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Explaining the fragmentation in the Brazilian Amazonian forest

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Although vast literature exists on the drivers of tropical deforestation and its ecological consequences, less is known about how patterns of forest fragmentation emerge in the first place. The purpose of this paper is to address this issue for the Brazilian portion of the Amazon basin by analyzing the social processes generative of five specific patterns, including rectangular, fishbone, radial, dendritic, and what we refer to as 'the stem of the rose.' We argue that forest fragmentation patterns in the Brazilian Amazon are largely determined by the types and arrival times of the agents who engage in land clearing. We also argue that the patterns manifest in the landscape by virtue of road construction and agricultural property formation, which often occur in tandem. We conclude by placing our discussion within legal and institutional contexts, and observe that fragmentation stemming from formal colonization projects is more consistent with biodiversity conservation than that associated with a laissez-faire occupation. However, erosive impacts may be greater in topographically sensitive areas.

Keywords: forest fragmentation; road network; Amazonia; land change; process to pattern

1. Introduction

Forest fragmentation has emerged as an important environmental issue in tropical environments, given that the spatial arrangement and geometric configuration of fragments can compromise ecological processes. For the Amazon Basin, researchers have documented how forest fragmentation alters animal habitats, compromises vegetative regeneration, and sparks biomass collapse along fragment edges (Aldrich & Hamrick, 1998; Benitez-Malvido, 1998; Ferreira & Laurance, 1997; Laurance, 1998; Laurance, Delamônica, Laurance, Vasconcelos, & Lovejoy, 2000; Laurance et al., 1997; Nepstad et al., 2001; Scariot, 1999). The present article takes up the issue of forest fragmentation in the Amazon basin, the world's largest contiguous tropical forest, which continues to disappear, although deforestation rates have come down in recent years. Our goal is to extend land change science in the direction of explicating the spatial dimensions of land cover change (Gutman et al., 2004).

Ecological degradation stemming from forest fragmentation concerns us, but our analytical interest resides in identifying the background factors giving rise to

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fragmentation in the first place, specifically the underlying social processes (Arima, Walker, Souza, Pereira, & Canto, 2013; Walker et al., 2013). Thus, the analytical objective of the paper is to provide a synthesis of what is presently known about the social processes generative of fragmentation patterns currently observed in the Amazon Basin, particularly Brazil.

The key to understanding such generative processes is to gain insight into road-building. Although roads have long been recognized as an important deforestation driver (Geist & Lambin, 2002; Nelson & Hellerstein, 1997), the interest here resides in the fact that road network architecture plays a critical role in shaping forest fragmentation patterns (Arima, Walker, Perz, & Caldas, 2005). Roads are one-dimensional and do not readily reveal themselves when viewed from afar, as via satellite imagery, nor do they represent a significant barrier to ecological processes dependent on mobility or spatial dispersion. The fragmentation impact of roads comes later, through those who follow and amplify the spatial signature of road patterns by clearing forest, typically to establish agricultural land uses (Figure 1) (Arima et al., 2008; Forman, 2003). Thus, an explanation of forest fragmentation resides partly in an explanation of how roads emerge spatially from the *tabula rasa* of primary tropical forest and partly in the formation of agricultural properties. These processes often occur in tandem and contemporary patterns of forest fragmentation are largely determined by the types and arrival times of the actors who engage in road construction and land clearance.

Road construction has usually been associated with governmental venture, but private citizens have been extremely active in this same endeavor in Amazonia. To maintain terminological consistency with the literature, we refer to federal, and also state, roads as *official*, and to those built by private citizens as *unofficial* (Brandão & Souza, 2006; Perz, Caldas, Arima, & Walker, 2007; Perz, Overdevest, Caldas, Walker, & Arima, 2007; Perz et al., 2005).

Our synthesis of fragmentation patterns yields a conceptual framework organized on the basis of the agents responsible for forest occupation, and the nature of their actions and interactions. In presenting it, we begin the article by noting a number of empirical regularities in spatial patterns of forest conversion that have been observed worldwide, and in the Amazon Basin as well. Following this, we consider aspects of temporal and spatial scale that enable us to draw a distinction between actions taken by the federal government to open the basin, and the spatial behaviors of the agents who came to Amazonia as a consequence, in the interest of resource exploitation. Our distinction in place, we move on to accounts of how the Brazilian

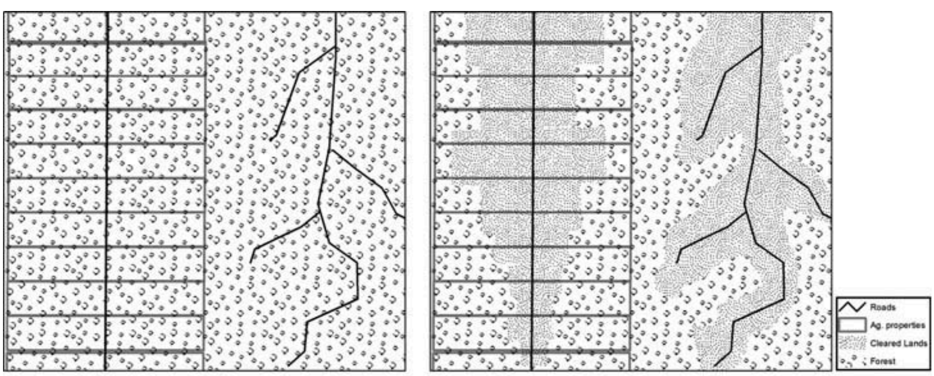

Figure 1. Roads and land clearings determine patterns of fragmentation.

Amazon's primary fragmentation patterns emerged. Included here are the federal highway network and five distinct patterns associated with private agents pursuing personal objectives. In addition to process descriptions, we provide estimates of the extents for each of these fragmentation patterns, as presently found in the Amazon Basin. Once we have addressed the observed patterns, we distil our conceptual synthesis, which traces social processes into landscape patterns on the basis of the agents involved and their spatial decision-making. We then conclude the article by considering implications for policy and modeling exercises in land change science.

