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BEHAVIORAL AND COMPUTATIONAL
MODELS OF ROAD BUILDING IN THE
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EUGENIO YATSUDA ARIMA

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Ph.D. degree in GEOGRAPHY

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LOGGERS AND FOREST FRAGMENTATION: BEHAVIORAL AND COMPUTATIONAL MODELS OF ROAD BUILDING IN THE AMAZON BASIN

By

Eugenio Yatsuda Arima

A DISSERTATION

Submitted to
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ABSTRACT

LOGGERS AND FOREST FRAGMENTATION: BEHAVIORAL AND COMPUTATIONAL MODELS OF ROAD BUILDING IN THE AMAZON BASIN

By

Eugenio Yatsuda Arima

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 dissertation is to consider emergent patterns of road networks, the initial proximate cause of fragmentation in tropical forest frontiers. Specifically, I address the road building processes of loggers, who are very active in the Amazonian landscape. To this end, I develop an explanation of road expansions combining a theoretical model of economic behavior with GIS software in order to mimic the spatial decisions of road builders. I simulate three types of road extensions commonly found in the Amazon basin. The first two types are roads that spur off the initial infrastructure constructed by the government in official settlement areas such as the Transamazon and are related to the fishbone pattern of fragmentation. The third type of roads are the skid trail networks, built to access individual trees. I developed several raster based GIS algorithms to model each type of

road. Although my simulation results are only partially successful, they call the 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.

To Norma, for her unlimited support and love. This degree belongs to her. To my parents and my brother, who always encouraged me to pursue my Ph.D.

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Many people have helped me get this far. First and foremost, I would like to thank my advisor, Bob Walker, who suggested this research topic and convinced me I could get an interesting dissertation. I also thank him for all the support from the first day I arrived in East Lansing until today. Several people have asked me how to choose an advisor. After this experience, I know the answer: look for someone who is genuinely interested in your success and also someone who you can call friend.

My committee also played an important role. Jeffrey Wooldridge, Ashton Shortridge, and Antoinette Winklerprins were the best instructors I ever had and am thankful for what I learned from their incredible knowledge pool. They also provided important constructive criticism during the whole dissertation process.

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Stephen Aldrich provided the official roads' dataset used in Chapter 2, Cynthia Simmons provided the vector data file used in figure 1.2., and Jimmy Grogan, Franklin Pantoja, Edson Vidal, and Dennis Vale from Imazon provided the dataset used in Chapter 4. Thank you all for sharing data.

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This dissertation was typed in LaTeX using a macro template, created by Brian J. Olson (Department of Mechanical Engineering at Michigan State University), that adheres to the formatting rules of MSU.

In my first three years in graduate school, I was a research assistant for the project 'Socio-spatial processes of road extension and forest fragmentation in the Amazon' funded by the National Science Foundation and for the project 'A basin-scale econometric model for projecting future Amazonian landscapes' funded by NASA-LBA.

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LIST OF ABBREVIATIONS

BNDES	Banco Nacional de Desenvolvimento Econômico e Social
DEM	Digital Elevation Model
ESRI	Environmental Systems Research Institute
ETM^+	Enhanced Thematic Mapper Plus
GIS	Geographic Information System
IBAMA	Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis
IBGE	Instituto Brasileiro de Geografia e Estatística
IDL	Interactive Data Language
IMAZON	Instituto do Homem e Meio Ambiente da Amazônia
INCRA	Instituto Nacional de Colonização e Reforma Agrária
INPE	Instituto Nacional de Pesquisas Espaciais
LCCHS	Least Cost Convex Hull Set
MST(P)	Minimum Steiner Tree (Problem)
MTAP	Multiple Target Access Problem
NASA	National Aeronautics and Space Administration
PDA	Plano de Desenvolvimento da Amazônia
PIC	Plano Integrado de Colonização
PIN	Plano de Integração Nacional
SPVEA	Superintendência do Plano de Valorização Econômica da Amazônia
SRTM	Shuttle Radar Topography Mission
TIN	Triangulated Irregular Network
USGS	United States Geological Survey
UTM	Universal Traverse Mercator

CHAPTER 1

Introduction

Global environmental change resulting from anthropogenic impacts on land cover and land use is widely recognized as an important issue (Ojima, Galvin, & Turner, 1994). One such change, tropical deforestation, has been of great concern to scientists and the public at large because of its possible effects on climate and biodiversity (Steffen & Tyson, 2001; Jenkins, 2004). A large literature on the issue has emerged in recent decades, and geographers and social scientists have made great strides to understand the factors that motivate humans to clear forested lands in tropical regions (Lambin, Geist, & 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% of deforestation has occurred within a 100 km buffer of roads built by the federal government (Alves, 2002). The extension of transportation infrastructure into tropical frontiers, especially roads, induces in-migration, 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.

Road construction has usually been associated with governmental venture. However, roads built by the private sector, often loggers, have been playing an important role in the dynamics of the frontier expansion in the Amazon, the largest tropical forest remaining in the world (Verissimo et al., 1995). Previous research on the Amazon has yet to systematically document the link between the socioeconomic-spatial processes driving logging road construction and the geometric signature of road networks on landscapes and ecosystems. On the one hand, the ecology and remote sensing literature approaches the issue of roads as a purely spatial phenomenon, and emphasizes the ensuing environmental impacts of habitat fragmentation without attending to the social processes driving road construction in the first place. Social scientists, on the other hand, have only addressed the aggregate impact of road construction on deforestation, a rather blunt measure given the important ecological implications of various spatial geometries of forest fragmentation. As a result, a gap remains between the knowledge bases of ecological and social scientists concerned about links between roads and environmental change.

The expansion of the road network in the Brazilian Amazon basin, beyond the initial development highways constructed by Federal and State governments, is mainly driven by the logging sector interacting with both planned and spontaneous colonization. Thus, to understand the processes of fragmentation currently affecting the Amazon basin, it is necessary to understand the road building activities of loggers. My dissertation is aimed specifically at these agents of land-cover change. This research aims to provide (1) insight into logger road building activities and (2) a simulation approach to predict the spatial outcomes of their economic behavior. The results of this dissertation shed light on the spatial pattern of road building, which has profound implications for biodiversity conservation and sustainable development of the region.

This introductory chapter is organized as follows. I first provide an overview of the ecological importance of forest fragmentation patterns to the conservation of biological diversity in tropical forests. Then, I examine the social science literature on the relationship between roads and deforestation. The goal of this literature review is to show that social scientists have not provided an explanation on how forest fragmentation patterns emerge, which is a critical piece of information to landscape ecologists, and environmental scientists more generally. I conclude by explaining the overall objectives of the dissertation and introducing the study area.

1.1 The Environment and Roads in Forest Frontiers

1.1.1 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 (W. F. Laurance, 1998; Schelhas & Greenber, 1996; Reid & Bowles, 1997).

Roads can impact biodiversity directly or indirectly. The direct impact is related to the physical barrier imposed on the movement of certain species. For example, Laurance et al. (2004) showed that roads significantly reduced the movement of understory forest-dependent insectivorous birds and that certain species tended to avoid edge-affected habitats near roads and road clearings themselves. Another concern for ecologists is the large number of animals killed by traffic. In this regard, many studies have been conducted in developed countries, where the road density is very high, to calculate road kills.[1] I have not found assessments of animals killed on roads in the Amazon but based on my personal, qualitative observations, the number of reptiles (snakes, lizards), mammals, and birds killed by vehicles is significant. A dead animal in an Amazonian road stretch is a very frequent event to observe, particularly far from large population centers.

More important than the direct impacts of roads on tropical forests are the indirect impacts of roads as determinants of the ensuing fragmentation pattern caused by deforestation. This indirect impact is of most concern to ecologists because of its greater effect on biodiversity. When continuous forested landscapes are converted to non-forest covers, the consequences for biodiversity can be severe. With very few exceptions, tropical rain forest fragmentation leads to local loss of species (Turner, 1996).

[1] The number of deer killed annually on roads in the U.S. ranges from 720,000 to 1.5 million (Forman, 2003). In Montana, Fowle (1990) recorded 205 turtles killed during a four month summer period on a 7.2 km road segment. In Australia, 5.5 million reptiles and frogs are estimated to be killed annually by traffic (Ehmann & Cogger, 1985).

Forest fragmentation alters vegetative structure and available habitats for many species (Aldrich & Hamrick, 1998; W. F. Laurance, 1998; Scariot, 1999; W. F. Laurance, Perez-Salicrup, et al., 2001). Fragmentation may modify or even curtail vegetative regeneration (Lovejoy et al., 1986) through heightened tree mortality (Ferreira & Laurance, 1997; W. F. Laurance et al., 2000) and reduced seedling recruitment (Benitez-Malvido, 1998). Such changes result in biomass collapse (W. F. 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 & Kauffman, 1990; Cochrane & Schulze, 1999; Nepstad, Moreira, & Alencar, 1999). Thus, the risk of forest fire is linked to roads and forest fragmentation (Holdsworth & Uhl, 1997; Nepstad et al., 2001).

The many ecological impacts of forest fragmentation depend on the size and spatial organization of the fragments themselves. Studies have shown that (1) microclimate, soil moisture, wind speed, and luminosity, are strongly correlated with distance to fragment boundaries, and that (2) these factors determine the likelihood of tree survival and the presence of animals (Murcia, 1995). This phenomenon is commonly known in the landscape ecology literature as the 'edge effect.' Smaller fragments, and those with longer perimeters relative to area, tend to exhibit greater ecological disturbance than large fragments with extensive interiors (W. F. Laurance et al., 1997). In a study conducted in forested areas in southern Ghana, Hill (2003) found that large forest fragments contained the greatest number of tree species and the highest proportion of rare tree species. On the other hand, very small fragments lose most of their vertebrate fauna and are floristically completely different than an expansive forested landscape (Turner, 1996). Rates of tree deaths can be up to eight times higher in edge than non-edge sites (Ferreira & Laurance, 1997).

1.1.2 Roads and the Social Science Literature

Social scientists have helped ecologists understand the drivers of landscape change, and in the case of the Amazon, the underlying causes of deforestation (Kaimowitz & Angelsen, 1998; Geist & Lambin, 2001). There are by now a multitude of studies that attempt to understand why humans convert forests into non-forested land uses. In the 1980s and early 1990s, social scientists implemented statistical and computable general equilibrium models to understand why certain countries or regions cut down their forests more rapidly than others. Some of the explanations included economic and population growth and density, exchange rates, interest rates, debt level, political and institutional factors, and density of roads (Allen & Barnes, 1985; Rudel, 1989; Deacon, 1994, 1995; Brown & Pearce, 1994; Reis & Guzmán, 1994; Cropper, Griffiths, & Mani, 1996). However, such models employ spatially aggregated measures of roads and forest loss for municipalities and other administrative units. This leaves us with blunt measures of road networks and land cover change that contain no information about road network architecture or the spatial geometry of forest fragmentation. In addition, aggregate models generally observe the state of roads and land cover using cross-sectional data, which hinders inferences about landscape dynamics over time.

More recently, with the advent of GIS technology, social scientists have implemented the so called 'spatially explicit model', which represents an advance beyond models based on aggregate land cover data (Walker, 2004). Typically, spatially explicit models use satellite image pixels as units of observation, and estimate the probability of land cover change in pixels with different socioeconomic and locational characteristics (Ludeke, Maggio, & Reid, 1990; Bockstael, 1996; Chomitz & Gray, 1996; Nelson & Hellerstein, 1997). The refined spatial resolution of the data allows for estimation of the effects of roads on the probability of forest being converted, as well as mapping of modeled probabilities. Spatially explicit models of land cover change reveal significant road impacts, and maps of modeled probabilities often indicate fragmentation as a result of the road network. Moreover, spatially explicit models using data from multiple points in time have produced estimation results that have been used to project trajectories of future landscape evolution (Mertens & Lambin, 2000).

Although spatially explicit models represent a significant advance, they often assume a limited concept of the roles played by roads in land cover change. All roads are presumed to be built by governments in the pursuit of regional development. Hence, all subsequent settlement, forest clearing, and fragmentation is a consequence of this initial infrastructure. While such a presumption no doubt holds in many instances, it only reflects part of the story, and overlooks the role of other non-government agents in maintaining and especially in extending roads. Indeed, once settlement has occurred in response to the state's road building efforts, local agents in newly opened regions often take it upon themselves to amplify the road network following initial efforts at land cover change. At the local level, then, road building is both a cause and a consequence of the processes of colonization and development, and not merely an exogenous factor.

1.1.3 Official and Unofficial Roads

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 US economy, and roads and transportation more generally have often been implemented in advance of demand for transportation services in frontier areas (Friedmann & Stuckey, 1973). The expansion of road infrastructure in the Brazilian Amazon basin is no exception, and during the 1970s highway construction was a hallmark of state-led development efforts in the region (Goodland & 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 & Cockburn, 1989; Skole & Tucker, 1993; Walker, 2004).

Government investment in transportation infrastructure is important to regional development, but it only reflects part of the story, and 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, 2003a). One implication is that the mechanisms driving road construction are scale-dependent (Gibson, Ostrom, & Ahn, 2000; Wood & Porro, 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 & Gillis, 1988; Kummer & Turner II, 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, which 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, roads built by private agents are the main proximate cause of fragmentation by virtue of their density. Lineal distance of the federal road system, as of 1993, covered 18,177 kilometers, or a density of 0.004 km of road per square kilometer of the Legal Amazonia (Figure 1.1). This stands in sharp contrast with the density of 0.062 km of private road per square kilometer in the study area along the Transamazon Highway between Altamira and Rurópolis (Figure 1.2). Clearly, roads built by local citizens represent a much great proximate threat to the integrity of Amazonian forests than the sparse federal system.

Remote sensing scientists have made progress to better understand such lower order, private, unofficial roads. They have been able to classify, identify, and map them using new remote sensing techniques, such as linear spectral mixture models, that improved their ability to detect logging roads from satellite images in several different environments, when compared to visual interpretation and maximum likelihood methods (Souza Jr. & Barreto, 2000; Monteiro, Souza, & Barreto, 2003). Likewise, new sensors and higher spatial resolution satellite images (e.g. IKONOS) can enhance the ability to detect logging roads (Asner et al., 2002; Souza Jr & Roberts, 2005). The emphasis of most of the related remote sensing research literature has been on road signature detection

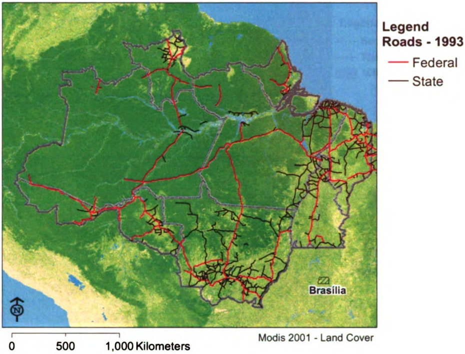

Figure 1.1. Federal and State Road System in the Brazilian Amazon

and forest degradation assessment. Social scientists have not profited greatly from the advances in remote sensing in efforts to develop theoretical models or to empirically understand how such roads are built.

