Loggers and Forest Fragmentation: Behavioral Models of Road Building in the Amazon Basin

Eugenio Y. Arima,* Robert T. Walker,** Stephen G. Perz,*** and Marcellus Caldas**

*Department of Geography, Michigan State University, and Instituto do Homem e Meio Ambiente da Amazônia (IMAZON), Brazil
**Department of Geography, Michigan State University
***Department of Sociology, University of Florida

Although a large literature now exists on the drivers of tropical deforestation, less is known about its spatial manifestation. This is a critical shortcoming in our knowledge base since the spatial pattern of land-cover change and forest fragmentation, in particular, strongly affect biodiversity. The purpose of this article is to consider emergent patterns of road networks, the initial proximate cause of fragmentation in tropical forest frontiers. Specifically, we address the road-building processes of loggers who are very active in the Amazon landscape. To this end, we develop an explanation of road expansions, using a positive approach combining a theoretical model of economic behavior with geographic information systems (GIS) software in order to mimic the spatial decisions of road builders. We simulate two types of road extensions commonly found in the Amazon basin in a region showing the fishbone pattern of fragmentation. Although our simulation results are only partially successful, they call attention to the role of multiple agents in the landscape, the importance of legal and institutional constraints on economic behavior, and the power of GIS as a research tool. *Key Words: Amazonia, land-use change, least-cost path.*

Global environmental change resulting from anthropogenic impacts on land cover and land use is widely recognized as an important issue (Ojima, Galvin, and Turner 1994). One such change, namely tropical deforestation, has been of great concern to scientists and the public at large because of its possible effects on climate and biodiversity (Steffen and Tyson 2001; Jenkins 2003). A large literature on the issue has emerged in recent decades, and geographers and social scientists have made great strides in understanding the factors that motivate humans to clear forested lands in tropical regions (Lambin, Geist, and Lepers 2003). Although we now know much about the human drivers in this regard, we know far less about the actual spatial pattern of forest degradation and loss. This is a critical shortcoming in our knowledge base, given the link between biodiversity and forest fragmentation implied by island biogeography (Whittaker 1998).

Roads and market accessibility, more generally, have long been recognized as important factors affecting land cover and land use in both tropical and temperate settings. Indeed, in the Brazilian Amazon, nearly 90 percent of the deforestation has occurred within a 100 km buffer from roads built by the federal government (Alves 2002). The extension of transportation infrastructure into tropical frontiers, especially roads, induces inmigration, increases agricultural rents, and fosters economic development. As a consequence, land covers are transformed into human artifacts by the urban and agricultural use of land. Although roads appear to be linked to aggregate measures of deforestation, they are also inherently spatial phenomena, and patterns of forest fragmentation are in large part determined by the architecture of the transportation network implemented. Thus, understanding how the spatial architecture of a road network emerges is key to gaining insight into fragmentation.

This article addresses a specific form of fragmentation in the Brazilian Amazon and attempts to develop an explanation based on economic decisions about road building. Specifically, we use geographic information systems (GIS) software to mimic the spatial behavior of road builders; then, we attempt to replicate an existing road pattern using the software. Thus, our application deploys GIS as a tool for understanding forest fragmentation processes and not for designing optimal road networks in a normative sense. In essence, GIS provides us with computerized thinking to address a process too difficult to resolve with analytical solutions (Fujita, Krugman, and Venables 1999; Walker 2003b).

The article is organized as follows. In the next section we motivate the modeling effort by considering the environmental impacts of forest fragmentation, links between roads and deforestation, and the pattern of the road network in the study area, an old colonization frontier in the state of Pará, Brazil. We also characterize

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the Amazonian logging sector since loggers build many of the roads constructed by private interests in the region. Then we discuss how GIS has been used in the past to address roads and their networks in a spatial domain and identify shortcomings of previous efforts relative to the present application. This is followed by (1) description of the types of roads found in the study area, (2) discussions of how to use GIS software to model the spatial processes of route selection, and (3) the presentation of actual simulation results comparing modeled routes to actual routes. We then discuss the results and limitations of the analysis. The final section calls attention to the importance of the fragmentation issue and the power of GIS as a spatial modeling tool.

The Environment and Roads in Forest Frontiers

Environmental Impacts. The environmental impacts of roads are of particular concern in regions where infrastructure networks are expanding rapidly in areas of high ecological value, such as the Amazon basin (Schelhas and Greenber 1996; Reid and Bowles 1997; Laurance 1998). In such regions, forest fragmentation alters vegetative structure and available habitats for many species (Aldrich and Hamrick 1998; Laurance 1998; Scariot 1999; Laurance et al. 2001). Fragmentation may modify or even curtail vegetative regeneration (Lovejoy et al. 1986) through heightened tree mortality (Ferreira and Laurance 1997; Laurance et al. 2000) and reduced seedling recruitment (Benitez-Malvido 1998). Such changes result in biomass collapse (Laurance et al. 1997) and carbon emissions that contribute to global climate change (Gash et al. 1996; Fearnside 1997). Further, road construction in tropical frontiers can contribute to feedback mechanisms that catalyze destructive changes in forest ecology. Fragmentation raises ground temperatures and reduces precipitation, thereby elevating the risk of drought. This, paired with increased litter fall from dying trees, accentuates the likelihood of fires (Uhl and Kauffman 1990; Cochrane and Schulze 1999; Nepstad, Moreira, and Alencar 1999). Thus, the risk of forest fire is linked to roads and forest fragmentation (Holdsworth and Uhl 1997; Nepstad et al. 2001).

The many ecological impacts of forest fragmentation depend on the size and spatial organization of the fragments themselves. Smaller fragments, and those with longer perimeters relative to area, tend to exhibit greater ecological disturbance than large fragments with extensive interiors (Laurance et al. 1997; Nepstad et al. 2001). Hence, understanding the environmental effects associated with forest fragmentation requires comprehension of the spatial architecture of the road networks that create the geometry of forest fragments in the first place. A key objective of the article is to do this for an important class of Amazonian roads, namely those built by private citizens in frontier settlements.

Roads and Land Cover Change. Despite the potential for ecological damage, the development of transportation infrastructure has been viewed as key to efforts at economic development, particularly in developing countries (Vance 1986; Owen 1987). Early investment in railroads proved critical to the integration of the U.S. economy, and roads and transportation more generally have often been implemented in advance of demand for transportation services in frontier areas (Friedmann and Stuckey 1973). The expansion of road infrastructure in the Brazilian Amazon basin is no exception, and during the 1970s highway construction, it was a hallmark of state-led development efforts in the region (Goodland and Irwin 1975; Mahar 1979; Smith 1982). The federal roads built to connect the Amazon region to other parts of Brazil stimulated in-migration by landless families as well as capitalized ranchers, loggers, and mining firms, and by the late 1980s, massive deforestation was taking place in the name of regional development, a trend that continues today (Mahar 1988; Hecht and Cockburn 1989; Skole and Tucker 1993).

Government investment in transportation infrastructure is important to regional development, but it only reflects part of the story, and it overlooks the role of private citizens and local agents in maintaining and, especially, in extending the initial road networks. Indeed, once settlement occurred in the Amazon basin, newly arrived individuals, both loggers and colonists, took it upon themselves to extend the federal system in ways suitable to their own specific interests and objectives (Walker 2003b). One implication is that the mechanisms driving road construction are scale dependent (Gibson, Ostrom, and Ahn 2000; Wood 2002). On a regional scale, roads are built by governments to improve the accessibility of resource-rich regions for the sake of national development. On the local scale, road building involves the extension of infrastructure by individuals on site seeking to exploit resources for private benefit. For example, logging firms construct new roads when seeking to exploit timber stands made valuable by timber depletion near existing roads, especially if timber prices rise or credit lines become available to facilitate infrastructure investments (Walker 1987; Repetto and Gillis 1988; Kummer and Turner 1994).

