level, the spatial pattern is explained by the spatial structure and connectivity of settlements by roads and rivers to markets, their land tenure and institutional arrangements, whereas the intensity of deforestation is explained by differences in settlement age, intensity and size of cohort arrivals, and the cycles and subsidies associated with government and non-government development projects. Finally, at the farm-lot level, variables such as the farmer's vision and intentions about land-use allocation, farm size and shape, location and proximity to roads, environmental endowment, and available land-use technology explain the spatial pattern, whereas changes in family size and composition, access to capital and technology, changes in market opportunities, and short- and long-term family goals explain the intensity of deforestation.

A meso-scope approach to deforestation: paying closer attention to regional variability

Attention to inter- and intra-regional variability (what we call a meso-scope approach), complements Amazon-wide or macroscopic analyses, because it provides an opportunity to tailor policy instruments needed for governance that are sensitive to how people in communities and sub-regions respond to external

Table 1 Suggested variables explaining the spatial pattern and temporal intensity of deforestation trajectories at different levels of analysis, 1970–2001

Spatial patterns	Temporal intensities
Brazilian Amazon	
Federal transportation network	Policy and credit incentives for land use
Colonization and settlement	Fluctuations in interregional migration
Spatial organization of institutional arrangements	Macroeconomic stability
Regional geography and topography	Regional, national, global market demands
Sub-regional level	
Spatial distribution of settlements	History of settlement occupation & land conflicts
Spatial organization of tenure systems	Rates of in- and outmigration
Environmental endowments and topography	Market prices for dominant commodities
State and municipal transportation networks	Economic incentives and subsidies
	Changes in land use regulations
Settlement level	
Density of local transportation network	Rates of in- and outmigration
Types of land tenure and institutional arrangements	Rates of lot-turn over
Dominant land-use system and technology	Fluctuation in market prices and opportunities
Spatial variability in environmental endowments	Cycles of development projects and subsidies
Farm location and proximity to roads	Localized conflicts
Farm-lot level	
Farm size and shape	Shifting size and composition of household
Local environmental endowment & topography	Access to capital
Land-use technology	Family short- and long-term goals
Proximity to roads and type of access	Reaction to market opportunities and prices
	Opportunities to increase land value

social, economic, political, and demographic forces and develop solutions to the use and conservation of their forested environment (Ostrom and Nagendra 2006). At a macro-level, one can appreciate the long-term role of structural determinants (infrastructure, policies and regulations, markets, and economic incentives), while at a lower level accounting for the ability of different social groups to respond to these conditions. These insights can be instrumental in tailoring policies at different levels. For instance, ecological economic zoning can provide a framework for long-term planning for infrastructure and conservation units at state and national levels, whereas local infrastructure and credit policies can target the needs of farmers at different stages of farm formation and consolidation of land-use activities aimed at different market niches and conservation needs. For decades, one of the key policy interventions in Brazil has been the use of credit as an incentive to development. Uneven and predefined credit programs have proven to be obstacles rather than aids (Tura and Costa 2000), because they are commonly defined without attention to social and environmental variability, farmers' needs, conditions of local markets, or available infrastructure. As discussed above, consistent trajectories of land use in areas of colonization are marked by pulses of deforestation representing phases of settlement and farm expansion and consolidation. These trajectories represent an important finding in its implication for credit policies: matching credit programs to the cycles of farm development.

Long-standing disregard by policy makers of the road and transportation infrastructure has underlined most failures in colonization areas and motivated high rates of lot turnover (>75% in the colonization areas reported here). Roads continue to be poorly maintained and are not passable year-round, long recognized as the major impediment to development in frontier zones (Nelson 1973). All-weather roads can facilitate economic development and the well-being of urban and rural communities and/or spread deforestation, land conflict, and poverty, depending on the strength of governance systems and social capital of different interest groups.

Similarly, despite their successful intensification and declining deforestation, estuarine farmers continue to be constrained by lack of credit, extension service, and access to markets and, particularly, industries locally capable of converting the raw commodity into marketable industrial products (Brondizio 2008). The lack of such "transformation industries" arrests the ability of producers to aggregate value to forest and agricultural resources, and the necessary tax revenues for municipalities to provide public services to local communities. Discovering what strategies result in declining deforestation without impoverishment and motivated local economies in transformation of regional resources is important to policy makers, but it requires attention to the particularities and potential of different parts of the region and strategies tailored to their differential socioeconomic histories, social groups, environmental conditions, and infrastructural deficiencies.

Amazon-wide (and national) colonization planning has created a spatial framework within which land use and occupation have been set in motion at various levels of intensity over time. It has promoted growing connectivity and interdependence among resource-use systems, ecosystems, and circulation of people and commodities within and beyond the region. As such, sub-regional and regional spatial patterns of deforestation emerge as we scale up local land-use systems interconnected through road-river transportation and colonization networks. The spatial–temporal variability of these arrangements carries differential implications for conservation, rural and urban populations, and indigenous communities. This interconnected, but nonlinear, relationship between micro- and macro-scale processes underscores the relevance of multi-level thinking for policymaking, particularly for a region increasingly shaped by the twin forces of global climate change and globalization: macro-scale planning matters, as does attention to regional variability.

Farmers and communities who gain knowledge of forest resources appreciate its importance, invest in management, and tend to have their own conservation goals (Campos and Nepstad 2006). Society also responds to images of widespread deforestation and the drought impacts of climate change with pressure on policy. At local and national levels, this process of feedback between people and deforestation (e.g., perception of diminishing forests to motivate action) takes time and is level specific. In this context, modeling future scenarios of Amazonian land use carries political implications for its role of informing society and impacting policies that will affect regional populations. Prognostic scenarios are instrumental in guiding discussions about national and regional development priorities but need to account for the nonlinearity and complex nature of processes at different levels that create regional diversity. Our analysis questions and informs the foundations of projecting future scenarios for a region undergoing intense transformation into a growing mosaic of social groups, economic systems, and landscapes requiring diverse but integrated forms of governance (Brondizio et al. 2009b). The evolving connectivity of different social groups, land-use systems, urban areas, and institutional arrangements in the Amazon renders necessary a complex system perspective. Long is gone the period when centralized planning provided a basis for monocausal and straight forward explanations of social and environmental change, and the one-size fits all policy solution to regional problems. Regional dynamics such as that of deforestation are nonlinear processes with a varied set of positive and negative feedbacks. Striking a balance between contemporary and historical and among national and international forces, regional conditions, and intraregional variability is and will increasingly be necessary to understand the present and to plan the future of the Amazon if sustainability is to be achieved.

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