This brief review of the literature suggests three conclusions that motivate my dissertation research. First, the pattern of forest fragmentation is an important piece of information of great interest to landscape ecologists and environmental scientists more generally. The geometric shape of forest patches and their isolation or contiguity, resulting from deforestation processes, is vital to the viability of many plant and

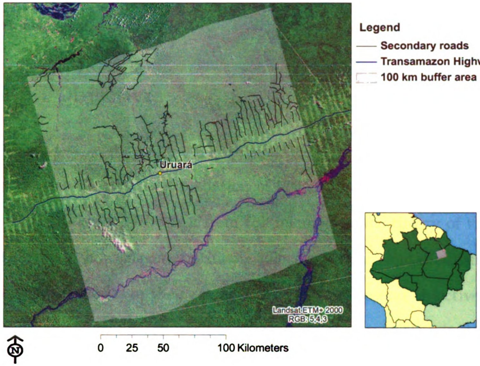

Figure 1.2. Unofficial roads in a 100 km buffer along the Transamazon Highway
Unofficial roads data provided by Simmons (2002)

animal populations. Second, roads play an important role in determining overall levels of deforestation and resulting landscape patterns, and third, social scientists, although aware of the causes of deforestation, have not fully explained how deforestation patterns are generated in the first place. Hence, understanding the underlying drivers of forest fragmentation requires comprehension of the spatial architecture of the road networks that create the geometry of forest fragments. A key objective of the dissertation is to do this for an important class of Amazonian roads, namely those built by private citizens, mainly loggers, in frontier settlements.

1.2 Objectives

I have two overarching objectives in this dissertation. The first is to provide a theoretical explanation of loggers' road construction behavior. To this end, I borrow from the microeconomic theory of the firm to explain how loggers optimally allocate scarce capital resources to maximize profits in their search for wood. The second objective is operational. The theory itself is abstract in the sense that it does not deliver a spatial product. Since I am interested in studying spatial patterns of road networks, I embed the theoretical model in a GIS application to produce spatial outcomes. Specifically, I modify currently available GIS algorithms to mimic the construction of three different types of logging roads.

The dissertation is organized as follows. In the second chapter, I provide a brief description of the evolution of the transportation system in the Brazilian Amazon and the relevant transportation geography and location analysis literature on patterns formed by line segments, or network patterns, and ensuing deforestation patterns. In Chapter 3, I develop a formal theoretical statement of loggers' road building behavior and simulate the construction of two types of logging roads, which I call *destination indeterminate* and *destination determinate.* I also discuss the local political ecology that is relevant to the emergence of roads' routes. In Chapter 4, I develop a new algorithm to model the construction of a third type of logging road, which I refer to as *skid logging trails.* Since this algorithm is based on a well known problem in mathematics and computer science, i.e. the Steiner tree problem, I first formally describe the problem using terminology from graph theory applied in a GIS context. Chapter 5 concludes the dissertation by highlighting the major findings and possible future research questions.

1.3 Study Area

The Amazon Basin is the largest river basin in the world with an area of approximately 6.4 million km^2 extending over the territory of nine countries: Brazil, Peru, Bolivia, Colombia, Ecuador, Venezuela, Guyana, Suriname, and French Guyana. Approximately 63% of the basin, or 4.0 million km^2, lies within Brazilian territory (Conservation International, 2004)(Figure 1.3).

Several geographic terminologies are available to describe the Brazilian Amazon. 'Classic Amazonia' encompasses the original northern states of Amapá, Acre, Roraima, Rondônia, Amazonas, and Pará.[2] In

[2] Prior to 1953, only Pará, Amazonas, and Mato Grosso were states under Brazil's republic system. From the early colonial years until 1943, Amapá, Rondônia, and Roraima were all part of one of those four states. During World War II, they were dismembered and became territories

1953, the Brazilian government created the *Superintendência do Plano de Valorização Econômica da Amazônia* (SPVEA) or the Economic Improvement Plan Superintendence, to oversees the application of 3% of total federal taxes over 20 years to develop the north (Mahar, 1978).[3] At the same time, a new political nomenclature was implemented to serve the economic development purposes of this plan. The new political entity, known as the 'Legal Brazilian Amazon', included all the 'classic Amazonia' plus Mato Grosso state north of the parallel 16°S, Tocantins north of parallel 13°S, and part of Maranhão west of the 44°W meridian.[4] All businesses, either industrial or agricultural, located in states belonging to the Legal Brazilian Amazon were eligible for a series of financial benefits including tax breaks, subsidized credit, and land acquisition on very favorable terms.[5] The Legal Amazon extends over 59% of Brazil's territory or approximately 5.0 million km^2 of which 76% was originally forested and the remainder mostly covered by savanna-like vegetation (Lentini, Verissimo, & Sobral, 2003).

administered by the federal government. Later, each territory became a state. Rondônia (previously known as Guaporé Territory and later Rondônia Territory) became a state in 1982 and was originally part of Amazonas (northern half) and Mato Grosso (southern half). Amapá and Roraima territories, the latter previously known as Rio Branco Territory, became states in 1988, when a democratically elected congress wrote a new constitution. Acre belonged to Bolivia until 1903, when Brazil gained possession of this territory under the Petrópolis Treaty signed between the two countries, and became a state in 1962.

[3] Law 1806 from January 6 1953.

[4] Mato Grosso belongs to the center-west region and was part of a larger state that was split into two in 1977: Mato Grosso itself and Mato Grosso do Sul. Tocantins, now incorporated into the northern region, was part of Goiás state (center-west region) and was also dismembered in 1988. Maranhão is part of the northeast region.

[5] For a good review of those policies and impact on deforestation, development, and social conflict

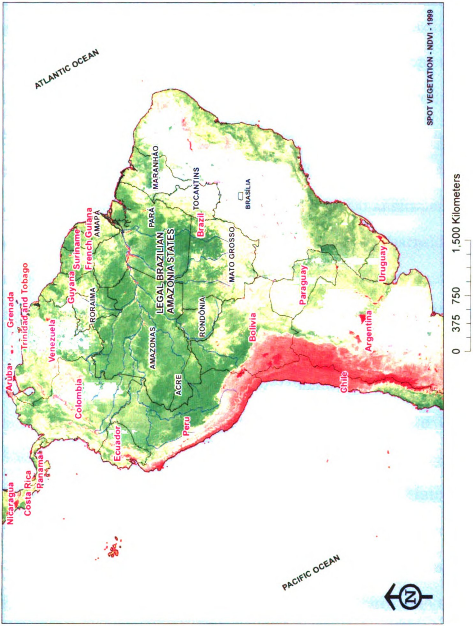

Figure 1.3. The Amazon Region

please refer to Mahar (1979) and Schmink and Wood (1984) among others.

Unless otherwise specified, I use throughout the dissertation the generic term *Amazon* or *Amazonia* to refer to the Legal Brazilian Amazon region. This region is the second largest producer of tropical timber in the world, second only to Indonesia, with an annual production of approximately 30 million m^3 (Lentini et al., 2003). Brazil as a whole is also extremely rich in biodiversity, much of it concentrated in the Amazon and Atlantic forests, with approximately 55,000 angiosperm plant, 428 mammal, 1,622 bird, and 516 amphibian species (Fearnside, 1999). Invertebrates are even more numerous; 1,080 species were found in just four sites near Manaus, capital of the state of Amazonas (Fearnside, 1999). Deforestation rates are also the highest among tropical forested countries. Deforestation peaked in 1994/1995 when almost 30,000 km^2 were converted. In the subsequent years, rates dropped to 13-18,000 km^2 $year^{-1}$. However, in the last two years, rates have increased again and been consistently above 23,000 km^2 (Table 1.1).[6] Mato Grosso, Pará, and Rondônia present the highest rates of deforestation. These are also states with a significant logging industry (Lentini et al., 2003). Despite these high annual rates of deforestation, 'only' about 17% of the region's forests have been lost because of the gigantic size of the Amazon (INPE, 2005).[7]

[6] In May 2005, the Brazilian government announced that during the year 2003/2004, 26,130 km^2 were deforested in the Amazon, the second highest rate in history. This number was estimated based on satellite imagery analysis.

[7] Indeed, the Amazon region is not classified as a hot spot for biological conservation by Myers

The Brazilian Amazon is a unique setting, with high biodiversity and a rapidly expanding regional economy based on resource exploitation. Thus, it constitutes an ideal location to study how logging roads affect spatial patterns of deforestation. I have chosen two localities in the Amazon where I focus my dissertation research. In Chapter 3, I consider destination determinate and destination indeterminate logging roads in the town of Uruará, along the Transamazon Highway in Pará state (Figure 1.4). In Chapter 4, I use data collected from a logging extraction site in Acre state, located in the western Amazonia, to model skid trails.

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at al. (2000) because the ecosystem as a whole is not yet in the verge of collapse.

Table 1.1. Deforestation rates in the Brazilian Amazon ($km^2\ year^{-1}$)

	STATES									
YEAR	Acre	Amapá	Amazonas	Maranhão	Mato Grosso	Pará	Rondônia	Roraima	Tocantins	**TOTAL**
77/88†	620	60	1,510	2,450	5,140	6,990	2,340	290	1,650	21,050
88/89	540	130	1,180	1,420	5,960	5,750	1,430	630	730	17,770
89/90	550	250	520	1,100	4,020	4,890	1,670	150	580	13,730
90/91	380	410	980	670	2,840	3,780	1,110	420	440	11,030
91/92	400	36	799	1,135	4,674	3,787	2,265	281	409	13,786
92/94‡	482	0	370	372	6,220	4,284	2,595	240	333	14,896
94/95	1,208	9	2,114	1,745	10,391	7,845	4,730	220	797	29,059
95/96	433	0	1,023	1,061	6,543	6,135	2,432	214	320	18,161
96/97	358	18	589	409	5,271	4,139	1,986	184	273	13,227
97/98	536	30	670	1,012	6,466	5,829	2,041	223	576	17,383
98/99	441	0	720	1,230	6,963	5,111	2,358	220	216	17,259
99/00	547	0	612	1,065	6,369	6,671	2,465	253	244	18,226
00/01	419	7	634	958	7,703	5,237	2,673	345	189	18,165
01/02	727	0	1,016	1,330	7,578	8,697	3,605	54	259	23,266
02/03§	549	4	797	766	10,416	7,293	3,463	326	136	23,750

†Decade mean ‡Biennium mean §Estimate

Source: INPE (2005)

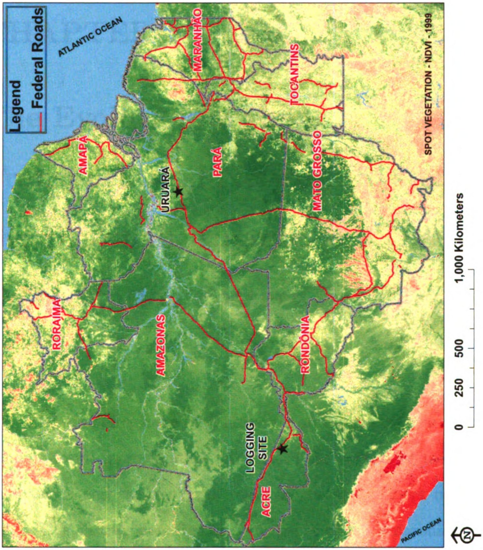


Figure 1.4. Study areas in Uruará - Pará and logging site in Acre, Brazil.

CHAPTER 2

The Evolution of the Transportation Network System in the Brazilian Amazon and Overall Deforestation Pattern

In Chapter 1, I reviewed the literature on the importance of understanding forest fragmentation patterns in the context of biodiversity conservation and the impact of roads on the environment more generally. This chapter describes the emergence of the Amazonian transportation network system. It begins by briefly describing the 'natural' transportation system formed by the immense hydrological system, with which the Amazon basin is endowed, followed by a description of the growth of the federal and state road systems in the second half of the 20^{th} century. Next, I discuss how the emergence of this transportation system compares to other cases described in the literature. Then, I describe the different spatial network patterns and how they relate to deforestation and fragmentation. The chapter concludes with the ongoing policy debate about the magnitude of the impact of roads on development and deforestation.

2.1 A Brief History of Transportation in the Amazon

Water is an important mode of transport in the Amazon region. The conformation of the Nazca and South American geologic plates and heavy rainfall created the largest river basin in the world, occupying an area over 6 million km^2, and the largest fresh water volume discharged into the ocean (214 million liters per second) (Goulding, Barthem, & Ferreira, 2003). The length of the Amazon River itself, according to the best estimates, ranges from 6,500 km to 6,800 km from its headwaters to the estuary (Goulding et al., 2003). The Amazon River, with its deep and long channel, is navigable from its mouth in the Atlantic up to Iquitos in Peru, nearly 3,500 km upriver. Three tributaries of the Amazon, the Purus, Juruá, and the Madeira rivers,

Table 2.1. Main rivers of the Amazon Basin

River	Length (km)
Amazon	6,400 - 6,800
Madeira	3,352
Juruá	3,283
Purus	3,211
Caquetá - Japurá	2,820
Ucayali	2,738
Tocantins	2,699
Negro	2,253
Xingu	2,100
Tapajós	1,992
Mamoré	1,900
Guaporé	1,749
Putamayo-Içá	1,609
Beni	1,600
Marañon	1,415
Madre de Dios	1,100
Napo	885
Branco	775
Trombetas	760

Adapted from Goulding et al. 2003

are longer than 3,000 km; five are in the 2,000 km-length class, and seven are 1,000−2,000 thousand km in extent (Table 2.1). In total, the length of these main rivers reaches 43,000 km. Although year-round navigability in some of them is constrained by rapids and waterfalls, boats are commonly utilized to transport people and goods.

The rivers in the Amazon basin have been widely used for transport for millennia. Some authors suggest that the higher densities of pre-Columbian indigenous population established along rivers was not only because of the better soils and abundant natural resources in the flood-plains but also because rivers facilitated movement of people (Denevan, 1996).[1] Epic voyages in Amazonian rivers have been documented by Europeans just after the conquest of the South American continent. Most notably was Francisco Orellana's trip downriver from Quito in Ecuador to the Atlantic ocean in February 1541. The expedition departed from Quito by land and reached the Napo river seventy days later. From this point on, Orellana's expedition proceeded eastward down to the ocean by water, where they arrived in the end of 1542 (Figure 2.1). In 1636, Pedro Teixeira did a round trip departing from Belém, founded in 1616, up to Quito. Teixeira arrived back to Belém three years later in 1639 (Bruno, 1966).

Despite its extensive hydrological network, navigability on tributaries to the north and south of the Amazon is frequently interrupted by waterfalls, particularly in places closer to the headwaters located mostly in the crystalline Guiana and Brazilian shields respectively. The existence of rapids and waterfalls to the south severely constrained economic relations with the most developed and populated part of Brazil, which stimulated the building of roads in the late 1950s. For example, the major southern tributaries of the Amazon such as the Tapajós, Xingu, and Tocantins rivers are navigable from their confluence with

[1] Archeologists, anthropologists, and geographers have also shown evidence that early pre-historic societies in the Bolivian Amazon raised mounds that served as causeways (Erickson, 2000; Denevan, 2001). Evidence also exists, throughout the Amazon basin, of canals excavated by indigenous populations (and traditional populations nowadays) that connected different water bodies to facilitate travel by water (Raffles & WinklerPrins, 2003).

the Amazon to only 280 km (near Itaituba), 236 km (near Altamira), and 250 km (near Tucuruí) upstream respectively (BNDES, 1998). The exceptions are the rivers to the west such as the Madeira, Purus, and Juruá rivers that are navigable for more than 1,100 km upstream, but their headwaters are far to the west and do not connect to southern Brazil (Figure 2.1).