A second implication of the sequential nature of infrastructure development in frontier areas is that patterns of fragmentation are likely to be linked to scale and the type of road-building agent active in the landscape. In the Amazon basin, highways constructed by federal and state-level agencies involve different methods and materials than road extensions by local agents. Local agents, such as loggers and colonists, pursue different spatial objectives than do state bureaucrats, and this affects the spatial architecture of the lower-order networks they build. In addition, their wide dispersion results in a much more dissected pattern than the one created by the state for development purposes. While the federal system exposes regions to in-migration and land occupation, the lower-order roads are the main proximate cause of fragmentation by virtue of their density. Figure 1 presents the federal road system for the entire basin as of 1991. Lineal distance of the system covers 18,177 km, or a density of 0.004 km of road per square kilometer of so-called legal Amazonia.[1] This compares with a density of 0.062 km of lower-order road per square kilometer in the study area along the Transamazon Highway between Altamira and Ruropolis (Figure 2). Clearly, the roads built by local citizens represent a much greater proximate threat to the integrity of the forests than the sparse federal system.

The modeling focus in this paper is on the fishbone pattern observed in smallholder colonization areas, such as along the Transamazonia Highway in Pará (Figure 2) and also in Rondônia State. The fishbone pattern of fragmentation is widespread throughout the basin, and its domain is likely to grow with ongoing government efforts to colonize the region in the interests of land reform by the implementation of *projetos de assentamento*.[2] We focus on Uruará, a town created during the official colonization efforts in the early 1970s through the so-called PIN program (Simmons 2002). Uruará was part of the Altamira PIC, or *projeto integrado de colonização*, one of the first official settlements in Amazonia pursuant to development of the federal highway system.

Roads off the Transamazon Highway. The design of the Uruará colonization project followed a standardized geometric pattern that was replicated throughout the basin, particularly in Rondônia. Lots were regularly demarcated along the main road (BR-230) and along parallel secondary roads that branched out perpendicularly from BR-230 every 5 km to the north and south (Figure 3). These secondary roads were initially constructed by the federal government as access spurs, leading 6–10 km off the federal highway (Simmons 2004). Colonists were given 100 ha lots and soon began deforesting to plant annual and perennial crops and pastures. The fragmentation pattern that emerged from the initial settlement geometry is well known as a "fishbone."

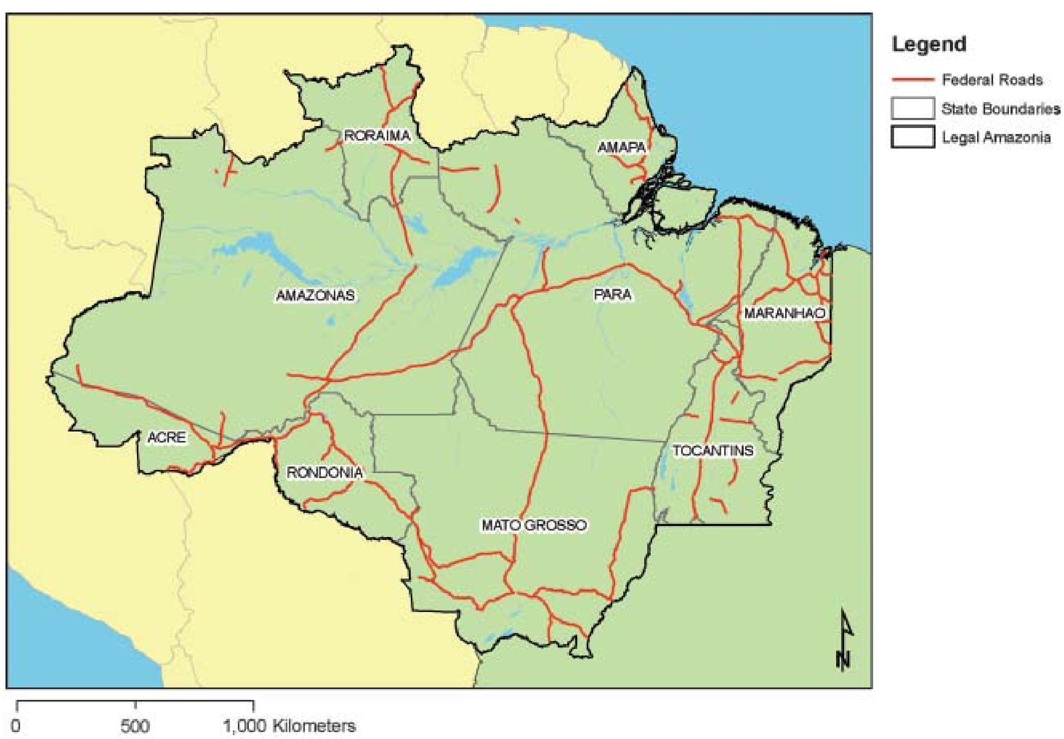

Figure 1. Federal road system in the Brazilian Amazon basin as of 1991.

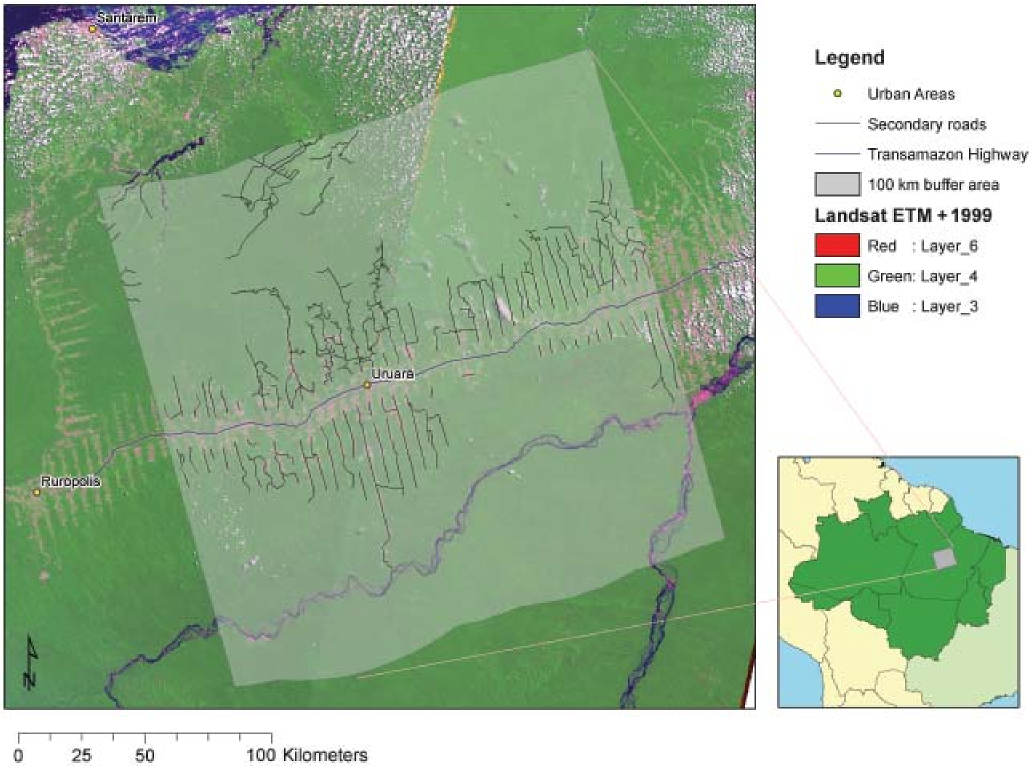

Figure 2. Secondary roads in a 100 km buffer along the Transamazon Highway; secondary roads provided by Simmons (2002).

Visual inspection of satellite imagery, as well as field experience, establishes that the federal infrastructure was subsequently extended by private interests in the area. In this regard, we have identified two main types of road extensions in our ongoing fieldwork. The first comprises simple extensions of the original secondary roads following the governmental spur, which we call *destination-indeterminate* roads. Such roads expand relatively slowly and replicate the initial settlement geography. The second type of road we refer to as *destination determinate*, since it achieves a discernible spatial objective. Two such roads are found in the region, named the *Transtutuí* and the *Transiriri* because they reach destinations on two rivers in the study area, the Tutuí and Iriri, respectively. These two roads are longer, better maintained, and more heavily traveled than those without destinations. Both destination-indeterminate and destination-determinate roads are typically built by well-capitalized loggers with help from colonists and local government.