2. Methods

The article draws information from the academic literature and from research efforts by the authors, including field surveys, simulation, and remote sensing. The field surveys involved hundreds of structured and open-ended interviews of long-time residents, state officials, agricultural landholders, loggers, and forestry engineers. They were conducted along federal highways BR-364 in Rondônia (2003), BR-163 in Pará and Mato Grosso (2004, 2009), and BR-230 in central Pará (2004, 2005, 2010), and in the *Terra do Meio* region of southern Pará (2009, 2011). For BR-230, we also documented the opening of 118 roads by private citizens, aside from the federal and state highways in our study site. Simulations complementing the fieldwork (Arima et al., 2008; Arima et al., 2005, 2013; Walker et al., 2013) used a comprehensive GIS data base for the Brazilian Amazon, derived from Landsat TM and ETM+ images (Figure 2, panel in the center) (Arima et al., 2013; Brandão & Souza, 2006). These data were created by manual digitalization of

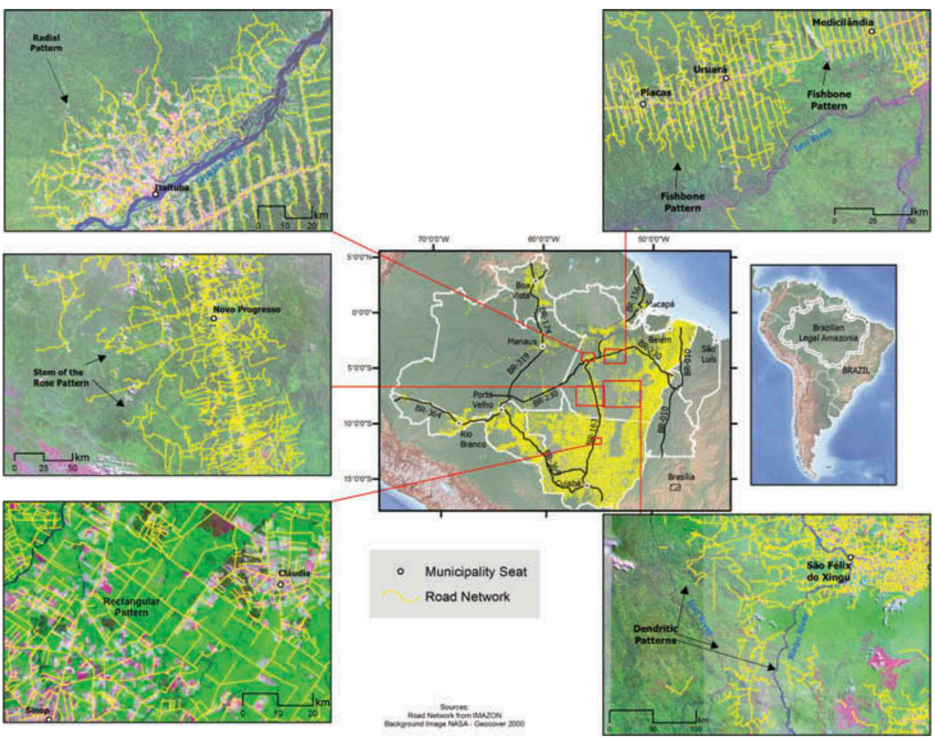

Figure 2. Road networks and patterns of forest fragmentation.

roads, identified by visual inspection of Landsat bands 3 and 5 on a 1:50,000 scale (Brandão & Souza, 2006). Also used was 'soil fractional cover,' which was obtained through spectral mixture analysis (Souza et al., 2013). Such methods enhance the contrast between exposed soils, which appear as bright pixels, and the surrounding dark vegetation, enabling visual identification. Overall accuracy of the data approaches 100% for permanent roads (Brandão & Souza, 2006). The database takes 2003 as a baseline, with yearly updating to 2012 using cloud-free images. More than 1200 images were used and almost 100,000 segments digitized.[1] The GIS database provides the only comprehensive coverage of unofficial roads for the Amazon Basin. As such, it enables order-of-magnitude calculations for associated road networks.

3. Fragmentation patterns in the Brazilian Amazon

3.1. Overview of fragmentation patterns

As a first step toward the synthesis of forest fragmentation processes, we present a typology of patterns observed in the Brazilian Amazon. Our approach does not invoke commonly used fragmentation measures such as fractal dimension. This is because we are interested in the actual shapes in question, which are not readily translatable into fragmentation indices. Helpful to our endeavor is the widespread replication of specific geometries associated with frontier penetration. At the global scale, six general patterns have been discerned in previous work (Geist & Lambin, 2002; Mertens & Lambin, 1997), and Oliveira Filho and Metzger (2006) suggest that three of these are dominant in the Brazilian Amazon, including what they refer to as the 'fishbone,' 'independent settlement,' and the 'large property' patterns. We do not take issue with this nomenclature, but note that it mixes spatial description (e.g., fishbone) with implicated agent (e.g., large property). Consequently, the present article seeks to avoid pattern–agent confusion by presenting a strictly spatial terminology. Each pattern is depicted in Figure 2 (thin lines). The background image, displayed in false color composite (RGB: bands 7,4,2), is from NASA's Geocover 2000. Forests are in dark colors and deforested areas and exposed soil/rock in light colors.

We retain the *fishbone* label (Figure 2, top right panel), apt as a spatial descriptor and with a long tradition in Amazonian research (e.g., Skole & Tucker, 1993), although variations have been noted (Batistella, Robeson, & Moran, 2003). For the *independent settlement pattern*, we use the term *dendritic* (Figure 2, bottom right panel), given its highly irregular, trellis-like structure (Arima et al., 2008; Arima et al., 2005; Chorley & Haggett, 1967). Finally, for the *large property pattern* of Oliveira Filho and Metzger (2006), we adopt the term *rectangular* (Figure 2, bottom left panel). Reminiscent of the term, *geometric*, of Mertens and Lambin (1997), *rectangular* is more precise in its reference to the fragments of cleared land often observed in areas of large-scale commercial agriculture, both ranching and mechanized farming.

To the patterns observed by Oliveira Filho and Metzger (2006), we append two that have come to our attention through fieldwork, including the *radial* pattern (Figure 2, upper left panel), and what we refer to as the *stem of the rose* (Figure 2, mid-left panel). Radial fragmentation comprises landscape impacts that cluster around urban nodes, suggestive of the *urban* pattern of deforestation proposed by Mertens and Lambin (1997). The *stem of the rose* combines the visual features of dendritic and fishbone fragmentation, with evenly spaced and stubby spines that quickly lose their initial parallel coherence. As a sixth meta-pattern, we also consider the broad landscape partition associated with Brazil's federal highways, or *official* roads. The impact of such highways on Amazonian migration and environmental change has been well documented (Mahar, 1988; Moran, 1981; Schmink & Wood, 1984). Less is known about how *official* roads distributed *unofficial* roads across the basin, thereby entraining fragmentation processes. Consequently, there remains a need to evaluate how fragmentation patterns are related to each other spatially, and how their various spatial signatures emerged over time.