In order to develop intraregional connectivity between nearby towns in the basin, several railway lines were built early in the 20^{th} century. However, no railway, such as the TransContinental or the TransSiberian railways, was built to connect the north to the south. In 1908 two short lines were constructed from Belém to Bragança (228 km stretch) and from Alcobaça to Breu Branco, a 43 km railroad was built to portage the waterfalls of Tucuruí, where a dam was later built in 1984. A third railway named The Madeira-Mamoré was built in 1911 as part of the Acre state acquisition agreement between the Brazilian and Bolivian government. This short-lived line granted the Bolivians access to the navigable portion of the Madeira River (near Porto Velho, capital of Rondônia State) and consequently access to the Atlantic Ocean (Bruno, 1966). None of these railways are currently operational (Figure 2.2 - right panel).

Until the beginning of the 1900s, costal waters provided the only route of transportation between the Amazon and the rest of the coun-

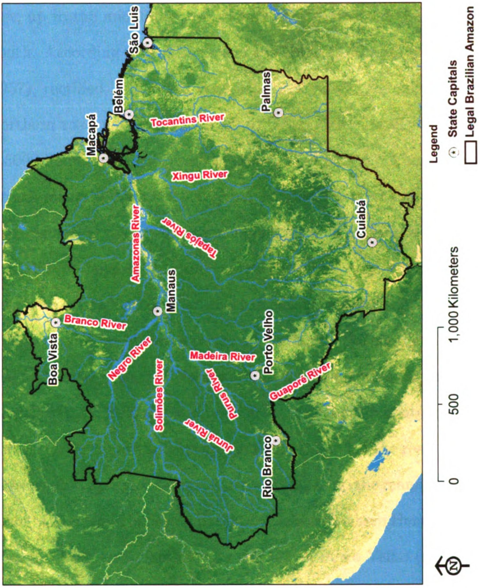


Figure 2.1. Main Rivers of the Brazilian Amazon Basin

try and abroad. During the Second World War, regular air flights began linking Amazonian state capitals to the rest of the country. Nevertheless, up to the mid 1960s not a single road connected the north to the south. According to IBGE maps of 1957 obtained in pdf format (IBGE, 1957), rectified and screen digitized in ArcGis®, the only substantial northern road network was in Mato Grosso state, with approximately 4,500 kilometers of dirt roads (Figure 2.2 - Panel A). These roads were denser near the capital Cuiabá and provided connection to Brazil's future capital, Brasília, which was inaugurated in 1960, and to São Paulo and Rio de Janeiro. In other northern states, only a handful of road networks existed, all of them short in extent, linking neighboring cities.

The second most developed road system at the time was located in the northeastern part of Pará state, in the Bragantina region, connecting the capital Belém to many cities nearby (approximately 700 km in total). Other important Amazonian roads included the road linking the present-day capital of Amapá State - Macapá - to the manganese mining town of Serra do Navio; Santarém to Belterra, where Henry Ford initiated a rubber tree plantation in the 1930s; Porto Velho (currently the capital of Rondônia) to Ariquemes, which was a rubber trading village; Boa Vista (currently the capital of Roraima) to Caracaraí, originally a cattle shipping yard on the banks of River Branco; and the city of Rio Branco (currently the capital of Acre) to a portion of River Abunã, an affluent of the Madeira River that merges with the Amazon hundreds of miles downstream (Figure 2.2 - Panel B). Even though the 1957 maps classify the segments described above as roads, it is very unlikely that they were of good quality.

The spatial distributions of the road, railway and hydrological systems show that the northern part of Brazil was isolated by land to the rest of the country until the early 1960s. Neither roads nor railways nor rivers connected northern Brazil to the more industrialized and urbanized southern portion.

Infrastructure development in the Amazon changed dramatically with the decision to relocate Brazil's capital from Rio de Janeiro to a new capital in the middle of the country. Brasília was founded in 1960 with the aim of occupying the central portion of the country and to encourage Brazilians to move from the coast to the interior. During the same period, in 1958, the construction of a 2,039 km road linking the new born capital to Belém was put in place. The Belém-Brasília highway (BR-010) was completed in 1965 and was the first connection by land from the Amazon to the southern portion of the country. This road was later paved in 1974. [2]

Policies towards the Amazon changed with the military coup in 1964. The military had national security concerns and was determined to pro-

[2] See also figure 2.7 in the end of this chapter to locate and identify each major federal road.

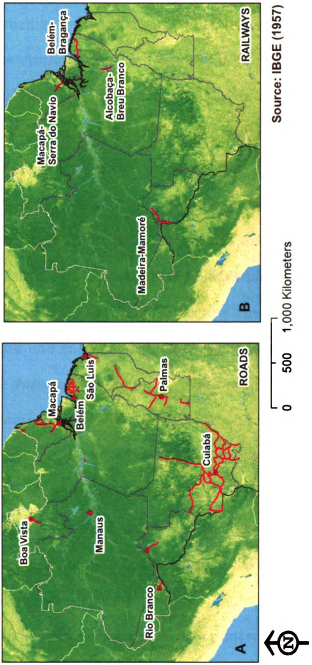


Figure 2.2. Roads (Panel A) and railways (Panel B) in the Brazilian Amazon - 1957

tect, control, and maintain Brazil's large frontier. They believed that Brazilian possession and control of a sparsely populated region such as the Amazon was vulnerable for the take, particularly when countries such as Peru, Bolivia, Colombia, and Venezuela built Andean highways and implemented policies to occupy the Amazonian lowlands in their respective countries (Moran, 1996). The discovery of oil in neighboring countries and the prospect of rich mineral deposits in the Amazon also fueled the fear of territorial disputes. Consequently, the military government implemented policies based on road building construction and subsidized credit to occupy the region. Their motto was *integrar para não entregar* or integrate not to hand over. As such, the *Programa de Integração Nacional* - National Integration Plan (PIN) was implemented. In 1967, the government began the construction of a road linking Cuiabá to Porto Velho and to Rio Branco (BR-364), which was completed in 1974 and later asphalted in 1983. A second stretch of BR-364 linking Porto Velho to Acre's capital, Rio Branco, was opened to traffic in 1975 (Sant'Anna, 1998) and reached Peru's frontier years later near the western-most point of Brazil. This road connected the whole western portion of the country to the center-south of Brazil, since Cuiabá already was connected to São Paulo and Brasília since the early 1960s (Figure 2.3).

Three other roads, Porto Velho-Manaus (BR-319), Manaus-Boa

Vista (BR-174), and Macapá-Oiapoque (BR-156) were built during this period as well. However, unlike the BR-230 (see below) and BR-364, these roads were not subject to intense colonization. Construction of BR-319 began in 1968 and was finished only in 1976. This road intersects the Transamazon at Humaitá and is, for commercial transportation purposes, not trafficable beyond this point. BR-174 and BR-156 were clearly built to protect Brazil's frontier. The first stretch of BR-174 to be built in 1975 was a 220 km segment linking the capital of Roraima, Rio Branco, to the frontier with Venezuela and to Caracaraí, 135 km south or Rio Branco. The longest part linking Caracaraí to Manaus was completed in 1977. In total, this road is 1,003 km in extent of which 730 are currently paved (Sant'Anna, 1998). Construction of BR-156 began in the early 1960s but was only completed in 1976 and links the capital of Amapá state, Macapá, to Oiapoque at the French Guiana border. For the first time in Brazil's history, the country had connection by land from north to south and from east to west.

In the beginning of the 1970s, the military government tried to balance national security concerns with social goals, namely poverty alleviation. After a visit to the severely drought-affected northeastern Brazil, the president at the time, Medici, launched a plan to redistribute lands along roads in the Amazon to small farmers from the northeast and landless farmers from the south. The *Plano de Desenvolvimento da*

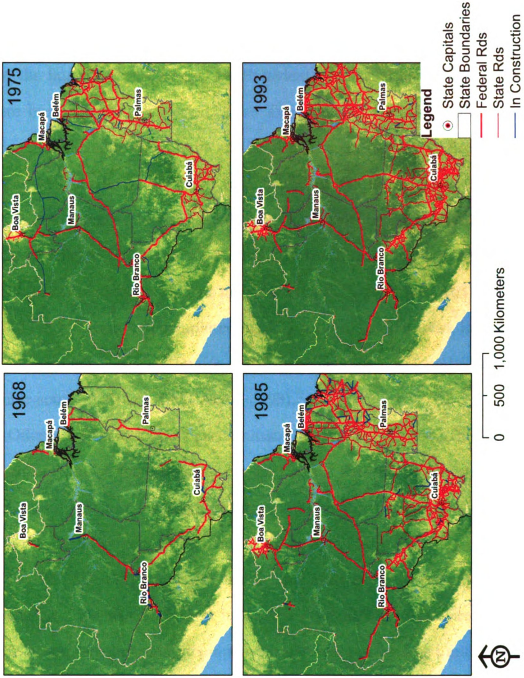


Figure 2.3. Evolution of the road system in the Brazilian Amazon from 1968 to 1993

Amazônia - Amazon Development Plan (PDA) was implemented with an objective to "bring people without land to a land without people", to use the famous phrase coined by President Medici. Two major roads were built during this period. The Transamazon Highway (BR-230) that cuts through the middle of the Amazon, in east-west direction, linked the northeast of Brazil to Itaituba in the west (completed in 1972). A second stretch of 1,000 km from Itaituba to Humaitá was later completed in 1974 (Mahar, 1978). In total, this road is more than 2,500 km in extent. A second major north-south road (BR-163) with 1,743 km in extent was completed in 1978 and linked Santarém, located at the confluence of the Tapajós and Amazonas rivers, to Cuiabá in the center-south of Brazil (Sant'Anna, 1998).

Official settlement plans predominated in two areas: along the Pará State portion of the Transamazon and along BR-364 in the state of Rondônia. In those two regions lots of 100 hectares, regularly demarcated in a grid system, were distributed to small farmers.

In 1985 the only currently operational railway was opened. The discovery of the world's largest iron ore deposit in Serra dos Carajás in 1967 prompted the mining company, which was state owned and later privatized, to build a railway from Carajás to the port of São Luís, approximately 1,000 km away.

In the 1980s the federal government refrained from building new roads owing to severe budgetary limitations following the so-called second oil shock sparked by the Iranian Revolution in 1979, the rise in interest rates on international loans, and poor macroeconomic policies, which led to hyperinflation, fiscal deficits, and erosion of public services. From 1980 to 1992, total investment as a percentage of the GDP plummeted from 24% to 14% reflecting Brazil's meager internal and external savings (Pinheiro, Giambiagi, & Gostkorzewicz, 2000). Nonetheless, several state roads were built as feeder routes linking the hinterland to the federal road system. The resulting pattern was a denser network particularly in the southern and eastern border of Legal Amazonia (Pará, Maranhão, Tocantins, and Mato Grosso states) and on the northernmost part of Brazil in Roraima state (Figure 2.3). Table 2.2 shows the evolution of both the federal and state road systems.[3] In the late 1960s there were only 484 km of state roads in the Amazon compared to the more than 12,000 km of federal roads. In the following decade, the state system was already near 13,000 km while

[3] This time series geographical dataset was created as follows by S. Aldrich (Dept. of Geography, Michigan State University). Digital maps of 1993 provided by C. Bohrer (Universidade Federal Fluminense) in Atlas GIS format were imported into ArcGIS. Then each road segment printed on the hard copy roads maps from 1968-1987 were compared with this digital file. Road features that were not present in the hard copy were deleted from the digital file. The remaining linear features in the digital file were saved as the digital version of the hard copies for the respective year. Each road segment had several attributes including the condition of the road (paved, unpaved, being constructed, bed road, planned, no information, etc.), name of the road, whether the road was state or federal, and other topological information. The original digital maps were in geographic coordinate system. In order to measure the extent of each segment, this map was projected into sinusoidal, which is an equal area projection. Simple GIS commands then calculated the length of each segment used in the analysis.

Table 2.2. Evolution of the federal and state road system (km)

Jurisdiction	YEAR 1968	1975	1985	1993
Federal	12.555	15.495	18.890	18.974
State	484	12.914	33.606	36.688
no data	0	448	21	0
TOTAL	13.039	28.857	52.517	55.663

Obs: these numbers reflect the official road network but transportation along some segments is not possible during the rainy period.

the federal increased by only 3,000 km. In the mid 1980s, the state system more than doubled in extent from the previous decade reaching 33,606 km. Meanwhile, the federal system increased by another 3,000 km totaling 18,890 km as of 1985.

In the 1990s the federal and state road system remained practically unchanged when compared to the fast growth observed in the previous decades. The federal system had an addition of less than 100 km while 3,000 km were added to the state network.

As of 1993, Mato Grosso had by far the largest road network with approximately 20,000 km. Pará had 10,000 km of roads followed by Maranhão, Tocantins Roraima, and Rondônia (Table 2.3). The road network, including both the federal and state systems, was slightly over 55,000 km of which only 28% was paved.

Table 2.3. Evolution of the road system by State (km)

STATE	YEAR							
	1968		1975		1985		1993	
	Paved	Unpaved	Paved	Unpaved	Paved	Unpaved	Paved	Unpaved
Rondônia	0	2,208	19	1,569	793	2,250	1,245	2,026
Acre	0	537	26	1,308	217	1,242	474	1,045
Amazonas	83	1,899	962	1,343	1,195	1,677	1,154	1,846
Roraima	0	284	0	1,426	41	2,926	222	2,677
Pará	495	708	787	3,698	2,220	7,514	3,010	6,889
Amapá	0	564	0	878	107	1,013	156	978
Tocantins	0	1,687	771	3,509	873	5,934	1,138	5,677
Maranhão	0	1	1,522	4,088	2,716	4,589	3,636	3,793
Mato Grosso	3	4,571	692	6,259	2,806	14,402	4,600	15,097
TOTAL	581	12,458	4,780	24,077	10,968	41,548	15,634	40,028

The pattern of transport system development observed in the Amazon resembles other patterns observed in other developing countries, which was first studied by Taaffe et al. (1963). These authors presented a typical sequence of transport development. In the first phase small ports are scattered along the sea cost as a result of colonial conquest without any connection to the interior. In the second phase, roads or railways departing from the most important ports are built and penetrate the hinterland. The third phase is characterized by the emergence of feeder roads that connect other portions of the interior to the original routes, enlarging the hinterland of the major ports. Eventually, some cities located in the interior will become centers of trade as important as the original ports. Finally, the Taaffe model predicts the emergence of major paved highways linking the most important centers of commerce. These major routes are also served by airline flights and even railways.

The Brazilian Amazon transport system development did not follow exactly the Taaffe model. Important centers of commerce in the Amazon, such as Belém and Manaus, emerged almost independently from other large cities in southern Brazil such as São Paulo and Rio de Janeiro. For historical reasons (i.e. the rubber boom) and geographical separation, the Amazonian economy was more connected to Europe than to the rest of the country. Indeed, Amazonian international trade, measured as the sum of imports and exports, was larger than the rest of the country during the rubber boom (Barham & Coomes, 1994). After the demise of the rubber economy in 1920 and the rapid industrialization of the southern part of Brazil, Amazonian cities became economically peripheral to their southern counterparts. Nonetheless, both Belém and Manaus acquired status as important centers of commerce prior to substantial linkages to the south of the country, or the development of much of the transportation system (Browder & Godfrey, 1997). Therefore, the expansion of the road system connecting the south to the north cannot be regarded as the construction of 'penetration roads' to the hinterland as proposed by Taaffe. Indeed, the construction of roads such as the Belém-Brasília is more characteristic of the latest phase of the Taaffe model. On the other hand, the roads built to the west, such as the Transamazon, and the Cuiabá-Porto Velho and the north-south Cuiabá-Santarém can be characterized as penetration roads, since the destinations were not, at the time, large centers of trade. Once these major roads were built, then the development of the secondary system, such as the state road system developed in the 1980s, follow the Taaffe model.