Loggers and Road Building. The expansion of the secondary network associated with settlement roads in the Amazon basin is mainly driven by the logging sector, interacting with both planned and spontaneous colonization. Currently, about 30–40 million m^3 of roundwood are extracted on an annual basis, producing 11 million m^3 of sawn wood and a gross revenue of US$2.5 billion (IBGE 2003; Lentini, Verissimo, and Sobral 2003).[3] These production values translate into an extensive spatial impact, which is estimated at 9,400 km^2 logged in 1996, and 23,400 km^2 in 1999 (Matricardi et al. 2001). In volumetric terms, most extraction is concentrated in the states of Pará (40 percent of total), Mato Grosso (36 percent), and Rondônia (17 percent), all of which have experienced dramatic extensions of their road networks in recent years. Amazonian wood is mainly consumed domestically (86 percent), while the rest is exported (Smeraldi and Verissimo 1999).

As of 1998, perhaps 2,570 sawmill firms were operating in the Brazilian Amazon (Lentini, Verissimo, and Sobral 2003), of which 53 percent were considered small operations processing less than 10 thousand m^3 of roundwood annually. Lentini, Verissimo, and Sobral (2003) estimate that 49 percent of all roundwood is processed by large, vertically integrated firms that do their own logging. Such firms make large investments in sawmill structures, in machinery (circular saws, bandsaws), and in the equipment necessary to cut, extract, and transport the wood to be sawn, which includes skidders, winches, bulldozers, tractors, and trucks (Verissimo et al. 1992; Verissimo et al. 1995). Along the Transamazon Highway, large integrated firms have been most active in road extensions, particularly for the des-

Figure 3. Geometric pattern of roads, settlement, and deforestation along the Transamazon Highway.

tination-determinate roads that are built quickly and with considerable capital investment. The models we use to replicate road-building activity assume road building by a vertically integrated firm possessing both mobile (e.g, skidders, bulldozers, trucks) and immobile capital, on-site at the sawmill (e.g., saws, buildings).

Computational Issues in Modeling Roads

GIS and Road Networks. GIS has many applications to transportation and network systems, but it has not yet been used to model patterns of forest fragmentation based on road building. Consequently, the GIS objective is to develop an algorithm reflecting human behavior that can replicate the actual spatial signature of road building. We undertake model construction with a formal conceptualization of human behavior; then we observe the extent to which model outcomes are consistent with the actual roads observed. If the predicted roads are close to the observed roads, we conclude that our model is consistent with the decision-making process that led to the placement of the actual roads. We base our conclusions largely on visual inspection, given the general lack of accuracy metrics for our particular application.[4]

Early, pre-GIS approaches to network optimization assume the existence of a road network represented by arcs and nodes and the direction of permissible flow.[5] Although an optimal route can be identified using linear programming techniques (Hillier and Lieberman 1995), the problem of linking multiple points without a prior network is more challenging. Several recent advances in this regard have been made in graph theory and computational science, which refer to this class of problems as Euclidean Steiner tree problems (Ivanov and Tuzhilin 1994; Warme 1998; Prömel and Steger 2002), analogous to the multiple-target access problem in geography (Dean 1997; Murray 1998). A key GIS-based advance enabling the identification of the routes themselves was the Dijkstra algorithm. Finding the least cumulative cost for movement from some arbitrary origin cell to all cells in a grid can be computationally very demanding since there are a great number of possible route combinations linking the origin to the other cells. Dijkstra (1959) showed how to compute a cumulative cost surface efficiently by analyzing the neighborhood around the origin and gradually expanding the calculation until all cells are assigned a least cumulative cost. When the least cumulative cost surface is generated, a direction-to-origin grid is also generated since each cell traversed in cumulating the least cost is identified. The Dijkstra algorithm provides the optimal solution when there is only one destination point.

Tomlin (1990) developed a heuristic solution to the multiple-target access problem (MTAP) by applying a version of the cumulative-cost-surface approach to the identification of logging roads, adapting algorithms developed in hydrology. For Tomlin, the cumulative cost surface is an elevation map, and, pursuing the hydrological analogy, trees will be "drained" to the origin by the least-cost path. Eventually, the various paths will converge just as water converges to streams. Paths with the highest hauling traffic are then identified as logging roads, just as highest accumulated flow paths are taken to be streams in the hydrological applications.

Although the Tomlin problem is highly relevant to our particular application, its solution is limited in at least three ways. First, the roads identified are arbitrarily defined since Tomlin necessarily assigns a cut-off based on hauling volume. Second, the solution is not globally optimal because it fails to minimize costs on the basis of access to multiple cells using shared road stretches.[6] And third, the Tomlin solution identifies potential logging roads because it is not known if the revenues generated by extraction will cover the costs of road construction, a shortcoming also present in computer science applications. Such solutions may be meaningful in the case of U.S. national forests when government constructs the roads, although presumably some standards of efficiency will emerge over the long run. Our goal is to use GIS software to define unique road paths that are optimal in the sense that they meet some behavioral objective, such as profit maximization or cost minimization, which is what we expect to underpin the road construction process by private individuals such as loggers.

Modeling Logging Roads on the Transamazon Highway. The two types of roads found in the study area (destination determinate and indeterminate) require two different approaches to modeling. When destinations are indeterminate, the solution algorithm necessitates a software adaptation of the cumulative cost surface that identifies paths yielding the greatest volume of roundwood; this is because optimality requires the greatest amount of extraction per unit cost of road building (see Appendix). On the other hand, the knowledge of a destination, such as with the river roads, greatly simplifies the computational problem and simply requires parameterization of existing least-cost software. Road identification is unique in both cases and does not require a "cut-off."

For all simulations, road-building costs are taken as increasing functions of slope. We define the friction cost, or the cost of building a road through a cell, as the slope in percentage terms, corresponding to the tangent of the angle. This was calculated with the Horn algorithm (Burrough and McDonnell 1998) using data from the Shuttle Radar Topography Mission (SRTM), which were recently generated for the Amazon basin and are available from the USGS Web site (USGS 2004). Figure 4 depicts the tract of the Transamazon Highway in the

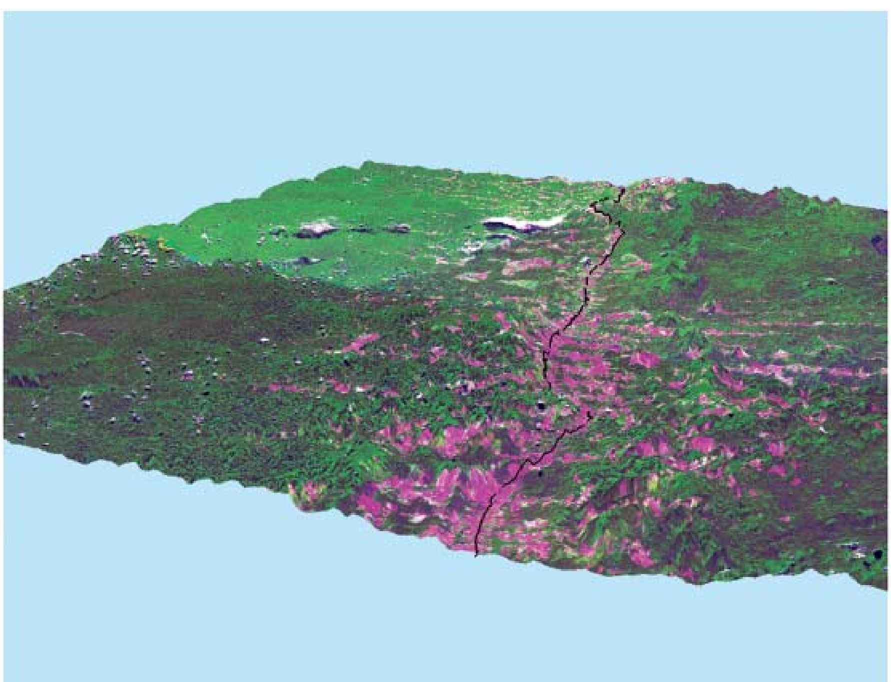

Figure 4. Perspective view of the Transamazon Highway. Landsat ETM$^+$ image (1999) draped over DEM (SRTM) vertically exaggerated fifteen times.

study area, reconstructing the topography of the region from the SRTM data. The view is to the east, with Altamira in the distance and Uruará in the foreground. The figure suggests that federal road builders paid some attention to construction costs associated with slope.