3.2. Temporal and spatial scale

Having noted a suite of geometric patterns of forest fragmentation, we now turn to the identification of the specific agents responsible for road construction and subsequent forest fragmentation, together with their temporal and spatial scales of operation. Research for Brazil often implicates loggers, smallholders, ranchers, farmers, and miners, especially for gold. Such individuals seek highly personalized objectives when they clear forest, whether to liquidate valuable mineral resources like miners, or to engage in long-term agriculture like smallholders and ranchers. Given our basin-scale interest, we augment this list with the politicians and bureaucrats whose activities open settlement frontiers in forest regions through the building of highways. Although they do not gain explicit rewards from the extraction of minerals or agricultural activity, their actions fulfill societal objectives, such as economically integrating new spaces of extraction, securing national borders, or promoting regional development to alleviate poverty.

The agents identified pursue their various objectives in specific temporal and spatial contexts, with the temporal context involving relative timing and duration. In the Brazilian case, politicians and bureaucrats began infrastructure developments prior to those who came later to exploit resources; moreover, federal highway construction took a considerable amount of time, about half a decade, and maintenance has persisted over decadal periods. As for resource-oriented actors, they often show meaningful sequencing, as when smallholders penetrate forest following the roads built by loggers. Such timing has been referred to as a logical tandem or sequential occupation (Geist & Lambin, 2001; Walker, 1987), and is observed in many parts of the world besides Brazil (Walker, 1987; Walker & Smith, 1993). In general, road construction by private individuals occurs with surprising rapidity, on the order of several kilometers per day when earth moving equipment is used. Unlike the federal system, maintenance is haphazard, and the roads, potentially ephemeral.

The temporal scale of operation articulates with the spatial extent of roadbuilding. The politicians and bureaucrats responsible for Brazil's federal and state systems implemented an official network that traverses much of the Brazilian portion of the Amazon basin, with some exceptions such as inaccessible terrains to the west of the Purus River Valley in Amazonas State. The spatial implication is that the first tier of basin fragmentation emerges from a rectilinear network of federal and state roads that presently covers 50,000 km (Figure 3), and yields a density of 0.011 km^{-1} (km of road/km^2 of area) (Plano Nacional de Logística e Transportes [PNLT], 2012).[2] As for the action realms of the resource users, these are considerably smaller, given the lack of capitalization and their localized economic interests. Nevertheless, unofficial roadbuilding activities are also significant, especially if they piggyback on segments of the federal system, as has been the case with much of the basin's *fishbone* fragmentation. The summed length of *unofficial* roads across numerous local networks adds up to approximately 460,000 km (Figure 3), resulting in an overall density of 0.103 km^{-1}, an order of magnitude greater than the *official* system (Arima et al., 2008; Arima et al., 2013).

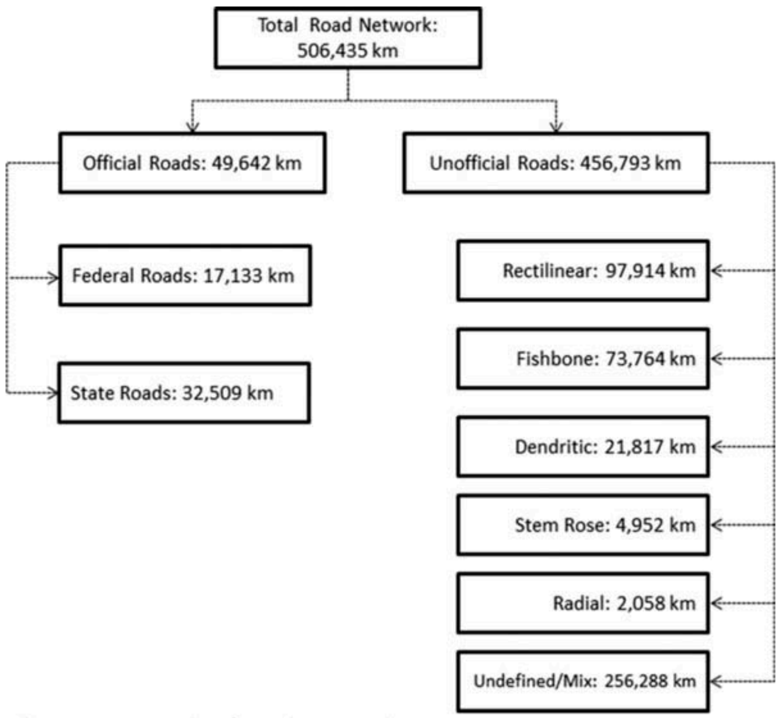

Figure 3. Length of road networks.

To summarize, the Brazilian Amazon's *official* and *unofficial* roads manifest important scalar characteristics in time and space. Paramount here is the fact that the federal highway system functioned as a temporal and spatial prior for the five patterns of fragmentation described. The construction and maintenance of *official* roads represent long-term political processes spanning presidential administrations and federal planning programs of decadal duration. In contrast, *unofficial* roads may be ephemeral, even seasonal, although profitable agriculture generates a spatial signature that persists as a discernible fragmentation pattern.

3.3. Agricultural property

Agricultural land use is the process that magnifies the spatial pattern of a particular road network into an actual fragmentation pattern (Arima et al., 2008; Forman, 2003). As a first step to identifying the fragmentation pattern produced, we assert that agricultural property manifest a rectangular shape, an assertion that reflects the empirical regularity. The theory of optimal property shape assumes rectangles *a priori* and focuses on road frontage and depth dimensions (Colwell & Scheu, 1989). Thus, we suggest that the optimality of rectangles stems from minimizing demarcation and production costs. As for demarcation costs, rectangular shapes involve a minimal number of survey points at right angles; this facilitates boundary identification, thereby reducing transactions costs in land markets. Because rectangles form convex sets, lines joining points within a property lie within its boundaries, which reduces production costs, such as for fencing or for the operation of farm equipment.

Consequently, it is not surprising that commercial interests opt for rectangular properties, an economic preference that underlies *rectangular* fragmentation. But the same is true for smallholders, in which case differences in land holdings are manifested in property size and in the relative dimensions of frontage versus depth. Commercial interests often show preference for nearly square properties, ranging up to tens of thousands of hectares. Smallholders occupy much smaller and more numerous parcels, which exhibit variability in shape as a function of the circumstances of colonization and land occupation. Where the federal government has promoted settlement, smallholders occupy elongated rectangles with limited road frontage (e.g., 400 m × 2500 m along BR-230), and forest clearing moves from front to back, with the result that a fishbone pattern emerges along parallel deforestation strips, anchored by the colonization roads.[3] Thus, our use of the term *rectangular* must not be construed as restricting rectangular properties to a single landscape pattern, since this also depends on property size and spatial arrangement along roads.