2.2 Road Pattern and Deforestation Pattern

The Taaffe model described in the previous section is largely based on inductive historical studies of transport growth in developing countries. Several other studies, conducted by geographers such as Morril, Haggett, and Chorley, have often relied on network theories and methods to explain the development of transportation networks. Hence, it is important to review some of these studies as they relate to network patterns.[4] Equally important is to describe how these network patterns translate into deforestation patterns.

The study of patterns formed by line segments, or network patterns, has a long history in the natural sciences, particularly in geological and hydrological applications (Strahler, 1952; Howard, 1967). Haggett and Chorley (1969) describe four general network patterns largely derived from hydrology: dendritic, parallel, rectangular, and trellis (Figure 2.4).[5] The dendritic pattern resembles the hierarchical branching pattern of stream networks commonly found in many places, where the tributaries merge with larger streams at acute angles. The streams

[4] For example, Morril (1962, 1963) used Monte Carlo simulations to model the development of settlement over time, the emergence of central places, and transportation network in Sweden. The localization of the network was based on population centers incomes (similar to a gravity model), which were ordered from largest to smallest. The two largest centers were first connected, and then other segments were subsequently added, also following the 'attraction force' between centers (Morril, 1965; Chorley & Haggett, 1967).

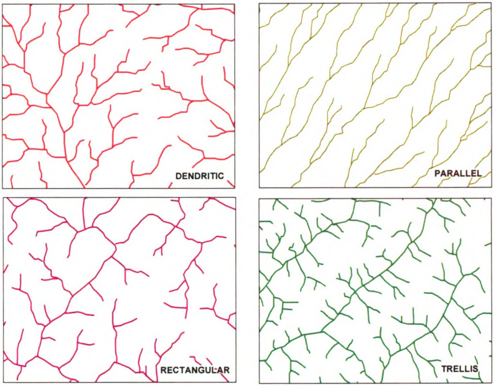
[5] Several metrics and relationships, including length of road or stream segment, order, area served by segment, angle of junction between segments, and flow along segments, were developed by many authors such as Haggett (1967) and Horton (1968), to characterize transportation networks.

themselves are not straight but exhibit an irregular, tortuous path. The parallel pattern shows elongated streams that run almost parallel with each other. In the rectangular pattern, streams curve at right angles with very few tortuous tributaries. Finally, the trellis pattern is a combination in which major streams show a rectangular pattern while the tributaries show a dense dendritic pattern. Network analysis was used in physical (description of hydrological networks), economic (relationship and connection between cities), and transportation geography (route optimization) studies.[6]

Roads and deforestation are closely related in the Brazilian Amazon, as discussed in Chapter 1. Not surprisingly, different patterns of roads will lead to different patterns of deforestation and fragmentation. Geist and Lambin (2001) consider deforestation patterns and the processes that generated them, classifying six types: geometric, corridor, fishbone, diffuse, patchy, and island (Figure 2.5).

The geometric pattern is characterized by large, continuous deforestation areas, usually associated with large-scale clearings for commercial agriculture or cattle ranching. The fishbone pattern is characteristic of small-holder colonization along the Transamazon Highway and in

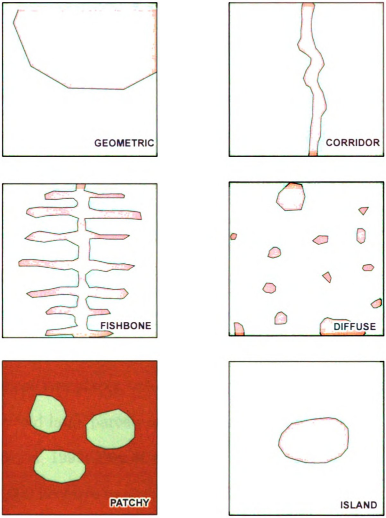
[6] More recently, network analysis, and graph theory in particular, have been used by ecologists to describe landscape patterns. Cantwell and Forman (1993) used nodes to represent land cover configurations and edges to represent connectivity between different land covers. They identified at least eight graphic configurations and studied the connectivity (e.g. number of connections in each node) between different land covers as a measure of interaction between them. The authors point out that such methods can be useful to model landscape function and future changes.



Adapted from Howard (1967)

Figure 2.4. Major network patterns

Rondônia State. The corridor pattern is characterized by deforestation along major axes of transportation, typically long linear road segments. In this case, deforestation occurs within a buffer along the road. The diffuse pattern is characterized by small, discontinuous clearings, usually associated with traditional, subsistence agriculture far from any transportation network (e.g. Indigenous people engaged in shifting cultivation). The patchy pattern is found near densely populated areas in which forests are isolated islands surrounded by human modified land covers. Finally, Geist and Lambin (2001) identify a continuous circular clearing pattern surrounding urban areas, which they labeled the 'island deforestation pattern.'



Adapted from Geist and Lambin (2001)

Figure 2.5. Deforestation and fragmentation patterns

As described in Figure 2.6, the design of small-holder colonization projects along the Transamazon followed a standardized geometric pattern that was replicated in other parts of 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 kilometer to the north and south. 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 hectare lots and soon began deforesting to plant annual and perennial crops and pastures. The fragmentation pattern that emerged from the initial settlement geometry resembles a 'fishbone.'

In other parts of the Amazon, most notably in southern Pará State and in Mato Grosso, roads followed a more rectangular pattern with many right angle turns and four-way intersections (Perz et al., 2004). In those two places, colonization projects were handed to private firms that sold large parcels of land to investors in southern Brazil (Schmink & Wood, 1992; Perz et al., 2004). Those parcels, some with more than 100,000 hectares in size, presented a rectilinear geometry. Feeder roads built to access farms farther from the main roads were usually placed on the boundaries of such parcels, forming rectangular patterns. The deforestation pattern that emerged from such a spatial arrangement had a 'geometric' characteristic, following Geist and Lambin's classification.

Figure 2.6. Geometric configuration of the lots along the Transamazon Highway

Those landowners deforested large, continuous blocks of forests to plant soybeans or pastures to raise cattle.

The placement of roads along boundaries is a well studied phenomenon in the United States. Two completely different surveying systems were used in the original thirteen colonies east of the Appalachians and on lands surveyed after the Land Ordinance of 1785. The first Anglo-European settlers in the United States used the 'metes and bound' system (also known as system of warrants and patents) in which surveyors placed boundaries based on physical features such as trees, streams, boulders, and even already existing roads. On the other hand, after the Land Ordinance, which adopted the Township/Range system, the land was divided into rectangular grids forming townships of six miles on each side, each of which are subdivided into 36 sections. For instance, roads in New England in the early colonial period were highly dependent on the physical geography. For example, many of the towns' roads and highways in New England converged to sawmills, which were dependent on water power to operate (Cronon, 1983). On the other hand, roads west of the Appalachians often followed a rectilinear pattern owing to the flat topography of the Midwest combined with the grid demarcation system. The deforestation and land use pattern that ensued was also different in both regions and is still persistent in the landscape. For example Bain and Brush (2004) were able to reconstruct the original property boundaries in the Gwynns Falls watershed in Baltimore, MD, which was originally surveyed in the 1600-1700s, because the original property lines and other physical attributes in rural areas are still imprinted in the landscape.

2.3 The Endogenous Road Debate

Although my dissertation does not aim at assessing the impact of roads on deforestation or the impact of roads in the landscape, it is important to contextualize the overall discussion about roads in the Amazon.

In the recent literature on roads and land cover change the term ‘endogenous roads’ has been frequently used. However, in many cases this term has been used to describe different phenomena. For example, Souza Jr. et al. (2004) use the term endogenous roads to denote those roads built by private agents as opposed to the official roads built by governments.

In the econometrics literature, the ‘endogenous roads’ term has a very specific meaning that arises from two different processes. The first case, described by Chomitz and Gray (1996), relates to the correlation between the control variables in a regression and the unobserved error term. Let $y_i = \mathbf{x}_i\beta + \mu_i$ be a population model where y could be, for example, a deforested parcel or any land use type, $\mathbf{x}$ a vector of explanatory variables, which usually includes a distance to the nearest road variable and μ the unobserved error term. The critical assumption to consistently estimate the vector β is that $E[\mathbf{x}'\mu] = 0$, or that the vector of explanatory variables must be uncorrelated with the unobserved error term.

Chomitz and Gray (1996) hypothesized that land would be allocated to its highest use and deforestation would be observed as long as rents from agricultural land uses were higher than rents from forestry, both being greater than or equal to zero. In their model implementation, rent is a function of distance to roads and they call attention to road construction motivated by agricultural development prospects. In particular, roads routed purposefully through areas with better soils can cause the estimation of the partial effect of roads on deforestation to be biased, usually overestimated. If agricultural suitability factors are not controlled for, then the variable roads, which is part of the vector $\mathbf{x}$, would be correlated with the error term μ (unobserved land qualities) and hence, the partial effects of roads would not be correctly estimated. In order to overcome this problem, the authors included a rich set of variables to control for land quality, including terrain slope, soil wetness and pH, available phosphorus, and dummy variables sandy and rocky areas. Nonetheless, the authors suggest that some land quality variables may have not been controlled for, possibly biasing the result.

The second case arises from a causality directionality issue. In other words, the population model of interest is actually a system of equations similar to:

$$y_{i1} = \alpha_{i1} y_{i2} + \mathbf{x}_{i1} \beta_1 + \mu_{i1}$$

$$y_{i2} = \alpha_{i2} y_{i1} + \mathbf{x}_{i2} \beta_2 + \mu_{i2}$$

where y_{i1} indicates deforestation in a certain place, and y_{i2}, the existence of a road segment and the vectors $\mathbf{x_1}$, $\mathbf{x_2}$ include other control variables that must not be identical in both equations in order to identify the system. The first equation shows the usual directional causality thoroughly described in the literature: deforestation is a consequence of roads or, the building of roads leads to deforestation. The second equation points to an inverse causal relationship which was not, until recently, much explored in the land cover change literature. Is it possible that deforestation actually precedes the building of roads? In other words, is it possible that roads are a response to development and are actually endogenous to the deforestation process? If this is the case, then usually y_1 will be correlated with u_2 and y_2 will be correlated with u_1. Therefore, the estimation of the parameters will be biased if we use the usual ordinary least square estimation procedure (Wooldridge, 2002).

Clearly, if time series geographic data on deforestation and roads, such as satellite imagery, were available, then causality could possibly be established by looking at whether or not roads precede deforestation in a particular region in the image.

The policy implication of this discussion is very important. The question whether roads cause deforestation or not and the 'magnitude' of such impact have deep political implications to the environmental protection versus development debate in tropical countries. In recent years, the Brazilian government launched a program named *Avança Brasil* with the objective of, among other things, upgrading Brazil's infrastructure. According to the original plan, 6,245 km of roads in the Amazon are to be renovated and ecologists predict severe consequences for the environment, including an increase in forest fires and deforestation rates (Nepstad et al., 2001; W. F. Laurance, Cochrane, et al., 2001).

On the other hand, Andersen et al. (2002) claim that paving roads promotes economic growth and even limits clearing, which is a win-win situation, particularly in more populated areas in the Amazon. Their conclusion is based on a panel evaluation of data aggregated at the municipality level. The principal drawback from their work is the lack of a model specification based on theoretical grounds. Instead, they adopted an estimation procedure in which observations considered to be outliers are dropped from the sample. Also, explanatory variables with robust t-statistics under 2.0 are randomly dropped from the estimated model. This procedure is repeated until the model fits some criteria of 'good' model. However, the results found by Andersen et al. (2002) are being contested by new econometric models and estimation methods (Pfaff et al., 2004).

Most federal roads seem to be exogenous to deforestation. Figure 2.7 shows population centers identified in the 1957 IBGE maps and the federal roads overlaid.[7] Not surprising, the vast majority of the pre-1957 cities were located near rivers. The road routes that emerged are basically lines connecting some of those population centers with very minor deviations, caused possibly because of micro-topography (Figure 2.7). This pattern indicates that there were very few, if any, detours to access areas of high agricultural potential. As such, official roads built by the federal government can be considered exogenous. The most notable examples are the Transamazon (BR-230) and BR-364 from Cuiabá to western Acre, whose routes seems to be generated by a connect-the-dots exercise. The Cuiabá-Santarém is the only road without any population center in between these two cities. However, according to key informant interviews, there existed a town on the current route in the southern part of Pará State, near the border of Mato Grosso State, that is not shown in the IBGE map of 1957 (R.

[7] This map was generated as follows. I converted the 1957 pdf maps from IBGE into tiff format and georectified it. Then, I overlaid this map with a 1997 digital map of all urban centers in the Brazilian Amazon obtained from IBGE (1997). Next, I selected all points (urban centers) that also appeared in the 1957 map. I also double checked the name of the cities in the index of the 1957 document to make sure that all pre-1957 cities were included in the digital dataset.

Walker, personal communication).

In retrospect, the placement of the federal road system was ultimately determined by physical geography. Cities such as Porto Velho, Ariquemes, Itaituba, Altamira, and Marabá became population centers because of physical geographical characteristics of rivers. Ariquemes was a rubber trade village on the margins of Jamari River, an important tributary of the Madeira River that provided access to the rubber-rich interior of this watershed.[8] Marabá also emerged as an important regional trade center because of its location near the confluence of two major rivers, the Tocantins and Araguaia that provided access to an area rich in rubber and brazil nuts (IBGE, 1957; Schmink & Wood, 1992). Porto Velho, Itaituba, and Altamira became population centers because of rapids and waterfalls that interrupted navigability.[9] Hence, it was necessary to portage those rapids or transfer products from one boat to another. In other cases, such as Santarém, indigenous villages were already established in strategic locations (confluence of Tapajós and Amazonas rivers) and were later transformed into trading posts by religious and commercial ventures (IBGE, 1957).[10]

[8] This information was obtained during field trip to Rondônia in 2003, when a team (myself included) interviewed key informants.

[9] Porto Velho was created during the Madeira-Mamoré Railway construction. Not surprisingly, it was decided to put the terminus of the railway on a navigable portion of the Madeira river. Key informants told the field team that there was a village upriver from Porto Velho, right below a major waterfall, that lost its importance as a trade center years after the construction of the railway.

[10] Itaituba, Altamira, and Marabá might also have been indigenous villages prior to colonization but references I found were not consistent to back up this claim.