To provide the necessary data for simulation, the one-by-one degree latitude and longitude tiles of the SRTM archive were mosaiced and projected to UTM Zone 22 south, with 90-m cell resolution, which is roughly the same as the original 3-arc-second resolution in low-latitude areas such as the study area. The study area was clipped to create the simulation template, resulting in a 2015 by 1503 grid extent; the grid was checked for blunt elevation errors, which were not found. These data give a mean slope value of 7.7 and standard deviation of 6.9 for the Uruará locale, with values ranging from 0.5 to 112. Assigning such friction values means that it is 200 times more expensive to build a road on a 45^0 slope (slope value of 100) than on the flattest cell on the grid (0.5). We also incorporated river features into the cost friction grid. Bridging a river is more expensive then simply building roads upland. We converted the third and higher-order stream-line vectors, as defined by Strahler (1952) and obtained from Instituto Sócio Ambiental (2000), into a raster, assigning a friction value of 75 to the cells. This value was arbitrarily chosen to be roughly ten times larger than the average slope in the study area.[7]

We now consider both cases in greater detail, giving a description of the algorithms used as well as the results obtained. We address the destination-indeterminate roads first and follow this with the determinate case. In order to develop a behaviorally based theory of road building and forest fragmentation, it is essential to place the search for optimal pathways within the context of the microeconomic behavior of the firm, which is explained in detail in the Appendix. As discussed, large firms that engage in both wood extraction and processing are presently responsible for a large component of Amazonian forest exploitation, and, on a per enterprise basis, they exercise far greater forest impact than smaller operations.[8] In addition, we hypothesize that only large, vertically integrated firms possess the necessary capital to regularly engage in road construction. Thus, the model development that follows addresses the decision-making activities of large, vertically integrated operations, which, from this point on, we will refer to with the generic term *loggers*. For the destination-indeterminate case, such firms face two optimization problems. The first is profit maximization involving factor allocation between wood extraction and processing, subject to financial constraints. The second is spatial and involves identifying the path or paths that provide the greatest volume of roundwood, given the quantity of capital allocated to extraction, or *mobile* capital. The first problem is *aspatial* in that it requires no geographical information; the solution indicates optimal allocations of roundwood input, labor, and fixed sawmill equipment, or *immobile* capital. The second problem is *spatial* because it depends on several forms of geographical information, including location of trees and infrastructure, distance measures, and terrain slopes, and because its solution is spatial, that is, a path or paths in two-dimensional space.

Profit maximization and the search for optimal pathways require fundamentally different solution approaches. Specifically, profit maximization presents an analytical problem, the solution to which constrains the computational spatial problem. In operational terms, profit maximization yields the amount of mobile capital as a function of the firm's financial capability. Mobile capital then constrains the road-construction process and its articulation in space. This is the mechanism by which we translate the economic constraints faced by the firm into the formation of a road network (see Appendix Part 1).

For the destination-determinate case, the behavioral problem is simplified, and this facilitates the operational search for optimal pathways. In particular, a destination is assumed to exist, which is part of the firm's overall strategy to maximize profits. But because the destination has already been identified, loggers presumably will minimize costs in building the roads to go there (see Appendix Part 2). Thus, the operational GIS model reflects only this stage of profit maximization, and, as a consequence, we can rely on existing software to identify the minimum-cost pathways.

Destination-Indeterminate Roads. The absence of a specific destination requires software modification to find the optimal road as well as information on topography (costs) and the distribution of trees (revenues). Because we do not have tree distribution data in our possession, we assume that valuable hardwood is distributed uniformly across the landscape. The algorithm implemented in this case identifies road paths in three steps. In the first step for the initial time period, the cumulative cost surface is calculated from the original road network because loggers free-ride on existing infrastructure; this is accomplished using the *costdistance* function in ArcInfo® (2003), which utilizes the Dijkstra algorithm. With the cumulative costs calculated for all grid cells $[v(g_i)]$, we define a level set $\boldsymbol{P}$ formed by cells g_i such that $\boldsymbol{P} = \{g_i: v(g_i) = c\}$, with constant c and N cells. We make constant c equal to 10,000 units of cost, taken to be the financial constraint on the units of mobile capital depreciable in each iteration period, or year.[9] Note that we assume the value of c in the present exposition, as well as in the modeling exercise. Nevertheless, c is derivable from the profit maximization problem shown in the Appendix (Part 1) and is therefore a function of financial constraints faced by the firm, production technology, and economic conditions more generally.

In the second step, the road extension segment is identified as the longest one joining each $g_i \in \mathbf{P}$ to the original road network, or Road = $\max[L(g_i)]$ $i = 1, \ldots, N$, where L is length. The rationale is the assumption that the most efficient use of a fixed quantity of mobile capital, or the yearly depreciable amount, is the one that gives the greatest volume of harvestable wood. This is obtainable along the longest path when trees are distributed in a spatially uniform fashion, as assumed. Once the road segment is selected, it is added to the original road network in Step 3. The friction grid is then updated and another cumulative cost surface recalculated, which changes with the additional segment. We repeat the process sixty times to simulate the temporal evolution of the road network.

Results of simulations for the destination-indeterminate case are given in Figure 5, which overlays the modeled paths onto actual roads existing in the study area. In all of the figures, the Transamazon Highway and original extent of the settlement roads constructed by government are given as black lines. The deforested areas are pink in color and show the actual road extensions that have occurred in the wake of early colonization, which began about thirty years ago. Simulated roads are depicted as yellow line segments. Note that simulation space has been constrained by the protected area of the Araras Reserve indigenous reserve to the south, shown in light magenta in Figure 5.[10]

Destination-Determinate Roads. The simulations for the destination-indeterminate case reflect a fully developed theoretical model based on profit maximization subject to financial constraints, which allows for a search over all possible routes for profit-maximizing purposes. Nevertheless, key informant interviews of loggers suggest that explicitly spatial objectives often highly constrain the route-selection process, particularly in the case of longer roads requiring substantial capital investment. The two most important logging roads in the study area, the so-called Transiriri and the Transtutuí, were built in order to reach specific destinations. The Transiriri links the Transamazon Highway and Uruará to the Iriri River in the south, a major tributary of the Xingu River, while the Transtutuí provides a link north to the Tutuí River, which ultimately flows to the Amazon River (Figure 6). The actual paths of these roads were identified by visual interpretation (RGB 5/4/3 color composite) of four 1999

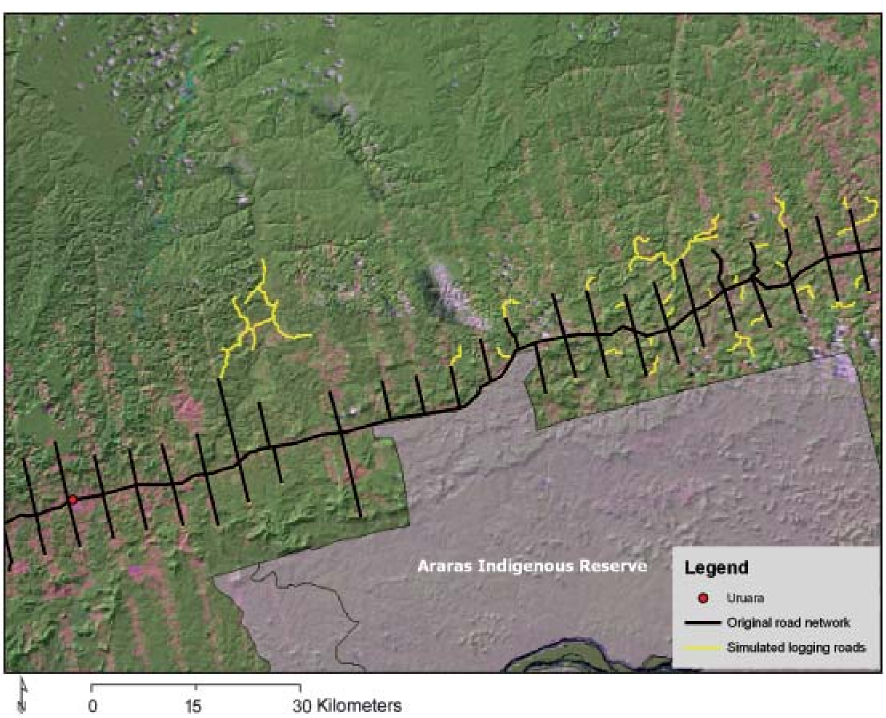

Figure 5. Destination-indeterminate simulation.