4. From social process to fragmentation pattern

Thus far, we have touched on the human behaviors associated with road construction and agricultural land use, which underlie most Amazonian forest fragmentation in Brazil. We now consider the social processes and the spatial decision-making that lead to the different landscape patterns. Our start point is Brazil's federal highway network, in particular the segments built to open its Amazonian region. We have referred to roads built by individual states as also belonging to the category of *official* roads. However, our discussion here addresses the federal system, because state roads formed only a small component of the official network in the Brazilian Amazon region for many years. Indeed, it was the federal highway network that functioned as the prime distributor of fragmentation patterns at subbasin scale. Facilitating the network's distributional role was a significant intervention by the federal government, which involved the transfer of state lands in Pará, Mato Grosso, and Rondônia, lying within 100 km on either side of the new highways, to federal jurisdiction for the purposes of agricultural development (Diário Oficial da União [DOU], 1971).[4]

4.1. The federal network

Until the mid-twentieth century, coastal waters provided the only connection between Amazonia and the rest of Brazil, and rivers maintained the region's internal connectivity (Becker, 1982). Significant infrastructure investment begins with the administration of President Kubitschek and the building of the Belém–Brasília highway (BR-010), which was completed in 1960 and paved in 1974. As the military government came into power in 1964, road construction became part of the regime's geopolitical strategy to secure national borders and provide access to resource frontiers (Kleinpenning, 1977; Smith, 1982). The military government began its infrastructure buildup in 1967 with highway BR-364, which connected Cuiába to Porto Velho by 1974 and Rio Branco by 1975. Asphalted in 1983, BR-364 now stretches to the Peruvian border, linking northwestern Brazil to the country's industrial core in the south. The military government next targeted central Amazonia, anxious to assert sovereignty over a large, relatively unpopulated region within its national borders (Hecht, 2011). Under the slogan, 'bring a people without land to a land without people,' massive investments opened the region by the mid-1970s with the completion of three major highways, BR-230 (the Transamazon Highway), BR-163 (Cuiabá–Santarém), and BR-319 (Porto Velho–Manaus).

BR-230 linked the drought-stricken northeast of Brazil to Itaituba in 1972 (Sant'Anna, 1998). Although planners intended to reach Benjamin Constant in the tri-border region of Brazil, Peru, and Colombia, construction stopped in 1974 at Lábrea, on the Purus River (Kleinpenning, 1977; Sant'Anna, 1998). From its start point in the State of Paraíba, the Transamazon Highway, mostly unpaved through the Amazon, traverses 4223 km. The second road targeting central Amazonia, BR-163, connects Cuiabá to Santarém over a 1743 km clay track currently being paved. Completed in 1976, BR-163 connects Santarém, an important town on the Amazon River, to the industrial south via Cuiabá (Araújo et al., 2008). Finally, BR-319 was built to connect Porto Velho (linked to the industrial south via BR-364) with Manaus, the largest city in the central Amazon, and a free trade zone since 1967. Started in 1968 and completed in 1976, BR-319 crosses BR-230 on the Madeira River at Humaitá (Sant'Anna, 1998). Heavy rains have minimized its developmental impacts, as they have for western segments of BR-230. The period of large-scale Amazonian road construction closed during the military regime with the opening of BR-174, linking Manaus to Boa Vista by 1977, and BR-156, linking Macapá to Oiapoque by 1976 (Sant'Anna, 1998). Both were built pursuant to geopolitical concerns, notably to reach and thereby secure borders with Venezuela, Guyana, and French Guiana.[5]

In all cases, federal highway design began with the specification of a *destination determinate* route linking population centers or points of strategic interest (Arima et al., 2005). Planning bureaucrats also considered the locations of preexisting settlements, which were used by road construction crews as logistical 'support points' (*pontos de apoio*). Often, such preexisting settlements reflected Amazonian hydrology (Instituto Brasileiro de Geografia e Estatística [IBGE], 1957), as with the east–west route of BR-230 that links Marabá, Altamira, and Itaituba (Figure 4). These are all old towns located on or near the fall line of the Brazilian shield and its drop to the Amazon stream course. Planners paid little heed to topography at local scale, but did avoid the hilly areas of the Serra do Cachimbo (BR-163) in southern Pará State, as well as extensively inundated lands in Amazonas State (BR-230). Given the route selection imperatives at play, the geometry of federal highways in the Brazilian Amazon takes the form of long straight segments that intersect and connect far-flung nodal points. This leads to a very sparse network of nearly 17,000 km of nearly continental extent (Figures 3 and 4).

While the federal system connected major population centers within Amazonia, and between Amazonia and the rest of Brazil, the state system vastly extended that connection to second-tier cities and into resource-rich locations with deposits of tin, gold, and iron ore in Pará, Amazonas, and Rondônia States. Although built later, the state system is now twice the size of the federal system, comprising 32,500 km (Figure 3).

4.2. The distributed fragmentation patterns

The imposition of the main features of the Federal Network (as mirrored and extended by the State System) had largely transpired by the mid to late 1970s, a period coincident with large colonization projects known as *Projetos de Colonização*, or PICs, in Pará and Rondônia State (Cardoso & Müller, 1977; Moran, 1981), as well as with substantial private initiatives in Mato Grosso and parts of Pará (Jepson, 2006; Schmink & Wood, 1992). These initiatives in infrastructure investment and colonization policy stimulated the expansion of spatially distributed settlement frontiers along the highway corridors, a