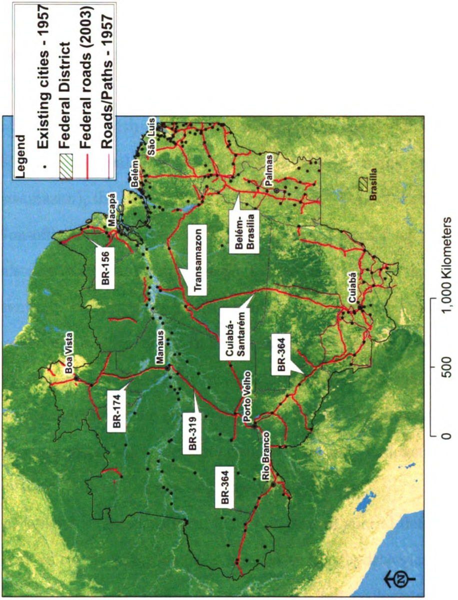


Figure 2.7. Existing towns prior to 1957 and the design of the Federal road system

In this dissertation, I use the term 'endogenous roads' in the context of the econometrics literature, or roads that are built after deforestation occurs or roads purposefully routed to gain access to natural resource (e.g. fertile soils, timber-rich sites, etc.). I will refer to the roads built by the state with the purpose of developing the region as 'official roads', either federal or state. Examples of such roads are BR-230 (Transamazon), the BR-010 (the Belém-Brasília), PA-150 and, BR-364.

'Non-official roads' are those built by local residents, such as loggers, colonists or even local governments, rather than state or federal governments. These roads are usually built to gain access to land, timber, and other natural resources and are usually endogenous to deforestation. In the case of roads built by the state government, this classification between endogenous and exogenous is not so clear cut. Anecdotal evidence suggests that some state roads are actually endogenous while others were built to link existing population centers.

The official road network explains the general spatial deforestation pattern, which in many cases is related to the hydrological characteristics of rivers (i.e. rapids and waterfalls), but ecologists are more concerned about the fragmentation pattern at the finer scale produced by the denser, longer, and intricate non-official network. Hence, this dissertation will focus on non-official roads built by loggers. In the next chapter I provide a theoretical and simulation models of two types of unofficial roads, destination determinate and destination indeterminate. In chapter 4, I develop an algorithm to model the third type of unofficial road, skid logging trails.

CHAPTER 3

Modeling Road Patterns

In the previous chapter I showed that the deforestation pattern is largely associated with the road network pattern. Hence, understanding how the spatial architecture of a road network pattern emerges is key to comprehending forest fragmentation resulting from deforestation.

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

I begin the chapter with a description of the different road types off the main Transamazon Highway and the role played by loggers in building such roads. Next, I develop a model of road construction based on the microeconomics of the firm to explain loggers' road building behavior. This is followed by an explanation of the computational issues involved in the GIS modeling work. Finally, I present and discuss the modeling results.

3.1 Roads and Land Cover Change

The modeling focus in this chapter is on the fishbone pattern observed in smallholder colonization areas such as along the Transamazonia Highway in Pará (Figure 3.1), and also in Rondônia State, but 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.*[1] I 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 Amazônia pursuant to development of the federal highway system.

[1] A *Projeto de Assentamento* is a government sanctioned area of small holder colonization that typically fragments the landscape in accordance with early schemes by INCRA, which allowed for 100 hectare holdings (400 × 2500 m) and road spurs to provide access every 5 kilometers.

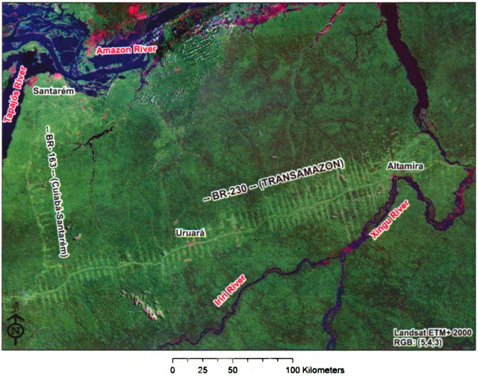


Figure 3.1. Portion of the Transamazon region in Pará State.

3.1.1 Roads off the Transamazon Highway

Colonization in Uruará followed the fishbone pattern described in the previous chapter in which lots were regularly demarcated along the Transamazon and along parallel secondary roads that were initially constructed by the federal government.

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, I have identified three main types of road extensions in my fieldwork. The first comprises simple extensions of the original secondary roads following the governmental spur, which I call destination *indeterminate roads.* Such roads expand relatively slowly and replicate the initial settlement geography. The second type of road I 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 determinate roads are typically built by well-capitalized loggers with help from colonists and local government. The third type of roads, referred to as *logging skid trails*, is a combination of destination determinate roads and the roads we typically associate with a logging operation, i.e. the dense network of logging trails that is built to reach each tree. The GIS model developed to address this third type of roads requires an explanation of graph theory and complexity theory. Terrain data must also be obtained in a highly detailed, fine scale. Hence, to facilitate exposition, I will describe destination indeterminate and determinate roads in this chapter and skid trails in Chapter 4.

3.1.2 Loggers and Road Building

The expansion of the secondary, unofficial 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 in the Brazilian Amazon region, producing 11 million m^3 of sawn wood and a gross revenue of US$ 2.5 billion (IBGE, 2003; Lentini et al., 2003).[2] 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% of total), Mato Grosso (36%), and Rondônia (17%), all of which have experienced dramatic extensions of their road networks in recent years. Amazonian wood is mainly consumed domestically (86%), while the rest is exported (Smeraldi & Verissimo, 1999).

As of 1998, perhaps 2570 sawmill firms were operating in the Brazilian Amazon (Lentini et al., 2003), of which 53% were considered small operations processing less than 10 thousand m^3 of roundwood annually. Lentini et al. (2003) estimate that 49% of all roundwood is processed by large, vertically integrated firms that do their own logging. Such

[2] Most of the wood exploited is illegal. Of the approximately 11 million m^3 exploited, less than 3 million m^3 have been authorized by the Brazilian environmental agency, IBAMA(O Liberal Newspaper, January 11, 2004).

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, 1995). Along the Transamazon Highway, large integrated firms have been most active in road extensions, particularly for the destination determinate roads that are built quickly and with considerable capital investment. The models I 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).

3.2 A Conceptual Framework for Logging Firm Behavior

In this section, I develop a behaviorally-based explanation of the expansion of settlement road networks, in particular those in which logging firms play an important role. The approach taken is computational and involves the deployment of GIS to identify 'optimal' roads. These are then compared to the actual roads by visual reference to satellite images. Road network optimization is not new to operations research, but little effort has been made to link the economic behavior of spatial agents such as loggers to the identification of optimal spatial configurations of road networks. The theory of the firm is largely aspatial in this context. For their part, network finding algorithms may neglect financial constraints in a particular setting, or economic conditions more generally. Thus, 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 micro-economic behavior of the firm, which is the purpose of the present section.

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. Thus, I assume only large, vertically integrated firms possess the capital necessary to regularly engage in road construction for both indeterminate and determinate cases. The model development that follows addresses the decision-making activities of such large, vertically integrated operations, which from this point on will be referred to with the generic term *loggers*, to be distinguished from the smaller operations that specialize in tree extraction.

In the following two subsections, I develop relevant theory addressing indeterminate and determinate roads individually. The indeterminate case presents a difficult problem, given that destinations are not known.

On the other hand, with destinations known, optimization of route selection is transformed into the identification of a least cost path, which is a simpler minimization problem.

3.2.1 Indeterminate Roads

In the present context of indeterminate road building and route selection, large integrated logging 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, namely a path or paths in two-dimensional space.

Profit maximization and the search for optimal pathways require fundamentally different solution approaches. I first consider factor allocation pursuant to profit maximization, an analytical problem, which then constrains the computational spatial problem. Profit maximization yields the amount of mobile capital as a function of the firm's financial capability. Mobile capital then constraints the road construction process and its articulation in space. This is the mechanism by which the economic constraints faced by the firm are translated into the formation of a road network in a GIS. I begin with a conventional production problem in which sawmill output is governed by a Cobb-Douglas function:

$$Y = AK_1^{\alpha}T^{\beta}L^{\gamma} \tag{3.1}$$

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, I take the extraction of roundwood (T) as a Cobb-Douglas function depending only on capital, in this case mobile capital (K_2):

$$Y = BK_2^{\theta}e^{\mu} \tag{3.2}$$

where μ is a random disturbance representing uncertainties regarding the search for wood. Substituting 3.2 into 3.1, defining $C \equiv AB^{\beta}$ and assuming $\theta = 1$ (constant returns to scale in roundwood production) the total revenue function is given as:

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

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 u. 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. The firm's objective is taken to be the maximization of expected revenues subject to this constraint. This model differs from the 'classical' firm profit maximization statement, in which firms do not face financial constraints. The present model is consistent with the situation observed in many frontier areas where institutions (including financial and legal) are not well established (Schneider, 1995). Hence, scarcity of resources available for investment do pose a constraint to the firm. This constrained maximization problem can be solved through the technique of Lagrangian maximization:

$$\max_{K_1,K_2,L,\lambda} \mathfrak{L} = pCK_1^{\alpha}K_2^{\beta}L^{\gamma}e^{\frac{1}{2}\beta^2\sigma} + \lambda[F - r(K_1 + K_2) - wL]$$

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

$$\frac{\partial \mathfrak{L}}{\partial K_1} = \alpha pCK_1^{\alpha-1}K_2^{\beta}L^{\gamma}e^{\frac{1}{2}\beta^2\sigma} - \lambda r = 0 \quad (3.3)$$

$$\frac{\partial \mathfrak{L}}{\partial K_2} = \beta pCK_1^{\alpha}K_2^{\beta-1}L^{\gamma}e^{\frac{1}{2}\beta^2\sigma} - \lambda r = 0 \quad (3.4)$$

$$\frac{\partial \mathfrak{L}}{\partial L} = \gamma pCK_1^{\alpha}K_2^{\beta}L^{\gamma-1}e^{\frac{1}{2}\beta^2\sigma} - \lambda w = 0 \quad (3.5)$$

$$\frac{\partial \mathfrak{L}}{\partial \lambda} = F - r(K_1 + K_2) - wL = 0 \quad (3.6)$$

Combining 3.3 and 3.4 yields:

$$K_2 = \frac{\beta}{\alpha}K_1 \quad (3.7)$$

Likewise, combining 3.3 and 3.5, we have:

$$L = \frac{\gamma r}{\alpha w}K_1 \quad (3.8)$$

Equations 3.7 and 3.8 are the usual expansion path for a firm with Cobb-Douglas technology given constant factor prices. By substituting 3.7 and 3.8 into 3.6 and solving initially for K_1 and later for K_2 and L, the optimal amount of inputs can be stated as:

$$\begin{aligned} K_1^\star &= \frac{\alpha F}{r[\alpha+\beta+\gamma]} \\ K_2^\star &= \frac{\beta F}{r[\alpha+\beta+\gamma]} \\ L^\star &= \frac{\gamma F}{w[\alpha+\beta+\gamma]} \end{aligned}$$

Under constant returns to scale, $\alpha + \beta + \gamma = 1$, the factor demand functions simplify to the ratio of the technological parameters multiplied by the constraint and the factor price.

Given input prices (r, w) and technological parameters $(\alpha, \beta, \theta, \gamma)$, the logger will devote $K_1^\star$ units of capital to the processing phase and $K_2^\star$ 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 financial capital 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 explained in below.

3.2.2 Determinate Roads

As discussed, loggers are also actively involved in building destination determinate roads, and in Uruará, two such roads have been built to reach points on two rivers, the Tutuí and Iriri. From field interviews (see

Appendix A), I know that loggers build such roads to get to navigable points on the rivers from where they load finished products, such as sawnwood, onto ships for transport to markets.

As such, the behavioral theory behind the construction of determinate roads is much simplified. Suppose a logger currently transports products from sawmill to a distant market, using a pre-existing 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 $i = 2, \cdots, N$ and will build the route i that maximizes profits or, $\pi^\star = R - PC - TC^\star$, where $TC^\star = \min(TC_i)$. This is necessarily a better option because $\pi^\star > \pi_1$ as long as $TC^\star < TC_1$. Therefore, profit maximization involves identification of the cost minimum route.

3.3 Computational Models of Roads

The theory presented in the section above is abstract in the sense that no spatial outcome is delivered. Since roads built by loggers are inherently spatial entities, I combine the theory with GIS to obtain spatial outcomes. In this section, I first describe the previous studies involving GIS and network optimization relevant to my current application. Then, I explain the dataset used in the modeling effort, followed by a description of the software adaptations I did to model indeterminate roads. At the end of this section, I describe the results for both indeterminate and determinate roads and the local socio-political ecology involved in determining the choice of road routes.

GIS and Road Networks

GIS has many applications to transportation and network systems but has not yet been used to model patterns of forest fragmentation based on road building. Consequently, the GIS objective of this dissertation is to develop an algorithm reflecting human behavior that can replicate the actual spatial signature of road building. I undertake model construction with a formal conceptualization of human behavior, then I observe the extent to which model outcomes are consistent with the actual roads observed. If the predicted roads are close to the observed roads, I conclude that my model is consistent with the decision-making process that led to the placement of the actual roads. I base my conclusions largely on visual inspection, given the general lack of accuracy metrics for this particular application.[3]

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.[4] Although an optimal route can be identified using linear programming techniques (Hillier & 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 & Tuzhilin, 1994; Warme, 1998; Prömel & Steger, 2002), analogous to the multiple target access problem in geography (Dean, 1997; Murray, 1998), which I will discuss in more detail in Chapter 4. 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 calcula-

[3] Accuracy assessment metrics exist for two dimensional spaces [e.g., Pontius (2000); Walker (2003b)]. This application would require metrics based on one-dimension, to reflect arc intersections.

[4] Indeed, routing problems date back to Euler (1707-1783) who proved the impossibility of crossing all seven bridges of Königsberg - Germany, without having to cross any bridge more than once, and Fermat (1601-1665), whose contribution to routing problems will be discussed in Chapter 4.

tion 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 this 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.[5] And third, the Tomlin

[5] 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

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 US national forests when government constructs the roads, although presumably some standards of efficiency will emerge over the long-run. My goal is to use GIS software to define unique road paths that are optimal in the sense that they meet some behavioral object, such as profit maximization or cost minimization, which is what I 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. On the other hand, the knowledge of a destination, such as

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potential roads to decrease the cost-elevation grid to assure 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.

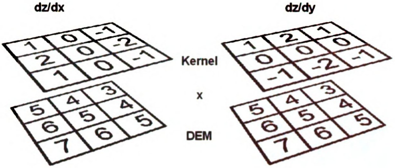
with the river roads, greatly simplifies the computational problem, and simply requires parameterization of existing least cost software. Road identification is unique in both cases, and does not require a 'cut-off.'

Topographic information is critical for assessing the cost of building roads. I obtained terrain 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). This space mission, carried out by the Endeavor shuttle on February 2000, contained two radar antennas, one in the main body of the vehicle and another located at the end of a 60 m extended mast. Each antenna emitted and received radar waves to the same portion of the Earth's surface at a given time. Since the distance between the two antennas was precisely known and held constant throughout the mission, the height of the surface could be determined by a method known as interferometry. The data was processed at NASA's Jet Propulsion Laboratory and gradually released to the public as each continent's data were processed. For the United States, SRTM data postings are of 1-arc second (30 meters) and 3-arc seconds for other areas of the world. NASA made data of the South American continent available for the public in 2002.