Landsat ETM+ images (paths: 226, 227, and rows: 62, 63) and were on-screen digitized at 1:50,000 scale. We consider each of the roads in turn. Although we know from key informants that the final destination of the Transtutuí is near the junction of the Tutuí and Uruará Rivers, we were not able to identify on satellite images the path beyond the digitized segment in Figure 6.

To replicate evolution of the Transiriri, we solve for the least-cost path from Uruará to any segment of the river, including movement along the Transamazon Highway using the built-in function *costdistance* from ArcInfo® software. The costs, as discussed, were calculated using topographic data from the SRTM project. According to field informants, the area along the Iriri River east of Uruará is susceptible to regular flooding during the rainy season, which imposes a serious cost increment to road builders. Indeed, we were able to identify those areas using 1:100,000 quad sheets MI-654, MI-721, and MI-722 from *Instituto Brasileiro de Geografia e Estatística*, or IBGE.[11] The results (Figure 7) show that the simulated least-cost path in yellow diverges from the actual Transiriri, given in blue. The "optimal" path starts directly in the town of Uruará, reaches the end of the official road network, then runs south contouring the major slope gradients, reaching the Iriri River 4 km downstream from the actual destination. As can be observed, the actual path begins 5 km west of Uruará and heads south to the river until it meanders right less than 10 km from its destination. Note that in this and the subsequent simulation, the initialized road network in black is set to 20 km rather than 6. Both the Transiriri and Transtutuí were built after 1980, when many of the settlement roads had already been extended to 20 km in relatively straight lines.

The other significant logging road in the region links Uruará to the junction of the Tutuí/Uruará Rivers where, according to informants, the road ends to the north. The yellow path is very different from the actual route but similar to historical accounts of the original route. The Transtutuí was originally a direct extension of the settlement road starting 15 km east of Uruará, as captured by the simulation in Figure 8A, its present-day path begins in the town itself and heads east until reaching its original route, where it continues north to the river.[12] We simulate this "second-best" solution by incorporating what key informants refer to as *pontos obrigatórios*, or necessary points of route passage. We take these to be the actual intersections of the Transtutuí with the settlement roads between Uruaríá and the original one selected for extension to the river. The simulation result given in Figure 8B is largely coincident with the actual route, given in blue, with two discrepancies at points A and B.

Discussion

The model applications perform better for the determinate than for the indeterminate case. The simulated indeterminate logging roads are dispersed and fragmented and begin to show direct extensions of individual

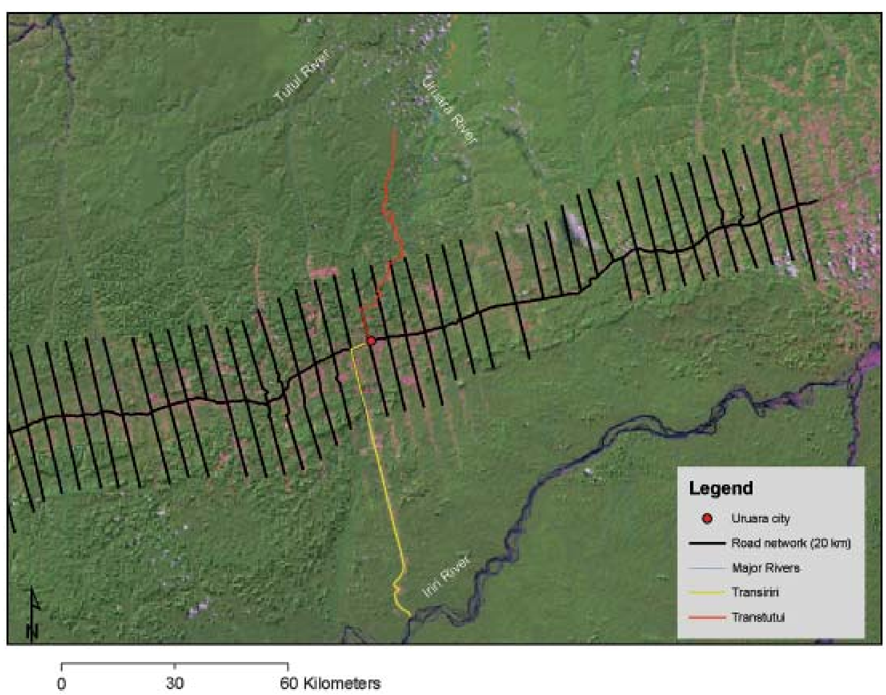

Figure 6. Major destination-determinate logging roads in Uruará, Brazil.