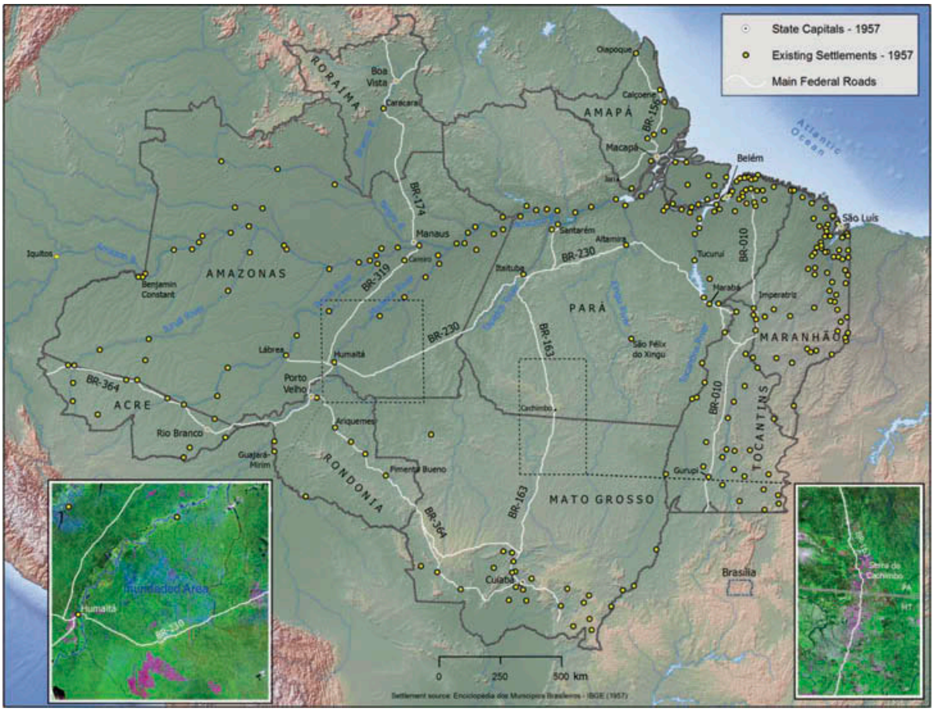

Figure 4. The emergence of the federal road system in the Brazilian Amazon.

process that has unfolded over the decades and given rise to the specific fragmentation patterns that we now consider.

4.2.1. Fishbone fragmentation

Fishbone fragmentation presents an orderly pattern of cleared land that organizes like the spines of a fish above and below a main artery; it is associated with the PICs aimed at colonizing the basin with colonist smallholders.[6] Along the Transamazon Highway between Altamira and Itaituba, and along BR-364 in Rondônia, the federal colonization agency, INCRA, created settlements with thousands of small lots (100 and 50 ha) demarcated along secondary roads or *travessões* that sprout from the highways at fixed intervals (e.g., 5 km). Colonists who occupied them deforested along these secondary roads, thereby initiating the pattern. In both places, the initial roads were insufficient to meet a growing demand for land. Along BR-230 in particular, the demand for land was far superior to the amount originally demarcated by INCRA due to a continuing inflow of migrants. These migrants therefore opened forest trails beyond the secondary roads and demarcated new lots by *limites de respeito* – limits of respect for demarcated lands that are *de facto* recognized by neighbors (Arima et al., 2013). Although outside the original settlement plan, the new lots replicated the settlement geometry of the original template in the hopes of winning INCRA recognition in the form of land titles. Fieldwork in Uruará (Figure 5, Panel A) indicates that loggers, together with local politicians and ranchers, actively participated in upgrading these trails into *unofficial* roads in exchange for timber. The road extensions proceeded in parallel, given loggers implicitly complied with the

Figure 5. (A) Fragmentation pattern in populist frontiers. (B) Fragmentation pattern in capitalist frontiers.

spatial constraints imposed by the demarcations (Arima et al., 2005). Thus, road construction into the forest beyond the government project followed exactly the same pattern laid out in the beginning, and the spines of fishbone fragmentation now extend to 50 km and even 100 km from BR-230, stretching over 73,000 km according to our GIS dataset (Figure 3).

4.2.2. *Rectangular fragmentation*

Rectangular fragmentation differs from fishbone fragmentation primarily by the manner in which individual properties structure road networks. As observable in Figure 5B, deforested land manifested spatially in an irregular lattice of large rectangular holdings that reflected the large size of the allotted properties. Private land companies were particularly active in Mato Grosso, given its rainfall conditions and accessibility to the rest of Brazil (Jepson, 2006). Such companies sold large land parcels, in many cases greater than

10,000 ha, to southern investors; they also built the initial road network (Perz, Caldas, Walker, Arima, & Souza, 2008). Ultimately, the landowners together with logging interests picked up where the companies left off, and extended the initial network to a considerable degree. These extensions run primarily along the boundaries of large properties because of the spatial constraints imposed by the private holdings in place before the decision to build roads (Figure 5B). Thus, the resulting road network shows a regular geometry with many right-angle intersections (Perz et al., 2008). Given that deforestation typically occurs in square blocks and closer to roads, a rectangular fragmentation patchwork emerges as a result of the geometry of property boundaries. This pattern is found in Mato Grosso, where rectilinear roads account for almost 100,000 km (Figure 3).

4.2.3. Dendritic fragmentation

Dendritic fragmentation exhibits a branching trellis structure with highly irregular segments (Figure 6). In this case, field research implicates loggers acting in advance of the agricultural frontier (Veríssimo, Barreto, Tarifa, & Uhl, 1995; Walker et al., 2013). The irregularity of the dendritic pattern indicates that logging roads are built in the absence of property constraints. In such circumstances, the spatial behavior of loggers generates road networks connecting logging sites through 'minimum trees,' in the language of graph theory (Walker et al., 2013). Loggers also consider topography in order to avoid steep slopes (Arima et al., 2008). Computer simulations performed to assess the roadbuilding behavior of loggers show that valuable but distant sites may be exploited before nearby ones, even if profitable (Walker et al., 2013). This suggests that loggers rush to liquidate timber stocks as quickly as possible, with little regard for future harvests or even the law, which is consistent with other research on Amazonian logging (Asner et al., 2005). The *Terra do Meio* (Figure 6), a region between the Xingu and Tapajós rivers in the state of Pará, provides a prime example of *dendritic* fragmentation, where several large logging firms engaged in mahogany exploitation from the mid-1980s to 2000 (Pinto, 2005; Walker et al., 2013). Dendritic roads built by loggers identified in our GIS database sum to almost 22,000 km (Figure 3).