For all simulations, road-building costs are taken as increasing functions of slope. I defined 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 & McDonnell, 1998). Translating slopes into costs is not a simple task in most GIS implementations because each cell has eight slope values, depending on the direction of movement to any of its neighbors. Since only one cost value can be stored in each cell, the Horn algorithm is a convenient way of assigning such value because it calculates a weighted average slope of the eight neighbors to any given cell as exemplified in figure 3.2.[6] The kernel moving window, with higher weights (2 or -2) assigned to the closest four neighbors, calculates the change in height values in both x and y directions (dz/dx and dz/dy), which then are squared, summed, and taken the square root, according to the example in figure 3.2. The SRTM template grid gave a mean Horn-slope, in percentage values, 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^o slope (slope value of 100) than on the flattest cell on the grid (0.5).

I also incorporated river features into the cost friction grid. Bridging a river is more expensive then simply building roads upland. I converted the third and higher order stream line vectors, as defined by Strahler (1952) and obtained from *Instituto Sócio-Ambiental* (2000),

[6] I wrote a program that calculates the least cost path taking into account each cell's eight slopes and applied to the skid logging trails modeling in Chapter 4.



$$\text{Slope} = \sqrt{[((5+12+7)-(3+8+5))/8]^2 + [((5+8+3)-(7+12+5))/8]^2}$$

Figure 3.2. Description of the Horn algorithm used to calculate slopes

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]

Figure 3.3 depicts the tract of the Transamazon Highway in the 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.

I now consider the destination indeterminate and determinate roads cases in greater detail, giving a description of the algorithms used as well as the results obtained. I address the destination indeterminate roads first, and follow this with the determinate case. It is essential to

[7] I 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.

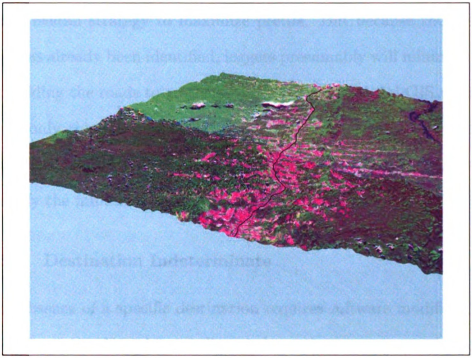


Figure 3.3. Perspective view of the Transamazon Highway. Landsat ETM$^+$ image (2000) draped over DEM (SRTM) vertically exaggerated fifteen times.

place the search for optimal pathways within the context of the microeconomic behavior of the firm, which was explained in detail in the previous section. The optimal amount of mobile capital K_1^* resulting from profit maximization constrains the road construction in the GIS algorithm. This is the mechanism by which I translate the economic constraints faced by the firm into the formation of a road network.

In the destination determinate case, the behavioral problem is simplified, which 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. Thus, the operational GIS model reflects only this stage of profit maximization, and as a consequence I can rely on the ArcGis® implementation of the Dijkstra algorithm to identify the minimum cost pathways.

3.3.1 Destination Indeterminate

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 I do not have tree distribution data in my possession, I 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®, which utilizes the Dijkstra algorithm (ESRI, 2002). Let the accumulative costs at a given cell g_i be described by the function $v(g_i)$. I define a level set $\mathbb{P}$ formed by cells g_i such that $\mathbb{P} = \{g_i : v(g_i) = c\}$, with constant c and N cells. Constant c was made 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.[8] Note that I 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 logging firm conceptual behavioral model, 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 $g_i \in \mathbb{P}$ to the original road network, or $Road = \max[L(g_i)] \quad i = 1, \cdots, N$, 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 three. The friction grid is then updated, and another cumulative cost surface recalculated, which changes with the additional segment. I repeated the process 60 times to simulate the temporal evolution of the road network.

Results of simulations for the destination indeterminate case are given in Figure 3.4, which overlays the modeled paths onto actual roads

[8] In reality, since the cumulative cost values are float numbers, I selected the grid cell with values greater than 10,000 and smaller than 10,010.

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 Indigenous Reserve to the South, shown in light magenta in Figure 3.4.[9]

3.3.2 Destination Determinate

The simulations for the destination indeterminate case reflects a fully developed theoretical model based on profit maximization subject to financial constraints, and 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

[9] I assigned a friction value of 120 to the cells inside the protected area. This value was chosen 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.

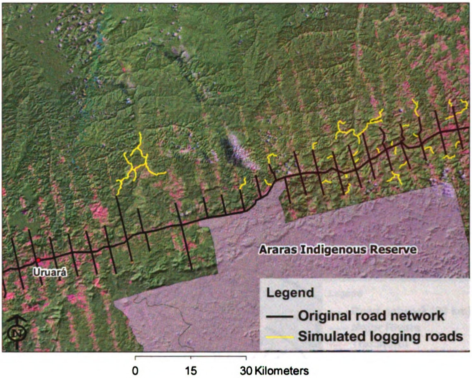


Figure 3.4. Destination indeterminate simulation.

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 3.5). The actual paths of these roads were identified by visual interpretation (RGB 5/4/3 color composite) of four 1999 Landsat ETM$^+$ images (paths: 226, 227 and rows: 62, 63) and were on-screen digitized at 1:50,000 scale. I consider each of the roads in turn. Although I know from key informants that the final destination of the Transtutuí is near the convergence of the Tutuí and Uruará Rivers, I was not able to identify on satellite images the path beyond the digitized segment in figure 3.5.

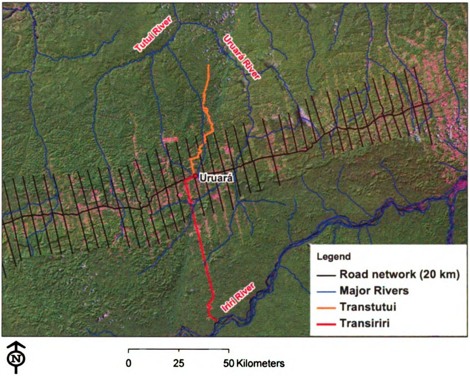


Figure 3.5. Major destination determinate logging roads in Uruará.

To replicate the evolution of the so-called Transiriri, I solve for the least cost path from Uruará to any segment of the river, including movement along the Transamazon Highway. The costs, as discussed, were calculated using topographic data from the SRTM project and hydrological maps. 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, I was 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.[10]

The results (Figure 3.6) 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, and reaching the Iriri River four kilometers 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 ten kilometers from its destination. Note that in this and the subsequent simulation, the initialized road network in black is set to 20 kilometers rather than six. Both the Transiriri and Transtutuí were built after 1980, when many of the settlement roads had already been extended to 20 kilometers 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, it 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 kilometers east of Uruará, as captured by the simulation in figure 3.7; its present-day path begins in the town itself and heads east until

[10] I also assigned a value of 120 for the cells inside these potentially floodable areas.

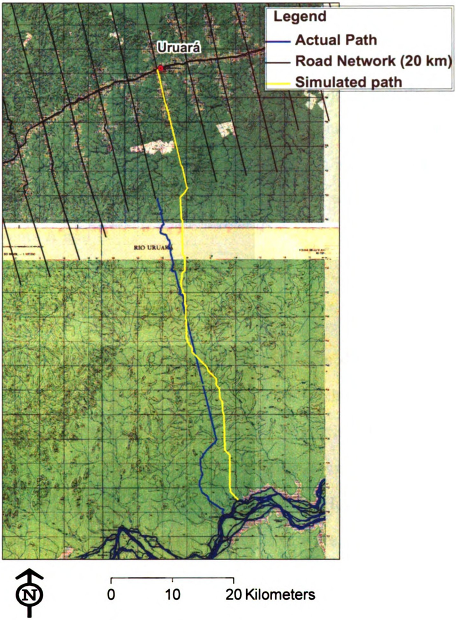


Figure 3.6. Simulation of destination determinate Transiriri logging road.

reaching its original route, where it continues north to the river.[11] I simulate this 'second best' solution by incorporating what key informants refer to as *pontos obrigatórios*, or necessary points of route passage. I take these to be the actual intersections of the Transtutuí with the settlement roads between Uruará and the original one selected for extension to the river. The simulation result given in Figure 3.8 is largely coincident with the actual route, given in blue, with two discrepancies at points A and B.

3.4 Discussion

The model applications perform better for the determinate than for the indeterminate case. The simulated indeterminate logging roads are dispersed and fragmented, similar to the dendritic pattern described in Haggett et al. (1977), and begin to show direct extensions of individual 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 hectare lots (400m x 2500m) identical to the first

[11] 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.

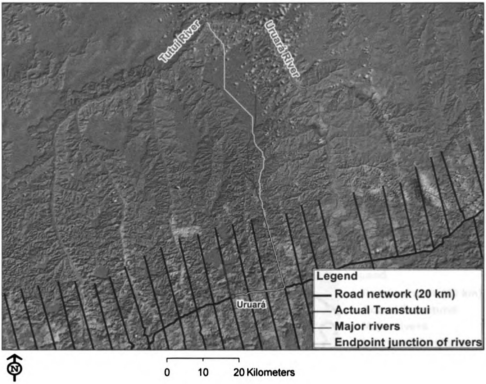


Figure 3.7. Simulated Transtutuí with destination determined at junction of Uruará and Tutuí Rivers.

settlers, hoping that government would subsequently regularize holdings. The settlement road to the north, five kilometers 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 nine kilometer addition in 1988. Loggers did not participate in

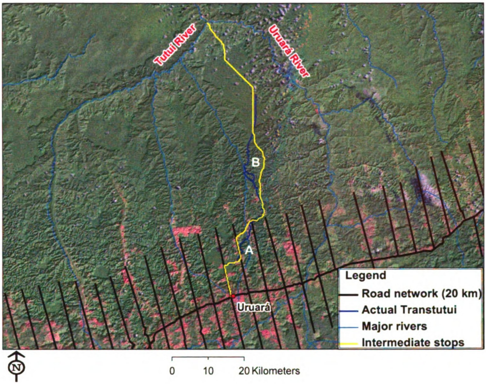


Figure 3.8. Simulated Transtutuí with *pontos obrigatórios* (mandatory waypoints) included.

extending the road until 1994, after it had already reached a distance of 25 kilometers 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 or even other regions in Amazonia, where loggers have often extended roads that were then followed by colonists (Walker, 1987).

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 destination indeterminate roads, at least out to about thirty kilometers, 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 by (2) 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 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 ($\leq$ 400 hectares) have fewer legal requirements than largeholders (such as sawmill owners), which facilitates exploitation of their standing timber. Up to fifty percent of a smallholding can be deforested, as compared to twenty percent for large properties.[12] In addition, smallholders can legally exploit up to 20 m^3ha^{-1} 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 found in my 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 eco-

[12] According to the Forestry Code of 1965, both large and small properties were allowed to deforest up to 50%. In 1996, a new regulation lowered this percentage to 20% for large properties but maintained the original percentage for small farmers (Provisory Measure 1511 from 25 July, 1996).

nomic 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 changed in the wake of a localized dispute over a detour. Of course, in both cases I 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 conceptual framework described in the previous section states a possible theoretical rationale.

In general, the present approaches suffer from three limitations. First, I 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.[13]

A related shortcoming pertains to my 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 land-owner. 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 fifteen kilometers east of Uruará (165N). I 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 3.7, the route deviates considerably from a straight line as it gains distance from the Transamazon Highway. Colonist occupation of distant

[13] To address certain institutional constraints, such as the inviolability of Indigenous Reserves, I 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.

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 my 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.[14]

[14] 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.

CHAPTER 4

Modeling Logging Skid Trails

In the previous chapter, I developed a behavioral model to explain the process of road expansion carried out by loggers. I also tried to mimic in a GIS the expansion of settlement roads (destination determinate and indeterminate) in a portion of the Brazilian Amazon near the town of Uruará on the Transamazon Highway. In this chapter, I will present a GIS algorithm to model logging skid trails, which are built by loggers to actually reach the trees to be harvested. The GIS model consists of two distinct stages that imitate the actual decision making process of loggers. In the first stage, loggers identity a logging site rich in timber to be extracted and build a main road linking the site to the nearest infrastructure, which is usually a state or federal road. In a GIS, this first stage is accomplished by defining a polygon encompassing the trees to be harvested, which I refer to the least cost convex hull set, and by finding the least cost path between currently existing infrastructure and the logging site polygon. In the second stage, loggers build a network of skid trails connecting each tree to the main road. The GIS objective here is to find the minimum-length (measured by a building cost metric) interconnection of all trees to an origin, from where the timber will be transported to a sawmill. This second stage is equivalent to finding the so-called 'minimum Steiner tree' (MST) that connects a set of *terminals*, which in the present application constitute the trees to be exploited.

The MST is an extremely difficult problem to solve. Given N points (or terminals) in a plane (Figure 4.1, panel A), it seems deceptively trivial to find a connected network linking all N points such that this network has minimum length. This apparently easy problem is indeed very difficult because one is allowed to add nodes in the network. Hence, the difficulty lies on finding how many extra nodes should be added and where should those nodes be placed in order to minimize the total network (Figure 4.1, panels B and C). Mathematicians and computer scientists have relied on computer algorithms to solve the MST problem (MSTP). But even algorithmic implementations have shown limitations. In fact, there is no known computer algorithm that guarantees a solution in a reasonable amount of time.[1]

[1] Indeed, the MST was not even known to be a finite problem until 1961 when Melzak (1961) showed it was bounded. To my knowledge, the Euclidean Steiner minimum tree with largest number of terminals (2.000) was found by Warme (1998).

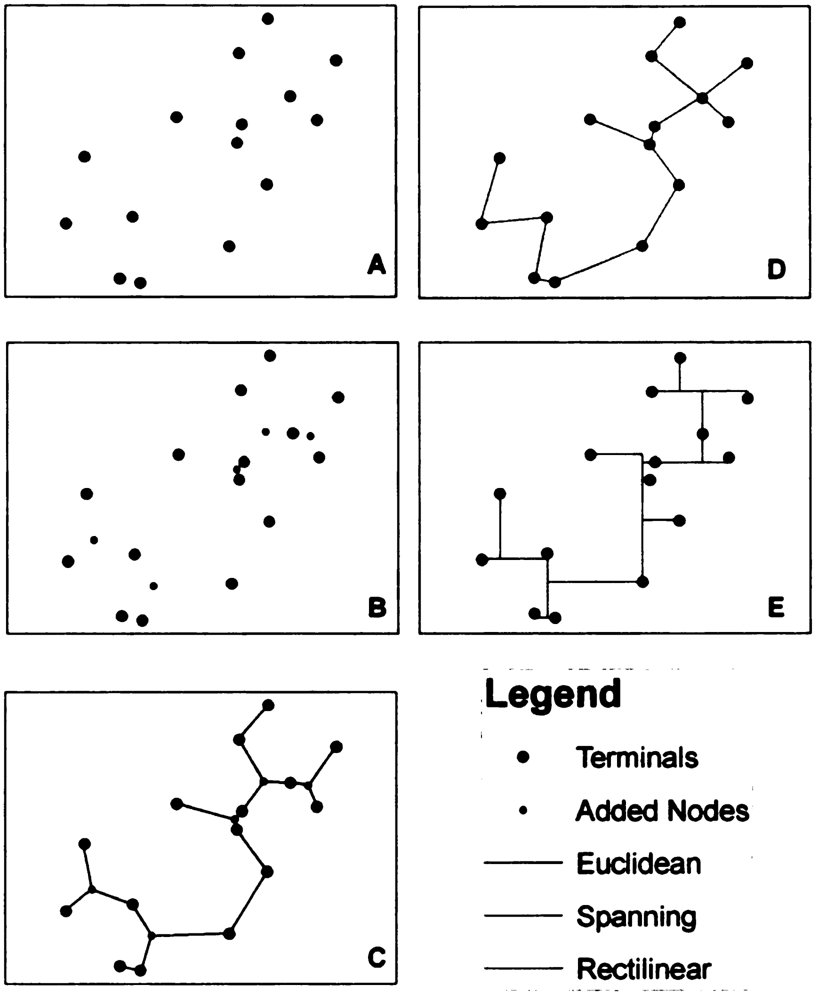


Figure 4.1. Euclidean Minimum Steiner, Spanning, and Rectilinear Trees

Most of the algorithms available to date were developed to find the minimum network in a Euclidean plane (Warme, 1998). Hence, these algorithms minimize the total network length in an Euclidean metric space. In a raster GIS data model, the MST problem differs from the Euclidean metric space in two ways. On the one hand, the MST problem is simplified because the nodes are fixed in a raster model, that is, the number of cells or the extent of the grid is fixed. Hence, one does not have to add extra nodes, although one still has to determine which nodes to choose in order to build the network. On the other hand, the MST problem becomes more difficult in a GIS, when compared to the Euclidean metric, because the objective is to minimize the cost of building the network. As such, terrain characteristics, such as slope, must be taken into account. For example, a minimum network might be tortuous, instead of composed of straight line segments, to avoid high building costs associated with steep slopes.