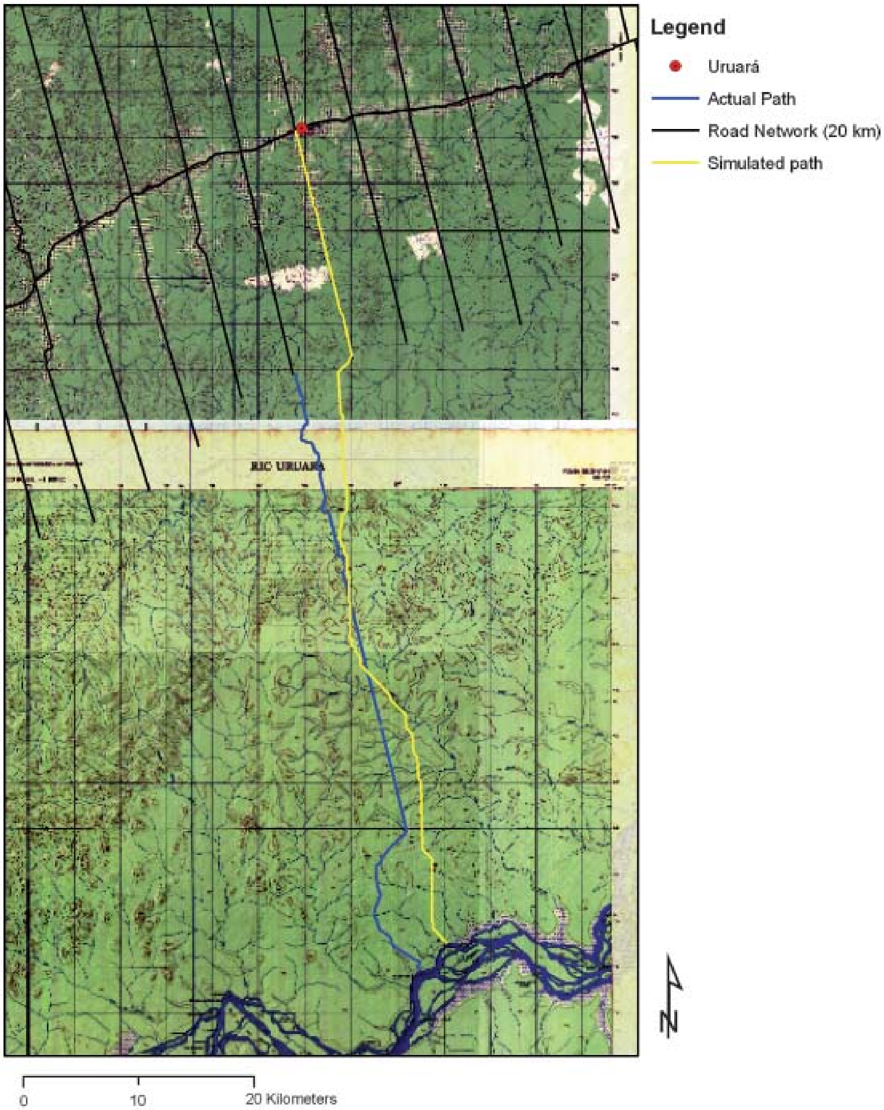

Figure 7. Simulation of destination-determinate Transiriri logging road

settlement roads, as has occurred historically. However, the actual extensions, as can be observed from satellite images, and as substantiated by field interviews, were mostly linear. Evidently, settlers arriving after initial colonization in the early 1970s extended the original spurs linearly by marking 100 ha lots (400 m × 2,500 m) identical to the first settlers, hoping that government would subsequently regularize holdings. The settlement road to the north, 5 km east of Uruará, is illustrative of this process (so-called 175N). According to key informants, the federal government opened the initial spur in 1975. This was followed by subsequent expansions in 1982, 1988, 1994, and 1999, given that colonist demand for land remained high. A local rancher undertook the second expansion in 1982, while municipal government added a 9 km addition in 1988. Loggers did not participate in extending the road until 1994, after it had already reached a distance of 25 km from the Transamazon Highway. As can be observed from the satellite imagery, the road itself shows a reasonably straight path, extending directly from the first opening by the federal government. It can reasonably be assumed that loggers, while not involved in the first three extensions, exploited wood from the newly colonized holdings, in which case they acted as free riders on the extension process until 1994, about twenty years after the initial opening. This sequencing contrasts with other parts of the world, where loggers have often extended roads that were then followed by colonists (e.g., Walker 1987).[13]

Expectations of colonists, responsiveness of federal government to land claims, and political relationships between colonists and local government appear to have set in motion the linear nature of the expansions of

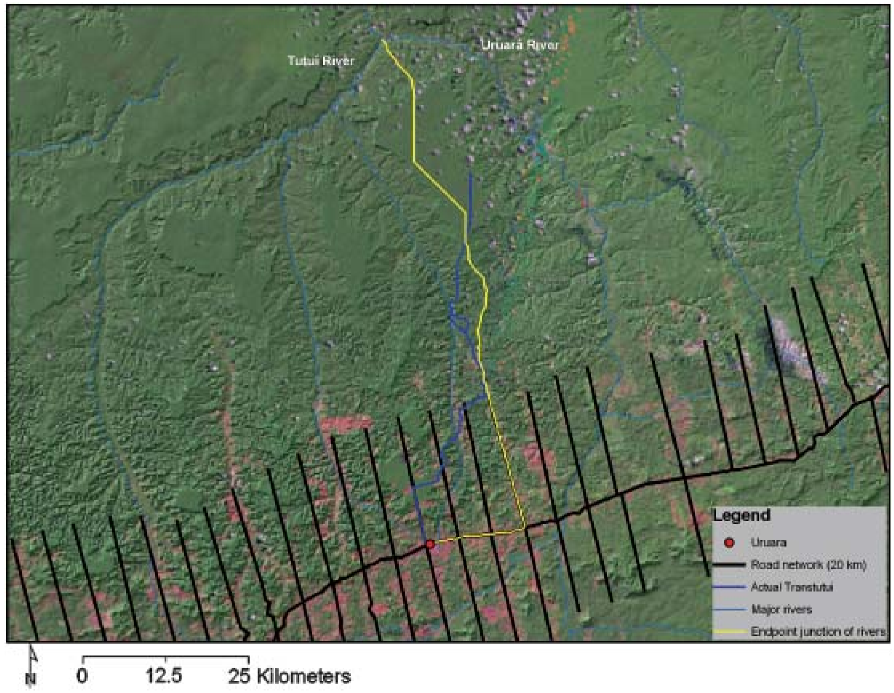

Figure 8A. Simulated Transtutuí with destination determined at junction of Uruará and Tutuí Rivers.

destination-indeterminate roads, at least out to about 30 km, beyond which loggers enter the picture as the primary road builders. The implication is that free riding by loggers has remained possible far beyond the initial construction of the spurs, although, eventually, they become responsible for new extensions. Current Brazilian law appears to encourage this by (1) drawing a distinction between the wood resources of loggers and colonists and (2) by giving loggers two legal ways to access standing timber.

In particular, the Brazilian Forestry Code (Law 4771/65) allows loggers to take timber from natural forests though deforestation (clear cutting) or via forest management (selective logging). The latter approach requires that forest engineers submit a forest management plan to Brazil's environmental agency, IBAMA, in a

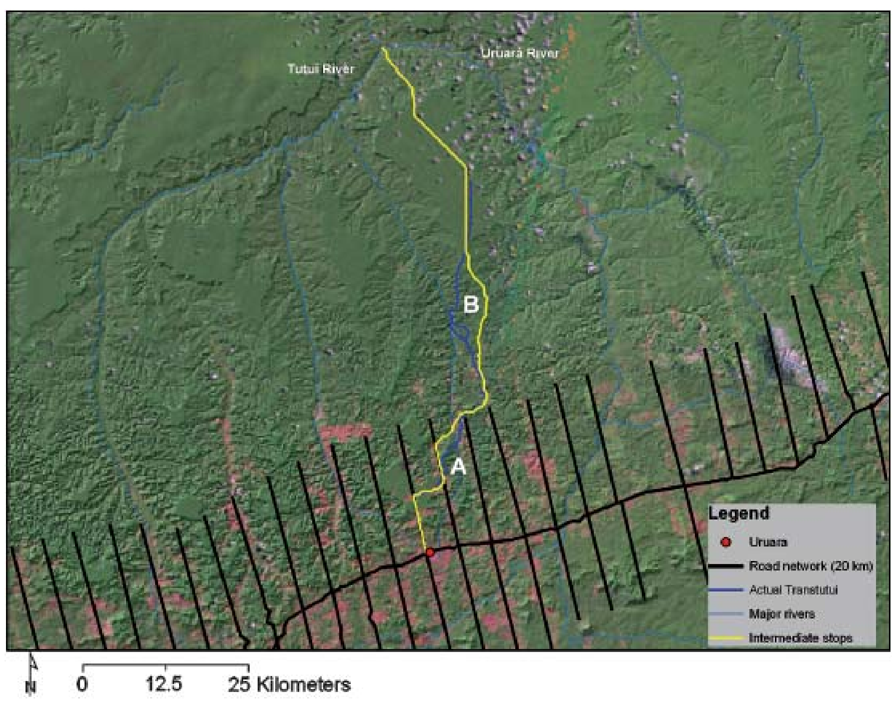

Figure 8B. Simulated Transtutuí with *pontos obrigatórios* (mandatory waypoints) included.

highly complex and bureaucratic process that includes on-site visits by enforcement officers and may take several years for approval. This turns out to be quite costly in terms of time and actual resources, so loggers often opt to secure their raw materials from allowable deforestation. In this regard, smallholders (<400 ha) have fewer legal requirements than largeholders (such as sawmill owners), which facilitates exploitation of their standing timber. Up to 50 percent of a smallholding can be deforested, as compared to 20 percent for large properties.[14] In addition, smallholders can legally exploit up to 20 m^3/ha of timber during the deforestation process without obtaining either a license or permission (Normative Instruction 003 from the Ministry of the Environment, 10 March 2002). This sharply contrasts with the legal burden on largeholders, who must submit an environmental-impact statement to IBAMA prior to obtaining a deforestation permit, which is costly (Barreto 2002). Largeholders must also prove that they have land title, a simple task for colonists settled by government-sponsored colonization projects. For reasons such as these, loggers often take their raw-material inputs from smallholdings in new colonization sites, such as those found in our study area.