4.2.4. Radial fragmentation

Radial fragmentation takes the form of a wheel with roads and forest clearing radiating out along 'spokes' from a central landscape node, typically a town (Figure 7). It is observable across the basin in places such as Altamira, Apuí, Itaituba, Manicoré, and Nova Aripuanã, where the network accounts for over 2000 km (Figure 3). Here, we consider radial fragmentation in the vicinity of Itaituba, on the banks of the Tapajós River upstream from Santarém. Although Itaituba was targeted for colonization as part of the federal initiative giving rise to *fishbone* fragmentation along BR-230 to the east, the government withdrew its support to focus on the vicinity of Altamira. Thus, in contrast to the *fishbone* pattern, *radial* fragmentation reflects a cessation of state investment in colonization. In Itaituba, a free-for-all unfolded, involving a competitive mix of *grileiros* (speculative land-grabbers), smallholders, ranchers, and loggers. The present-day pattern originated in the initial penetration of the Itaituba hinterland by a single logger, who sought to restrict access for personal gain. He was unable to do so in the face of stiff competition by in-migrants, who invaded the tenuous claim for their own purposes. *Radial* fragmentation emerged as a spontaneous response to demographic growth, particularly of smallholders, in the absence of government regulation or intervention. As

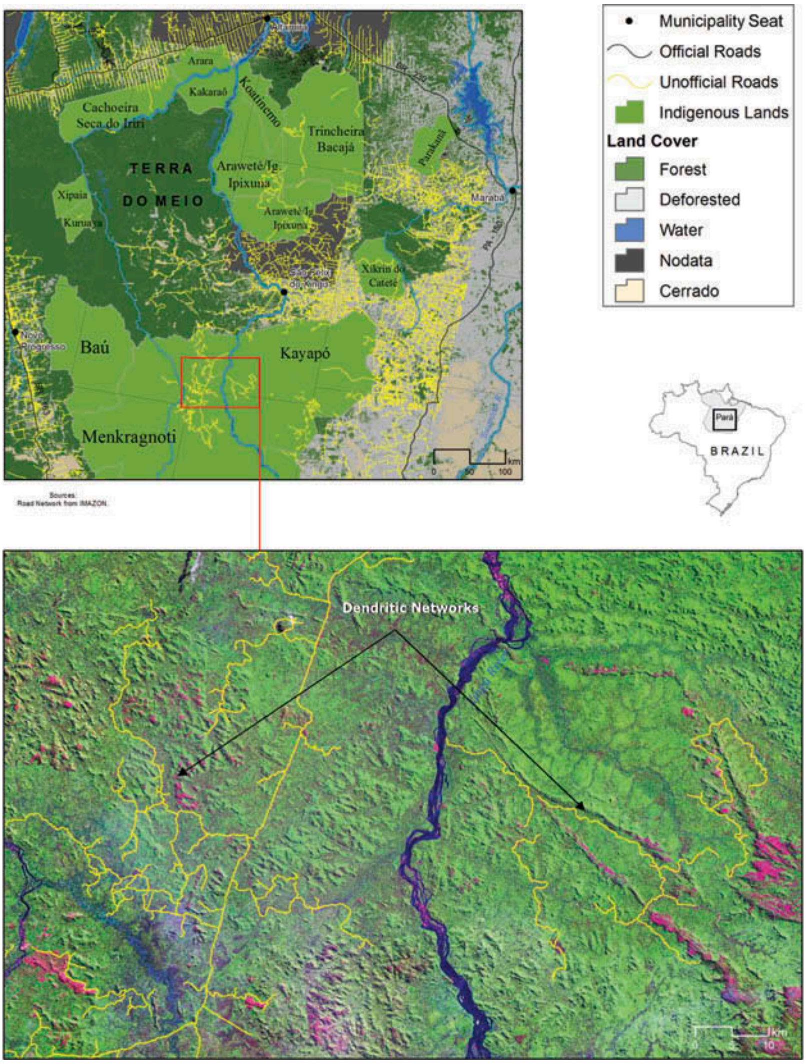

Figure 6. Dendritic fragmentation in Terra do Meio.

demand for land grew from the late 1980s, the spokes that give the pattern its radial form were created one by one, and extended, along a crescent-shaped thoroughfare linking Itaituba to Vila Brasília Legal, 40 km downstream on the Tapajós River (Arima et al., 2013). Caviglia-Harris and Harris (2011) use the term radial to describe multi-property landscapes embedded in the PICs of Rondônia, in the interest of promoting social interactions among neighbors. We deploy the term to describe landscapes of greater extent, specifically entire regional hinterlands organized around urban nodes.

4.2.5. *The stem of the rose*

This pattern represents a specific case associated with mining, namely the sprouting of *unofficial* roads from the BR-163 corridor (Figure 2, left middle panel). These roads

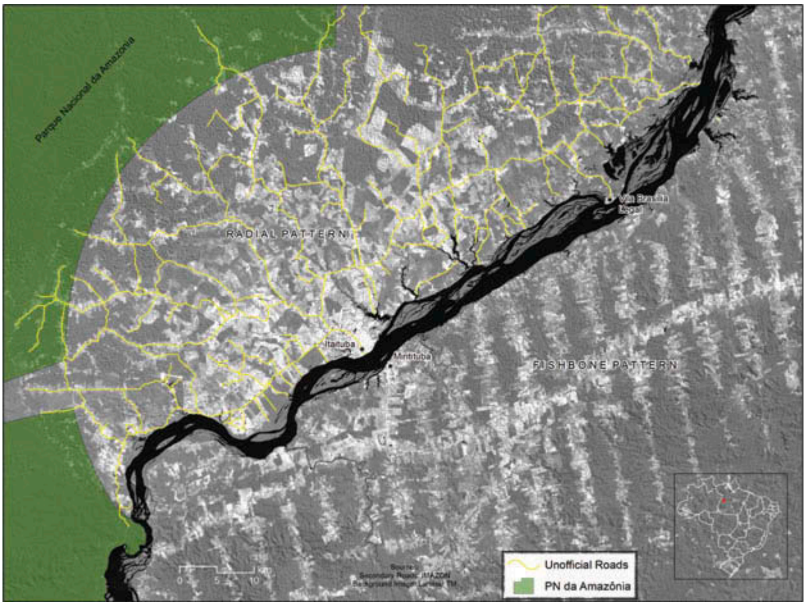

Figure 7. Radial pattern of forest fragmentation in Central Amazonia.

typically start with some degree of equal spacing along the highway. They extend with relatively straight routes for several kilometers, then begin to produce a trellis-like geometry reminiscent of dendritic fragmentation. Fieldwork by the authors has established that these roads were built by miners accessing gold strikes. The regularity of the initial spacing is explained by network routing along the straight-line boundaries of informal holdings claimed by agriculturalists, who migrated to the region in anticipation of a federal colonization scheme. The Brazilian Government never implemented the anticipated project, which has left the holdings in a juridical limbo for decades. Nevertheless, miners continue to respect associated boundaries in building roads to their mining sites, which lie beyond the properties. Altogether, this pattern accounts for roughly 5000 km (Figure 3).