Current GIS minimum path cost algorithms such as Dijkstra's and Tomlin's, described in the previous chapter, do not produce minimal networks when the number of terminals is greater than two. Therefore, modifications of current algorithms are necessary to produce better results. Although the algorithms I developed do not produce the minimal possible network either (i.e. the ultimate optimal solution), they do return better results than those advanced by Dijkstra and Tomlin.

The chapter is organized as follows. In the first part, I explain the algorithmic GIS implementation in the context of the behavioral profit maximization theory of Chapter 3. Next, I present the Steiner tree problem, adapting graph theory concepts to the GIS environment, and explain the complexity of such optimization problem. I then outline the GIS algorithms I developed to model the building of logging skid trails. Finally, I describe the dataset used in the exercise and the results of the simulations, and I discuss the impact of skid trails on forest fragmentation.

4.1 Skid Trails

The behavioral theory behind logging skid trails is similar to the case of determinate roads. From field interviews (see Appendix A), I have learned that the most valuable timber species, such as cedro (*Cedrela odorata*), ipê (*Tabebuia sp.*) and mahogany (*Swietenia macrophylla*), usually occur in clusters in the landscape. Loggers typically hire experienced surveyors, called *mateiros*, who are incredibly knowledgeable about timber and possess an acute sense of orientation under closed forests. These surveyors assess the economic potential of certain sites, which can be tens or even hundreds of kilometers away from the nearest infrastructure. The mateiros find trees, mark them on the ground and plot their location on a hardcopy map. In some cases, when openings in the canopy allow, GPS coordinates are also recorded. This information is then passed on to the logger, who assesses the expected profit of the site. Once s/he is convinced that it is profitable under his/her current capital constraint, s/he will move on to the build road/trails. Profit maximization behavior here also implies minimizing road/trails building costs, since capital allocation decisions between extraction and processing were previously made, and can be considered fixed in the short-run.

Key informant interviews also suggest that loggers separate the road building task into two distinct phases. In the first phase, they build a main road to connect the extraction site to the nearest built infrastructure. This phase is similar to the destination determinate case, with the extraction site being the destination. In the second phase, loggers engage in building a series of small skid trails to access the trees to be harvested. Road building cost minimization implies finding a trail network, not a single line segment, linking the main road to multiple terminals, namely the trees to be harvested. Therefore, profit maximization involves identification of the cost minimum network or the minimum Steiner tree.

The GIS approach I developed mimics these two phases. In the first phase, I adapt the concept of convex sets to define the logging site and then link this site to the current infrastructure by the least cost path. In the second stage, I create the minimum cost network to connect each tree and the main road. Before I explain these two algorithms, I first describe the Steiner problem and the GIS challenges to solve it.

4.2 An Introduction to Complexity Theory

As mentioned above, finding the least cost network in the logging skid trails case is the same as finding the minimum Steiner tree in the building cost metric space. However, this is not a trivial optimization problem that can be solved numerically or algebraically.

Computer scientists classify how hard any optimization problem is by measuring the number of operations or the execution time (also known as time complexity) an algorithm needs to perform to return a solution as a function of the amount n of bits of input data. For example, sorting problems (ascending or descending sorting of numbers or strings) are considered to be easy problems because there exist algorithms that return the ordered list relatively fast (Andersson et al., 1998). Moreover, if a list consists of two elements ($n = 2$), the correct ordering can be obtained much faster than if a list contains $20,000$ elements.

A problem of size n bits of input data is said to be easy if there exists an algorithm that can solve it in n^p time, where p is a constant. These easy problems belong to a set labeled P and are said to have polynomial complexity because they can be solved in polynomial time (constant p is the degree of the polynomial term). In other words, easy problems are tractable because there is an algorithm to solve them quickly. Formally, fast algorithms are known to have $O(n^p)$ complexity.

A formal definition of the 'O' (big O) notation is provided as follows. We say that a function f is $O(g(n))$ if there exist a constant C and an integer N such that $|f(n)| < Cg(n)$ for all $n > N$. One can think of this statement as "f certainly doesn't grow at a faster rate than g" as the size of a given problem increases (Wilf, 1994).

The least cost path between two points belongs to the set P because the Dijkstra algorithm can solve it in $O(n^2)$ time (Greenberg, 2001). A larger superset named nondeterministic polynomial (NP) contains the problems for which a *trial* solution can be verified in polynomial time. In other words, once presented with a potential solution, there exists an algorithm to verify whether this solution is correct or not in polynomial time. A mathematical analogy can help understand this concept: it is much easier to verify the correctness of a proof of a theorem than actually find the proof itself (Wilf, 1994).

A subset of NP, called NP-complete, contains those NP problems for which an algorithmic transformation or reduction in polynomial time can be performed. Sometimes, in order to solve a problem, it is necessary first to transform one problem into another. For example, suppose we want to solve a system of equations such as $\mathbf{Ax} = \mathbf{b}$, where $\mathbf{A}$ is a non-symmetric matrix. If we pre-multiply both sides by $\mathbf{A}'$, we get $\mathbf{A}'\mathbf{Ax} = \mathbf{A}'\mathbf{b}$, which is a much easier system to solve because the inverse of a symmetric matrix is easier to obtain. In this example, we basically reduce one problem into another. One characteristic of NP-complete problems is that if any problem were in P then all would also be in P because one could simply reduce, in polynomial time, this problem into another problem that could be solved in polynomial time. I say 'could' because, to this day, there is no NP-complete problem known to be in P. In other words, there is no known algorithm to solve any NP-complete problem in polynomial time.[2] Finally NP-hard problems are those optimization problems that call an NP-complete problem as a subroutine. Steiner minimum problems are known to be NP-hard (Garey, Graham, & Johnson, 1977), the most difficult class of optimization problems. When exact algorithms exist to solve NP-complete problems, the time complexity grows exponentially (n is the exponent not the base as it is the case of polynomial complex problems) or superexponentially as the size of the problem increases.

'Hard' problems can have particular easy instances that can be solved though. These algorithmic complexity classifications are applied to the 'worse' possible instance of a given problem or when n gets very large. For example, a system of linear equations can be solved using Gauss-Jordan elimination algorithms in $O(n^3)$ time by multiply-

[2] The possibility the set P is the same as NP ($P \stackrel{?}{=} NP$) is still a famous open problem in computer science and mathematics but most computer scientists believe NP is a much larger set that contains P or $NP \cap P = P$ (Greenberg 2001).

ing, adding, or interchanging matrix rows. Clearly, it is much faster to find the solution if the original system is already similar to an identity matrix (Greenberg, 2001).

Despite the nonexistence of a fast algorithm to find a minimum network to the Steiner tree problem, approximate solutions exist once adequate information is given to the algorithm. Moreover, there are exact solutions for easy instances of the MSTP. In particular, a GIS solution using the Dijkstra algorithm as a subroutine is feasible involving two or three terminals. For the two terminal case, the minimum Steiner tree problem reduces to a simple least cost path between an origin and destination that can be solved in polynomial time using the Dijkstra algorithm.[3] For the three-terminal case, the solution can be found with a bit of manipulation. The idea is to find a fourth node p and calculate the minimum cost distance from p to the original three terminals. The addition of this 'extra' node is crucial for finding a better (cheaper) network.

In the next section I will formally describe the Steiner problem and will show two algorithmic approaches to finding an approximate solution in a raster data model. Before this, though, I must first provide several definitions taken from graph theory and apply them to the GIS environment. The notation and definitions were mostly taken from

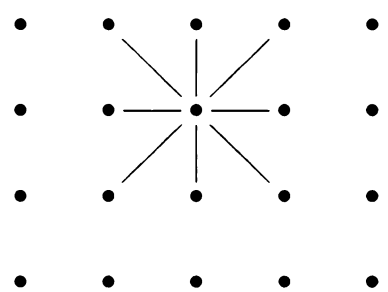
[3] In the case of two points on a plane, the Greeks knew thousands of years ago that the shortest path connecting those two points is a straight line.

chapter 1 of Prömel and Steger's (2002) book.

4.3 Graph Theory and the Steiner Tree Problem

A *raster* is a finite regular lattice where each cell's center point or node is linked to the adjacent cells' centers. The nodes are the vertices in graph theory terminology and belong to a set labeled V and the lines linking any two adjacent vertices are the edges in set E (Figure 4.2). *Terminals* are a subset K of V ($K \subseteq V$), or origins and destinations in transportation geography. A graph G is defined as a pair $G(V, E)$, where E are the edges or the finite set of linked unordered pairs of vertices in set V that make up the graph. A weighted graph W is defined as a triple $W = [V, E, \gamma]$, where the function γ assigns a nonnegative value (or cost) to each element in E, or $\gamma(E) \mapsto \mathbb{R}_{\geq 0}$. In raster terminology, this function $\gamma(E)$ is the cost of building or traversing all the edges E that form the paths connecting the vertices V in graph W (see also equation 4.1 below).

Two vertices (or nodes) v_i and v_j are adjacent in G if they form an edge or $v_i, v_j \in E$. The neighborhood of a vertex v are all nodes $u \in V$ such that $v, u \in E$. The number of neighbors of a vertex v is called the degree of v, which is known as the beta index in transportation geography (Haggett & Chorley, 1969), and is denoted by $d(v)$. In a typical raster environment, $d(v)$ for any given cell can be at most eight (queen movement or Moore neighborhood), for cells not located at the border of the grid.[4] Figure 4.2 is a representation of a 4×5 raster or grid showing the nodes (black dots) at each cell center and the corresponding edges (line segments) linking the cell in the middle to all its neighbors.



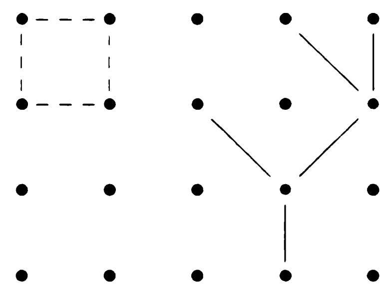
— Edges
• Set V of nodes or vertices
• Set K of terminals or origin/destination

Figure 4.2. Raster data model

A *tree* is an acyclic connected graph G, that is, between every pair of distinct vertices there is a unique path to them (Figure 4.3). In other words, each terminal can be reached by a single, unique route. Also, a *leaf* is a vertex of degree one, which makes it a terminal point in a tree, although the converse is not true. The *branching points* of a tree are all the vertices v such that $d(v) \geqslant 3$. [5]

Given $W = [V, E, \gamma]$, the minimum Steiner tree for K, where K is

[4] In an $m \times n$ rectangular grid ($m, n > 1$), the largest numbers of elements in V and E are easy to determine. V is simply m times n and $E = \sum_{i=1}^{4} \rho_i d(v_i)/2$ where $\rho_1 = 4$ and $d(v_1) = 3$; $\rho_2 = 2 \times (m-2)$ and $d(v_2) = 5$; $\rho_3 = 2 \times (n-2)$ and $d(v_3) = 5$; $\rho_4 = (m-2) \times (n-2)$ and $d(v_4) = 8$. The four vertices on the corners (v_1 type) of the grid extent have only 3 neighbors; vertices on the border of the grid (v_2 and v_3 types) have 5 neighbors, while vertices in the interior of the grid (v_4



— — Cyclic graph ⇒ not a tree
—— Acyclic graph or tree
• Terminals
• Branching points of a tree. $d(v) = 3$

Figure 4.3. Acyclic and cyclic graphs

the set of terminals, is a subgraph S of $G(V, E)$ containing all vertices of K and possibly elements of V as well such that $\gamma(S)$ is minimum. The cost of a path (or the subgraph) S joining all vertices of K is:

$$\gamma(S) = \sum_{e \in E(S)} \gamma(e) \tag{4.1}$$

Taking the acyclic graph in figure 4.3 as an example, $\gamma(S)$ is the sum of the cost of building or traversing five edges e.

In a raster environment, the cost (γ) of traversing an edge e connecting two adjacent cells' centers (v_1, v_2) is given by:

type) have eight neighbors.

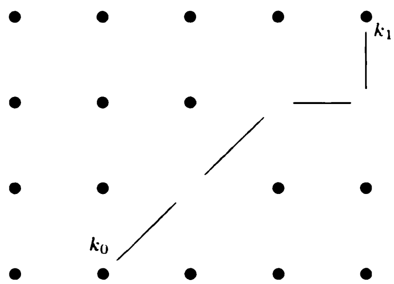
[5] Graph theory terminology applied to a forestry operation is a little confusing because a tree is a connected graph while the trees to be harvested are actually the terminals in graph theory.

$$\gamma(e) = \begin{cases} \frac{c_1+c_2}{2} & \text{if connected horizontally or vertically} \\ \frac{c_1+c_2}{2} \times \sqrt{2} & \text{if connected diagonally} \end{cases} \tag{4.2}$$

where c_1, c_2 are the friction costs or the cost of traversing each cell. The least cost network is then simply the cheapest route linking all points in set K, $\gamma(S) = min\{\gamma(S')|S'$ are all possible Steiner trees for K in $V\}$.

As mentioned above, if K is formed by two elements $\{k_0, k_1\}$, or an origin and a single destination, then the Steiner tree is formed by segments with degree at most 2, that is, each node is connected to at most two other nodes and the origin and destination terminals are necessarily of degree 1 (Figure 4.4). The optimal least cost path can be easily found by applying the Dijkstra algorithm. For reasons to be explained shortly (i.e. adaptation of spanning and rectilinear algorithm), define a new set Q that contains the terminals K and the nodes that make up the least cost path between $\{k_0, k_1\}$. In reference to figure 4.4, this set Q contains five elements (two terminals and three nodes).

A *spanning* minimum tree for K is a subgraph S of $G(V, E)$ such that all terminals K are also the nodes (i.e. no Steiner point is inserted to generate a smaller tree) and $\gamma(S)$ is minimum (Figure 4.1 panel D). A *rectilinear* Steiner minimum tree is only interconnected by horizontal or vertical segments. Hence, all intersecting lines form either a 180^o or 90^o angle (Figure 4.1 panel E).