Evidently, concerns about the regulatory environment, together with a growing population of colonists, have provided loggers with strong incentives to help extend the original settlement roads into the emergent fishbone pattern, even if they are not optimal according to the economic model presented here. Of course, if local government bears the road-building costs and loggers are permitted to take wood off lands allocated to settlement as currently permitted by Brazilian law, the straight extensions will be economically optimal.

Simulations for the determinate case, based on straightforward least-cost calculations, do appear to have predictive ability for the large sawmill interests intent on substantial expansion of individual roads beyond sanctioned areas of colonization. For the two major logging roads in the study area, the simulations come reasonably close to finding the actual routes. This is especially so for the Transtutuí, although the routing ultimately was changed in the wake of a localized dispute over a detour. Of course, in both cases, we introduced a known destination into the search algorithm, namely a river segment. How water access fits into the overall strategy of profit maximization in these specific cases remains an empirical question, although the Appendix (Part 2) states a possible theoretical rationale.

In general, the present approaches suffer from three limitations. First, we have stated the models to reflect choices of individual agents acting freely in pursuit of purely economic objectives. It appears, however, for the destination-indeterminate case, that multiple agents, including colonists, loggers, and local government, have been at work in shaping the landscape within both institutional and legal constraints. Thus, the conceptualization of the destination-indeterminate process as arising from a single agent acting freely in the absence of social context is incomplete and does not give rise to the fishbone pattern of forest fragmentation.[15]

Another shortcoming pertains to our inability to reflect the contingent and often unpredictable nature of social and political interactions at ground level in the road construction process. Key informant interviews indicate that the Transtutuí route was strongly influenced by a struggle between a well-capitalized logger, aligned with municipal government, and a colonist landowner. In addition, a secondary struggle emerged when spontaneous colonists attempted to occupy the lands that the logger desired to pass through. The first conflict affected the final route, which detoured considerably from the initial one that was a straightforward extension of the settlement road 15 km east of Uruará (165N). We do not know the impact of the second conflict, although the logger was evidently successful in appropriating these lands and displacing the colonists. As can be observed by reference to Figure 8, the route deviates considerably from a straight line as it gains distance from the Transamazon Highway. Colonist occupation of distant lands would probably have imposed costly constraints on road construction had they insisted on replication of the settlement geometry closer to the Transamazon Highway. Presumably, the road builder's desire to reach the Tutuí River outweighed interest in potential revenues obtainable from colonization.

A final limitation is our assumption about the uniform spatial distribution of trees, which transforms the longest into the optimal route for the destination-indeterminate case. Imposing empirical tree distributions onto the cumulative least-cost surface would represent a considerable improvement, particularly for extensions of fishbone networks far from main highways, in parts of the landscape less desirable to colonists because of transportation costs.[16]

Conclusions

This article presents a simulation approach that attempts to replicate the fishbone pattern of forest fragmentation as a function of the economic behavior of loggers, key agents of land-cover change in the region. Although our success is somewhat limited in generating the observed network, we are able to draw several conclusions that give insight into the ground-level processes at work in the region. In particular, the destination-indeterminate simulations provide evidence that profit maximization in the interest of wood extraction is probably not the primary driver of forest fragmentation in colonization frontiers. Key informant interviews suggest that, although loggers are involved in extensions of settlement roads in the study area, colonists themselves often take the initiative and pressure municipal government to act. The objective of property regularization by smallholders is the force behind much of the observed fragmentation, at least in the short- to midrun period of several decades following initial colonization. Consequently, the fishbone pattern most likely arises on the basis of multiagent interactions, in which colonists are dominant, and loggers free-ride on road construction and exploit the extraction loophole in Brazilian law that enables them to buy wood from colonists.

Our approach is more successful in identifying specific routes for the destination-determinate case. The two instances of rapid road extension beyond the boundaries of colonization appear to be consistent with cost minimization by loggers, who seek to reach rivers as part of their overall profit-maximization strategy. Understanding this strategy is key to understanding the selection of the destinations, a critical next step to modeling the road extension process in the study area, which is probably of more general significance throughout the basin. Over the long run, destination-determinate roads like the Transtutuí and the Transiriri, given their economic importance, will probably exert substantial influence on the pattern of fragmentation at a regional scale although in the study area, such effects are only incipient.[17]

Our understanding of the human drivers of deforestation has deepened considerably in recent years, but many challenges remain in knowing how forest clearance is articulated in space. This is an important issue, given that the spatial patterns of clearing strongly affect ecological processes and conditions and, by implication, biodiversity. While ecologists have paid considerable attention to the environmental impacts of forest-fragmentation patterns attending the clearance of tropical forests, social scientists have not been so quick to provide insight into how the fragmentation patterns arise in the first place. This article provides an initial attempt to do so for an old colonization frontier in the Amazon basin.

We argue that road building by local agents is the primary proximate cause of the patterns of forest loss and that loggers, together with colonists, are the primary lower-order road builders in the Amazon basin. This motivates our focus on loggers as spatial agents and the use of GIS software to model their spatial decision-making processes. Although our results are only partially successful, they call attention to the role of multiple agents in the landscape and thereby provide insight into a specific form of forest fragmentation observed throughout the basin. Additional work, both theoretical and empirical, is needed to better understand the manner in which these agents interact and also how specific destinations are chosen as part of a profit-maximization strategy. Improving the GIS approach on these grounds could provide powerful methodology for answering spatial questions about the patterns of forest loss, so important to the biodiversity issue.

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Appendix

Part 1: Indeterminate Roads

Assume the sawmill output is governed by a Cobb-Douglas production function as:

$$Y = AK_1^{\alpha}T^{\beta}L^{\gamma} \tag{1}$$

where K_1 is the amount of capital used in the sawmill (immobile capital), T is the amount of roundwood input to production, and L is labor input. Y represents marketed sawmill output such as boards, plywood, and veneer. To simplify the exposition, we take the extraction of roundwood (T) as a Cobb-Douglas function depending only on capital, in this case mobile capital (K_2):

$$T = BK_2^{\theta} e^{\mu} \tag{2}$$

where μ is a random disturbance representing uncertainties regarding the search for wood. Substituting (1) into (2), defining $C \equiv AB^{\beta}$ and assuming $\theta = 1$ (constant returns to scale in roundwood production) we obtain the total revenue function:

$$R = pCK_1^{\alpha}K_2^{\beta}L^{\gamma}e^{\mu\beta} \quad \alpha, \beta, \theta > 0$$

where p is the price of processed timber. The random error μ is taken to be normally distributed, leading to a multiplicative, lognormally distributed error term $\exp(\mu\beta)$. Given perfect competition in product and factor markets and independence of the disturbance, the expected total revenue becomes (Feldstein 1971):

$$E[R] = pCK_1^{\alpha}K_2^{\beta}L^{\gamma}e^{\frac{1}{2}\beta^2\sigma}$$

where σ is $E[\mu^2]$, or the variance of the production function disturbance μ. The cost function can be defined as:

$$r(K_1 + K_2) + wL = F$$

where r is the price of capital, w is wage rate, and F is the financial constraint faced by the firm. We take the firm's objective to be the maximization of *expected* profits subject to this constraint, a problem that can be solved through the technique of Lagrangian maximization.