5. Discussion

The descriptions just presented suggest that specific agents or groups of agents can be associated with each of the fragmentation patterns discussed. Furthermore, agriculturalists, whether poor colonists or well-financed corporate interests, appear to play a role in nearly all cases, as do loggers. In the Brazilian Amazon, initial agricultural occupation occurred in advance of logging. Government colonization projects along newly opened federal highways and fiscal incentives attracted smallholders and capitalists alike, who established their holdings before the logging industry set foot in the region (Mahar, 1988; Moran, 1981; Simmons et al., 2010).[7] Two different colonization schemes were implemented during this initial phase, leading to two different *unofficial* road networks and fragmentation patterns. Smallholders settled lands demarcated by the federal government, at least at the outset, creating *fishbone* patterns, whereas well-capitalized individuals attracted to the Amazon by private colonization companies (and incentives) created *rectangular* ones. In both cases, agriculture shaped the initial landscape, in which case the fragmentation patterns differentiate on the basis of wealth of landholder, as opposed to agent type. Taken together, these landscapes dominate the Amazon Basin in terms of the number of kilometers of associated road networks (Figure 3).

When the federal government opened roads throughout the Brazilian Amazon, smallholders and commercial agricultural interests took possession of large forest tracks rich in timber. Thus, loggers first exploited timber resources on already occupied lands, a relationship predicted by Von Thünen's rent model, and sanctioned by legislation allowing extraction off legally sanctioned properties (Arima et al., 2005). Later, once the agricultural frontier consolidated near the federal highways, loggers leapfrogged into unclaimed lands (e.g., *Terra do Meio*) in search of highly valued timber, like mahogany. The wide distribution of this species across the basin (Grogan, 2001) and the high rents generated by its exploitation enabled them to reach unoccupied regions where they built profit-maximizing road networks, leading to *dendritic* fragmentation.

As for *radial* fragmentation, this associates with urban nodes undergoing a growth process, in the absence of government or private sector intervention to grid the landscape for small or large holdings. Evidently, such an institutional setting does not translate automatically into a logger-dominated landscape, given the appearance of a degree of orderliness suggestive of the spatial constraints imposed by agricultural production objectives. Alternatively, the *stem of the rose* combines fishbone order in its initial spatial structure and dendritic-style routing in search of gold strikes beyond where the roads begin.

The patterns, as described, vary from the orderly extreme of farmer-dominated landscapes, to the unconstrained *dendritic* frontiers of the loggers acting far beyond the agricultural frontier. We suggest that relatively ordered landscapes (i.e., *fishbone* and *rectangular*) emerge when agricultural interests occupy forest areas ahead of logging. In such situations, landscape dominance belongs to the agriculturalists who shape production space according to their shared objectives. Although loggers do participate in roadbuilding, their spatial decisions are constrained by the agricultural resource users. Furthermore, *fishbone* and *rectangular* landscapes both rest on the same spatial building block, a rectangular property ranging in size from 10^2 to 10^4 hectares. The spatial mechanisms of forest penetration are also similar in that both colonists and capitalized farmers (or ranchers) collaborate with other agents to build roads that follow or define property boundaries. Consequently, both the *fishbone* and *rectangular* patterns show some regularity in their geometrical form, despite the vast economic differences that distinguish the colonist from the mechanized farmer or wealthy rancher. Although *fishbone* fragmentation might appear more orderly with satellite imagery, this is an artifact of viewing scale. Remotely sensed data tends to smooth colonist clearings to narrow bands along the more prominent spatial feature comprised of the roads themselves, which are evenly spaced.

When loggers occupy forest ahead of farmers, geometric regularity fails to manifest given the lack of interest in agricultural production with long-term attachment to the land. In its place arises *dendritic* fragmentation showing excessively long segments that connect timber-rich areas to points of extraction. Such segments present nonlinear routes that minimize roadbuilding costs as they follow topographic contours. This apparently inefficient use of space is enabled by an abundance of *terras devolutas* (unclaimed lands) in which landscape dominance belongs to the logger. Here, space is structured by road networks expressing short-run profit maximization and resource liquidation.

Evidently *fishbone, rectangular*, and *dendritic* fragmentation bracket the empirical extremes vis-à-vis geometric regularity, and they are differentiated in large part by the arrival times of the agents on one hand, and by differentials in economic power, on the other. Within the spectrum of spatial form so constructed, we place the patterns of *radial* fragmentation and the *stem of the rose*. Both display partly regular, partly irregular structural components. *Radial* fragmentation is the outgrowth of simultaneous occupation involving competition among agriculturalists, both small and large holders, and loggers. In contrast, the *stem of the rose* reveals a temporal and spatial succession, with agriculturalists arriving first, and miners perhaps a decade later. That a fishbone pattern failed to emerge reflects the federal government's generalized retreat from PIC projects in the 1970s, as well as population characteristics of the BR-163 colonists. Mostly from the southern part of Brazil, they did not suffer origin push factors as strong as those experienced by settlers along BR-230, who were mostly poor Northeasterners escaping drought and persistent poverty. Those who came to the region in the 1980s were searching for gold, not land, and the valuable mineral was deposited at some distance from the federal highway in a large number of dispersed sites.

To summarize, our conceptual synthesis explains fragmentation outcomes for the Brazilian Amazon with a two-step temporal sequence beginning with the imposition of a federal highway system by politicians and federal bureaucrats pursuing societal goals. Following this, the second step transpires as a variety of resource-using agents infiltrate the basin landscapes.[8] Their relative arrival times, in turn, determine the type of fragmentation observed. If agriculturalists arrive before loggers, then *fishbone* or *rectangular* patterns result as a function of the wealth status of the primary agricultural population (smallholder vs. large holder). If loggers arrive before agriculture, then the outcome is *dendritic*. Simultaneous arrivals appear to produce a *radial* pattern, particularly when colonization appears to organize around an urban node. This is likely to be the case in the absence of a federal program specifically designed for spatial dispersion, as with the early PICs. Special cases arise on the basis of contingent events, as with the *stem of the rose*, which reflects both the regularity of colonization and the unconstrained spatial decision-making of resource liquidators, in this case gold miners.

Although the nature of the final imprint reflects relative arrival times and the landscape dominance of specific agents, it is important to note that different landscapes may exist in close proximity, in which case the scale of observation can be the key to pattern recognition. For example, the northern side of the Transamazon Highway (BR-230), a much studied zone of *fishbone* fragmentation, exhibits *rectangular* features in places, given INCRA's original plan to bring a few large-scale agro-industrial interests to the region, in addition to smallholders (Aldrich et al., 2006). Furthermore, if one moves far enough from the highway, a number of the colonization roads begin to manifest *dendritic* features, which we know from fieldwork to be attributable to loggers. Thus, the various patterns can exist in close proximity, and transitions from one to the other may be subtle.

6. Conclusions

We draw several conclusions with implications both for policy and for land-change modeling. Before doing so, we briefly consider the applicability of our results outside of Brazil. A number of nation-states possess lands within the Amazon Basin, which means that the region has been occupied under variable degrees of intensity and investment. We speculate that the spatial forms of occupation we describe are likely to replicate across national borders, although with variable mixes as a function of frontier demographics and the types of agents engaged in land change. One difference might appear to involve fossil fuel exploitation in Ecuador, although the Brazilian Amazon presents a number of cases in which roads have been built expressly to tap mineral resources, particularly iron ore, in the State of Pará. The typology advanced by Mertens and Lambin (1997) offers some measure of support for our speculation, given the patterns presented here show considerable overlap with theirs.

As for policy implications, a question naturally arises about how the patterns, as described, impact the basin's ecological processes. Specifically, is one type of fragmentation less damaging than the rest? It has been argued that the maintenance of corridors lessens disturbance, in which case *fishbone* fragmentation might possess sustainability characteristics related to species dispersal and mobility, given the persistence of native forest cover in long strips between the individual roads of the network (Arima et al., 2013; Caviglia-Harris & Harris, 2011; Metzger & Décamps, 1997; Walker et al., 2013). This conjecture has been validated in a comparative study of *radial* and *fishbone* fragmentation (Arima et al., 2013). We speculate that extending the analysis to the full suite of fragmentation patterns would support the optimality claim for *fishbone* landscapes, at least with respect to biodiversity concerns.

Although *fishbone* fragmentation appears to promote species dispersal and mobility in the face of environmental change, it could compromise other ecological processes, thereby off-setting to some degree the biodiversity benefits. Taking up the comparison again between *fishbone* and *radial* fragmentation, it has been observed that the straight roads shaping the *fishbone* pay little attention to topography, unlike the *radial* network, or even the *dendritic* case. Here, routing gives little attention to topographic contour, with implication for surface hydrology and runoff. Thus, *fishbone* fragmentation may promote terrestrial species survival at the same time as it degrades riverine ecosystems with increased sediment loads, especially in rugged landscapes susceptible to erosive forces (Arima et al., 2013; Walker et al., 2013) (Figure 8).

The relative extents of corridor-preserving fragmentation (e.g., fishbone) versus topographically sensitive patterns (e.g., radial) suggest that the spatial manifestation of

Figure 8. Erosion on secondary road 155 N, 2004 in the vicinity of Uruará (Credit: E. Arima).

deforestation in the Amazon Basin has tended to favor terrestrial species rather than riverine ones. Thus, resource managers and policy makers aiming at developing tropical areas should favor the more orderly structure of PIC colonization when topography is flat and adapt the road network and lot configuration of the regularized structure of PICs in accordance with the local hydrology if soil erosion is a concern. In any event, the identification of a globally optimal pattern of forest fragmentation will require additional research based on a full set of ecological processes likely to be affected by the spatial form of human disturbance.[9]

As noted in the 'Introduction,' much research has addressed the human drivers of deforestation in an aspatial setting, spatially explicit models notwithstanding. Less is known, however, about the social and behavioral processes that generate the patterns of fragmentation that result from forest conversions to human land use. Thus, descriptions of land change, such as developed here, can inform advances in land-change modeling, when the prediction of pattern is the analytical objective (Brown, Aspinall, & Bennett, 2006), as opposed to the prediction of aggregate quantities of change (Pontius & Millones, 2011). We have just suggested that different fragmentation patterns associate with different sets of ecological impacts. Thus, our analysis can enhance policy scenario simulations with respect to gauging sustainability outcomes (Brown et al., 2013).

Amazonian deforestation rates have come down in recent years, at the same time that Brazil has advanced forest management principles consistent with the UN's program to reduce carbon emissions from deforestation and forest degradation, or REDD. That said, demand projections suggest more deforestation may be necessary to meet the world's growing appetite for agricultural commodities produced in the Brazilian Amazon (Lapola et al., 2010; Walker et al., 2009). Whatever the future holds, policy makers should be ready for it. If additional Amazonian lands are needed to accommodate an exploding agricultural sector, then associated ecological impacts should be kept at a minimum. This article describes the social mechanisms and behaviors that dictate the spatial forms of forest occupation, which matters in the final tally of the ecological impacts of deforestation. Thus, its synthesis can contribute to environmental policy making when sustainable development is the prime objective.

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Notes

1. This digital dataset possesses at least two limitations that constrain our ability to do any temporal analysis: we do not know when road segments were built prior to our baseline year 2003, only after, and some roads may be ephemeral (e.g., certain logging roads and trails) and may have been abandoned after detection. We did not concurrently detect deforestation either and cannot make basin-wide claims about the road-fragmentation pattern nexus, although such work has been conducted for certain regions (e.g., Arima et al., 2005, 2013; Perz et al., 2008; Walker et al., 2013).
2. Network length measured within a GIS and included the following states: Acre, Amapá, Amazonas, Mato Grosso, Pará, Rondônia, and Roraima. Tocantins and Maranhão were not included because the predominant vegetation in these latter states is not evergreen forest.
3. We use the term colonization road here, even though they fit our classification as *unofficial*. Along BR-230, the federal government sometimes built an initial spur to 10 km, but most of the time private agents initiated construction. In all cases studied by the authors on BR-230, private citizens expanded the roads to their current length.
4. Although restricting our assessment to federal investment facilitates our presentation, it fails to capture social dynamics that have at times impacted the building of state roads, which can also distribute fragmentation patterns across the landscape (Schmink & Wood, 1984).
5. Another road, Perimetral Norte (BR-210) linking Boa Vista to Macapá along Brazil's northern borders, was planned but only a few segments were actually built.
6. *Projetos de Assentamento* (PA) formed pursuant to Direct Action Land Reform (Simmons et al., 2010) often display the same spiny organization of space, but on a much smaller scale than the PICs strung out along the federal highways.
7. Schmink and Wood (1984) described how first colonists and ranchers sometimes burned down hardwood trees because the logging industry was incipient in the early stages of frontier expansion in Amazonia, an indication that the agricultural frontier was ahead of the logging frontier at the time.
8. Other meso-scale organizations, such as land companies and social movement organizations (SMOs), also played a role in the process. To facilitate our presentation, we have focused on the upper-tier agency of the 'state,' and on the ground-level behaviors of resource-using agents.
9. Caviglia-Harris and Harris (2011) find variations in the relationship between deforestation and settlement patterns in Rondônia, with landscapes on the order of 10^1–10^2 km^2. The fragmentation patterns in this article extend over 10^4–10^5 km^2, excepting the extent of the federal network at 10^6 km^2.

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