$$\max_{K_1,K_2,L} \Im = pcK_1^{\alpha}K_2^{\beta}L^{\gamma}e^{\frac{1}{2}\beta^2\sigma} + \lambda[F - r(K_1 + K_2) - wL]$$

where λ is the Lagrangian multiplier. The first-order conditions are:

$$\frac{\partial \Im}{\partial K_1} = \alpha pCK_1^{\alpha-1}K_2^{\beta}L^{\gamma}e^{\frac{1}{2}\beta^2\sigma} - \lambda r = 0 \tag{A1}$$

$$\frac{\partial \Im}{\partial K_2} = \beta pCK_1^{\alpha}K_2^{\beta-1}L^{\gamma}e^{\frac{1}{2}\beta^2\sigma} - \lambda r = 0 \tag{A2}$$

$$\frac{\partial \Im}{\partial L} = \gamma pCK_1^{\alpha}K_2^{\beta}L^{\gamma-1}e^{\frac{1}{2}\beta^2\sigma} - \lambda w = 0 \tag{A3}$$

$$\frac{\partial \Im}{\partial \lambda} = F - r(K_1 + K_2) - wL = 0 \tag{A4}$$

Combining (A1) and (A2), we get:

$$K_2 = \frac{\beta}{\alpha}K_1 \tag{A5}$$

Likewise, combining (A1) and (A3), we obtain:

$$L = \frac{\gamma r}{\alpha w}K_1 \tag{A6}$$

Equations (A5) and (A6) are the usual expansion path for a firm with Cobb-Douglas technology given constant factor prices. Substituting (A5) and (A6) into (A4) and solving initially for K_1 and later for K_2 and L, we obtain the optimal amount of inputs:

$$K_1^* = \frac{\alpha F}{r[\alpha + \beta + \gamma]}$$

$$K_2^* = \frac{\beta F}{r[\alpha + \beta + \gamma]}$$

$$L^* = \frac{\gamma F}{w[\alpha + \beta + \gamma]}$$

If we assume constant returns to scale, then $\alpha+\beta+\gamma = 1$, and the factor demand functions simplify to the ratio of the technological parameters and the factor prices, multiplied by the constraint.

Given input prices (r,w) and technological parameters (α,β,θ,γ), the logger will devote K_1^* units of capital to the processing phase and K_2^* to the extraction phase. Note that this factor allocation does not depend on the uncertainty in roundwood production but only on the technological parameters and financial constraint. The result gives the amount of capital that needs to be allocated to labor, and to mobile and to immobile capital. Now that the amount of mobile capital is known, the spatial problem can be addressed, since this is the constraint c that bounds the search in the GIS optimization problem.

Part 2: Determinate Roads

Suppose a logger currently transports products from sawmill to a distant market, using a preexisting route. Let associated transport costs be TC_1. Also suppose that the current state of operations is profitable, which implies that $\pi_1 = R - PC - TC_1 > 0$, where R is the revenue and PC are production costs, both of which are independent of distance. Since the logger has mobile capital available to build new routes, s/he will search for possible alternative routes to bring products to market. Given imperfect information about all possible routes, s/he will examine a finite set of possible routes $i = 2, \ldots, N$ and will build the route i that maximizes profits, or $\pi^* = R - PC - TC^*$, where $TC^* = \min(TC_i)$. This is necessarily a better option because $\pi^* > \pi_1$ as long as $TC^* < TC_1$. Therefore, profit maximization involves identification of the cost-minimum route.

Notes

1. Legal Amazônia consists of Acre, Amazonas, Amapá, Pará, Rondônia, Roraima, Tocantins, and Mato Grosso states and part of Maranhão state, and its area is 5.03 million km.[2]

2. A *Projeto de Assentamento* is a government-sanctioned area of smallholder colonization that typically fragments the landscape in accordance with early schemes by INCRA, which allowed for 100 ha holdings (400 × 2,500 m) and road spurs to provide access every 5 km.
3. *O Liberal*, Sunday, 11 January 2004. Most of the wood exploited is illegal. Of the approximately 11 m^3 exploited, less than 3 m^3 have been authorized by the Brazilian environmental agency, IBAMA
4. Accuracy-assessment metrics exists for two-dimensional spaces (e.g., Pontius 2000; Walker 2003a). Our case would require metrics, based on one dimension, to reflect arc intersections.
5. Indeed, routing problems date back to Euler (1707–1783) and Fermat (1601–1665). The latter formulated the problem of finding the point (known as Fermat point) such that the sum of the distance from this point to the vertices of a triangle is minimum, which is the three-point version of the Euclidean Steiner tree problem.
6. Tomlin (1990) recognized this problem in his book and dealt with it by artificially decreasing the cost of transportation on the most-used road segments. In other words, he "burned in" the potential roads to decrease the cost-elevation grid to ensure that, in subsequent iterations, more timber would be transported on fewer road segments. Unfortunately, this procedure works only if we have a relatively rugged cumulative cost surface. If the cost surface has the same traversing cost in all cells (i.e., the 3D representation of the cumulative cost is a perfect bowl with the origin in the center), the Tomlin solution is a straight line linking each tree to the origin, which is clearly not a global optimum.
7. We consider it to be equally expensive to traverse a point on a river located either upstream or downstream in the study area. This assumption is reasonable for the rivers in question. For example, the Uruará River requires a substantial bridge far upstream, below the Transamazon Highway.
8. Although this article focuses on the landscape phenomenon of the forest fragmentation associated with the expansion of road networks, the immediate environmental impacts of logging can be severe. Logging operations are very selective and take only five to ten trees per hectare, but the extraction process damages many nearby trees. For each tree extracted, twenty-seven others are damaged, and the surrounding canopy is reduced by 40 to 80 percent (Uhl et al. 1997). Such degradation increases forest vulnerability to fire and liana growth (Holdsworth and Uhl 1997; Gerwing 2002), which can ultimately lead to a complete change in species composition and in land cover (Cochrane and Schulze 1999). Intensive logging, such as practiced in Indonesia, can be even more damaging (Curran et al. 2004).
9. In reality, since the cumulative cost values are float numbers, we selected the grid cell with values greater than 10,000 and smaller than 10,010.
10. We assigned a friction value of 120 to the cells inside the protected area. We chose this value because it is slightly above the maximum slope value of 112. Since the friction value was defined as slope in percentage terms, a value of 120 is equivalent to a 50° slope, which effectively makes road construction too costly.
11. We also assigned a value of 120 for the cells inside these potentially floodable areas.
12. This detour from the optimal route arose due to a conflict between a colonist, whose lands were on the best route, and the road builder, who owns one of the two largest sawmills in town. The logger wanted to construct a detour through the colonist's lands to avoid a low-drainage spot and offered money. The colonist did not accept the offer, and the road builder opted for the present path, which originates in town and traverses two settlement roads to merge with its original, optimal path.
13. Indeed, other parts of the Amazon have experienced initial penetration by loggers, with subsequent occupation by smallholders.
14. According to the Forestry Code of 1965, both large and small properties were allowed to deforest up to 50 percent. In 1996, a new regulation lowered this percentage to 20 percent for large properties but maintained the original percentage for small farmers (Provisory Measure 1511 from 25 July 1996).
15. We did address certain institutional constraints, such as the inviolability of Indigenous Reserves. To accomplish this, we resorted to using a high friction value in the simulations. This has the effect of making passage too costly, in economic terms. Walker (2001) conceptualized environmental protection in south Florida in a similar fashion. Moral issues aside, profit maximizers resist incursions into unused public lands—and appropriation of public resources—if the cost of doing so, through legal sanction, exceeds the benefit.
16. Field interviews suggest that such information, particularly at regional scale, could help to shape some of the destination choices made by well-capitalized loggers, like those who opened the Transiriri and Transtutuí. Model simulations that fully endogenize such points on the landscape await the incorporation of complete data, including tree distributions.
17. Key informant interviews in the summer of 2004 suggest that such destinations were chosen in order to expand export opportunities, subject to physical characteristics of the landscape. For instance, the Tutuí River is only navigable beyond the junction with the Uruará River, where the destination of the Transtutuí is supposedly located. Thus, in order to export sawn wood to the mouth of the Amazon River, the logger needed to reach this point by road. In addition, he wanted to reach a plateau between the Uruará and Tutuí Rivers as part of a strategy to diversify his business into soybean production. In the Transiriri case, a good explanation for the destination is yet to be determined.

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Correspondence: Department of Geography, Michigan State University, East Lansing, MI 48824, e-mail: arimaeug@msu.edu (Arima); Department of Geography, Michigan State University, East Lansing, MI 48824, e-mail: rwalker@msu.edu (Walker); Department of Sociology, University of Florida, Gainesville, FL 32611–7330, e-mail: sperz@soc.ufl.edu (Perz); Department of Geography, Michigan State University, East Lansing, MI 48824, e-mail: caldasma@msu.edu (Caldas).