• Set K with two terminals

Elements of $V \backslash K$ (V not in K) that are part of the solution

All vertices in path have $d(v) \leq 2$

Figure 4.4. Example of a fictitious least cost path between two terminals

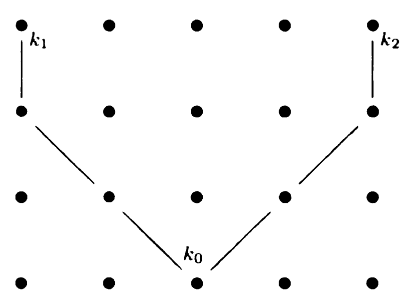
Suppose now that K is formed by three elements $\{k_0, k_1, k_2\}$. Let $\gamma(S_1)$ be the least cost path associated with graph S_1 (one of the sides of a triangle) that links k_0 to k_1 or,

$$\gamma(S_1) = \sum_{e^1 \in E(S_1)} \gamma(e^1)$$

Likewise, let $\gamma(S_2)$ be the least cost path associated with graph S_2 (another side of a triangle) that links k_0 to k_2. Now, suppose we want to find the least cost path $\gamma(S)$ associated with the graph S that connects the three vertices in K. Define a graph S' formed by the union of the two previous graphs S_1 and S_2 and let $\gamma(S')$ be its associated combined cost:

$$\gamma(S') = \sum_{e^1 \in E(S_1)} \gamma(e^1) + \sum_{e^2 \in E(S_2)} \gamma(e^2) - \sum_{e^u \in (E(S_1) \cap E(S_2))} \gamma(e^u) \quad (4.3)$$

The last term on the right hand side is the cost of the segments e^u that are part of both graphs S_1 and S_2 and, therefore, should not be double-counted. In the case of a triangle in plane geometry, this last term is zero because both paths overlay only at point k_0. If we apply the current GIS functions, which use the Dijkstra algorithm, to this problem and assuming a homogeneous surface (i.e. same friction cost for all cells), the graph displayed in figure 4.5 is the output solution.



- S_1 Least cost path from k_1 to k_0
- S_2 Least cost path from k_2 to k_0

Figure 4.5. Ordinary least cost path for a triangle in a raster model

This network is the optimal solution if one wants to minimize the *transportation time* from points k_1 and k_2 to k_0. However, in most applications involving roads, the interest lies on minimizing the *building* *cost* (Bunge, 1966). As such, the objective is to find the network with minimum length or, in my GIS application, the minimum length in a building cost metric.

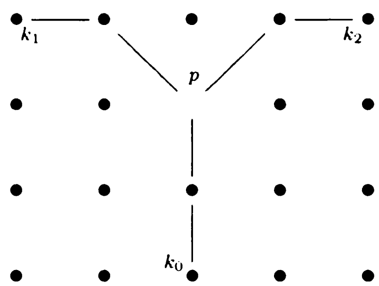
It can be shown that there exists a 'smaller' or 'cheaper' graph S such that the cost of building it is smaller than or equal to the cost of building S', or $\gamma(S) \leq \gamma(S')$. When K has three elements, the Steiner tree problem is also known as the Fermat triangle problem, named after the French mathematician who proposed this problem in the 17^{th} century. In a two dimensional Euclidean plane, the three elements of K are the vertices of a triangle and the graph S' comprises two edges of the triangle such that $d(k_0) = 2$. In raster language, Fermat showed that there exists a point $p \in V$ such that:

$$\gamma(S) = \sum_{p^0 \in E(P_0)} \gamma(p^0) + \sum_{p^1 \in E(P_1)} \gamma(p^1) + \sum_{p^2 \in E(P_2)} \gamma(p^2)$$

where $\sum \gamma(p^i)$ is the least cost path linking the point p to each of the triangle vertices $k_i = 0, 1, 2$. The sum of these three least cost paths, $\gamma(S)$, is the minimal network linking the three vertices in K. The point p is also known as the Fermat or Torricelli point of a triangle (Figure 4.6).

If any angle formed by two edges of the triangle is greater than 120^o then p is the vertex of such angle, i.e. $p \in K$;[6] otherwise $p \in V \backslash K$ (read

[6] In this case, the Steiner tree will be the same as the spanning tree.



• Terminals
Fermat Point (branching point)

Figure 4.6. Minimum network in a raster model with 3 terminals

p is a vertex (node) not in the set of terminals). Note that $d(p) = 3$ if the angles of this triangle are smaller than 120^o and the Steiner tree graph will resemble a 'Y' with point p located exactly in the intersection of the three lines and the $k's$ being the endpoints of such lines. In other words, p is a branching point (Figure 4.6).

The discussion above shows that the least cost path functions currently available in many GIS software, which use the Dijkstra algorithm, can find the minimal network connecting two points, but once more than two points are included in K, the solution may not be optimal if one is interested in minimizing the total network length. The major challenge in a GIS environment is to find the branching points $p \notin K$ that make part of the solution to $\gamma(S)$.

It turns out that a series of manipulations using the Dijkstra algorithm can also provide the optimal solution to the problem of finding the minimum network linking three points. Suppose we have a raster grid with $j = 1, \cdots, N$ cells. Let g_{ij} be the minimum cumulative cost from cell j to the terminal $k_i : i = 1, 2, 3$ provided by the Dijsktra algorithm. In other words, g_{ij} is the result of running the Dijkstra algorithm considering each terminal k_i as the source or origin. Then,

$$p = \min \left[\sum_{i=1}^{3} g_{ij} \right], \quad j = 1, \cdots, N$$

The paths linking p to the terminals $\{k_0, k_1, k_2\}$ is the minimum Steiner tree. The proof is almost definitional because p is the smallest sum of the minimum distances (or costs) to the three points. Therefore, the point p is the Fermat point or the branching point of the minimum Steiner tree.

Hence, we can find the node (or cell) p by running the Dijkstra algorithm from each k_i separately, summing the three accumulative cost grids and checking for the smallest value in the resulting grid. The minimum network linking the three cells can be calculated backwards from the cell p to the three original terminals ($k_{i's}$) by running the Dijkstra algorithm again but taking the node p as the origin and the three terminals ($k_{i's}$) as the destinations. The incorporation of the point p basically transforms the Steiner tree problem into a least cost path problem. As such, the solution basically requires applying the Dijkstra algorithm (at most) four times.[7]

Geographers have been working on problems similar to this for many years. In fact, a similar approach to the one described above has been used to study the location of firms. These studies data back to 1909 when Alfred Weber published a book on the topic, although some authors suggest that Wilhelm Launhardt found the same results much earlier in 1882 (Weber, 1909; Puu, 2003). Indeed, geographers might be familiar with the term 'Weber triangle' but completely unaware of the term 'Fermat point.' An important group of geographers worked on location and network problem during the so-called quantitative revolution in geography in the 1960s and 1970s. These works are best summarized in the book "Location analysis in Human Geography", where Haggett et al. (1977) described several methods designed to tackle the minimal network problem such as the mechanical link-length minimizer, which is also known as Varignon machine, nonlinear optimization, and the soap-film method [see Haggett (1967); Haggett et al. (1977) and Morgan (1967) for details on these methods]. Surprisingly none of these authors mention either the Fermat problem or the Steiner problem which have a much older history in mathematics. More

[7] A similar approach could be used to find the minimum tree connecting four points but experiments I did (not shown in this dissertation) suggest the need to calculate seven accumulative least cost surfaces. The number of operations necessary to find a solution seems to increase at least exponentially as the size increase from a two-terminal to a four-terminal problem, which is a characteristic of NP-complete problems.

recently, Dean (1997) showed how to calculate the Steiner point in a GIS but he did not provide a rigorous description of his methods or relate his approach to either the Fermat point or the branching point of the Steiner tree, either.[8]

4.4 Modeling logging skid trails in a GIS

The GIS application in this section assumes that the costs of building skid trails are much higher than the cost of transporting logs and hence, the objective of the logger is to minimize building costs, not transportation costs or a combination of both. Indeed, empirical studies in the Amazon have shown that the cost of building these feeder roads are at least four times more expensive than the cost of transporting cut logs (Stone, 1998; Verissimo et al., 1998). I also assume that this is a one-time minimization problem or that there is no dynamics involved in it. In practice, the evolution of the road network is dynamic. According to field informants, loggers usually build roads to exploit timber in one site in a given year and are aware of potencial logging sites nearby for subsequent exploitation in following years. Hence, the optimal design of roads in a dynamic context might be different than for a one-time exploitation.

[8] Dean (1997) did not claim that the path linking the Fermat point to three terminals is the minimum network either.

In the previous section I showed that finding the minimum network interconnecting several terminals is a very difficult problem and that exact minimum length networks are possible to obtain in a GIS for the case of two and three terminals. In this section, I will describe the algorithms I developed to emulate the two different phases of the logging extraction process adopted by loggers, namely (1) the definition of the logging site and (2) the construction of a skid trail network cheaper than the solution provided by current GIS algorithms. For this second logging extraction stage, I developed two algorithms that make use of the graph theoretical material presented above.

As described in section 4.1, in the first step of the logging extraction process, taken to exploit an area, a logger defines the boundaries of the logging site after a surveyor has identified valuable trees. In a GIS, I define the 'logging site' by computing the 'least cost convex hull set' (LCCHS) of all trees, presumably identified by a surveyor. A set X is said to be strictly convex if for any pair of points $x_0, x_1 \in X$, the point x is also an element of X, where

$$x = \lambda x_0 + (1 - \lambda)x_1 \qquad \lambda \in (0, 1)$$

In other words, a convex set has the property that all points on a segment, connecting any two points in the set are also in the set. The convex hull is the smallest convex set that contains all elements of a given set.

I adapt this definition to the least cost path problem as follows. Suppose we have a set T with n elements, or terminals. Then, a LCCHS is defined as the smallest set containing all elements of T such that all points that are part of the least cost path between any two points $t_0, t_1 \in T$ also lie entirely within this set. Thus, the logging site is taken to be the boundary of the LCCHS, which includes all trees to be harvested.

The LCCHS can be determined as follows. First, calculate the least cost path of every element of T to all other elements. Then, the LCCHS boundary is formed by the 'external edges' or the paths that enclose all other paths. This process can be computationally very expensive because for a set with n terminals, $n-1$ accumulative least cost surfaces and $\sum_{i=1}^{n-1} n - i$ paths will have to be calculated. However, least cost paths between points that are located in the middle of the set are very unlikely to be part of the set boundary. Hence, I devised a simpler method that starts by calculating the convex hull of the set T in a Euclidean plane. In a GIS, this is easily accomplished by first creating a triangulated irregular network (TIN),[9] and dissolving all internal lines to form a single polygon (Figure 4.7 A). Let the terminals forming the

[9] A TIN is a vector data model used to represent continuous surfaces by linked triangles that creates diamond-like facets. These triangles are constructed such that one vertex of the triangle is connected to its two nearest neighbors. See Krevelt (1997) for details.

vertices of this single polygon be grouped in the set $W \subseteq T$. Next, I calculate the least cost path of each element of W to all other elements of W and proceed by selecting the 'external edges' (Figure 4.7 B). If any terminal $t \in T \backslash W$ (read terminal t which is an element of set T but not an element of W) is outside the paths forming the external edge, then this terminal t is moved to set W and the process is repeated until all terminals are on or inside the boundary (Figure 4.7 C). With luck, this process is repeated only a few times. If the number of elements in W is much smaller than those in T, then savings in computational time can be substantial. The resulting boundary is taken to be the LCCHS. Notice that the LCCHS is not always a convex set in the Euclidean geometric sense.

With the logging site defined, the logger proceeds to build the main road from the current infrastructure to the logging site. In a GIS, this step is easily accomplished since this is a simple two-terminal problem, where the current infrastructure is the origin and the logging site the destination. Therefore, the application of the Dijkstra algorithm returns such minimal cost path between these two terminals. This least cost path is taken to be the main road that provides access to the logging site.

In order to recreate the second step in the logging process, I adapted two algorithms to create a 'better' network than the solution provided

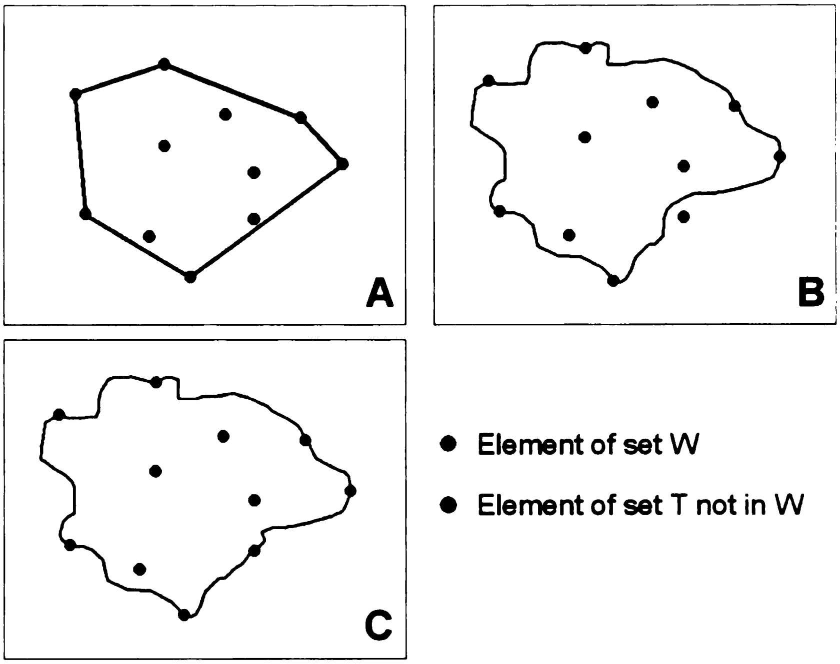


Figure 4.7. Algorithm to generate the least cost convex hull set.

by the ordinary least cost path implementations. Better is taken here to be a network with building costs less than the ones provided by the GIS functions. In the first algorithm, I use the 'spanning and rectilinear tree' idea to successively form the network. The algorithm works as follows (Figure 4.8). Three data grid inputs are used: the DEM, a binary grid with values set to one if a terminal (tree to be harvested) exists in the cell (**Terminals** grid), and a grid with the current road infrastructure to where all trees should be brought (**Road** grid). For this exercise, I take this to be a point (cell) where the LCCHS intersects the main road. Next, I calculate the accumulative cost, using the Dijkstra algorithm, from `Road` to the nearest (cheapest) terminal. Then, I build the least cost path (skid trail) linking these two points. Finally the `Road` and `Terminals` grids are updated, by including this newly built segment and by eliminating the closest terminal that was just reached. This process is repeated until all terminals are reached. This algorithm is a combination of the spanning and rectilinear trees in the Euclidean space metric (Figure 4.1, panels D and E). In a spanning tree, one terminal is connected to its closest neighbor and subsequent connections are allowed only to already connected terminals. In other words, all elements of set K of terminals are also the nodes (set V). On one hand, my algorithm is similar to the spanning tree because it searches the closest neighbor, in the building cost metric, that is then linked by the minimum path. On the other hand, my algorithm allows connection to any portion of the `Roads` grid, just like rectilinear trees can intersect any portion of a line segment. Using graph theory terminology, the set of nodes that make up the least cost path between two terminals (set Q) is added to the set of terminals K that were already searched (Figure 4.4). Hence, any node in this new set K is a potential branching point for a new skid trail segment in the next iteration.

The second algorithm implements the Steiner solution to the three vertices case explained in the graph theory section above. The same

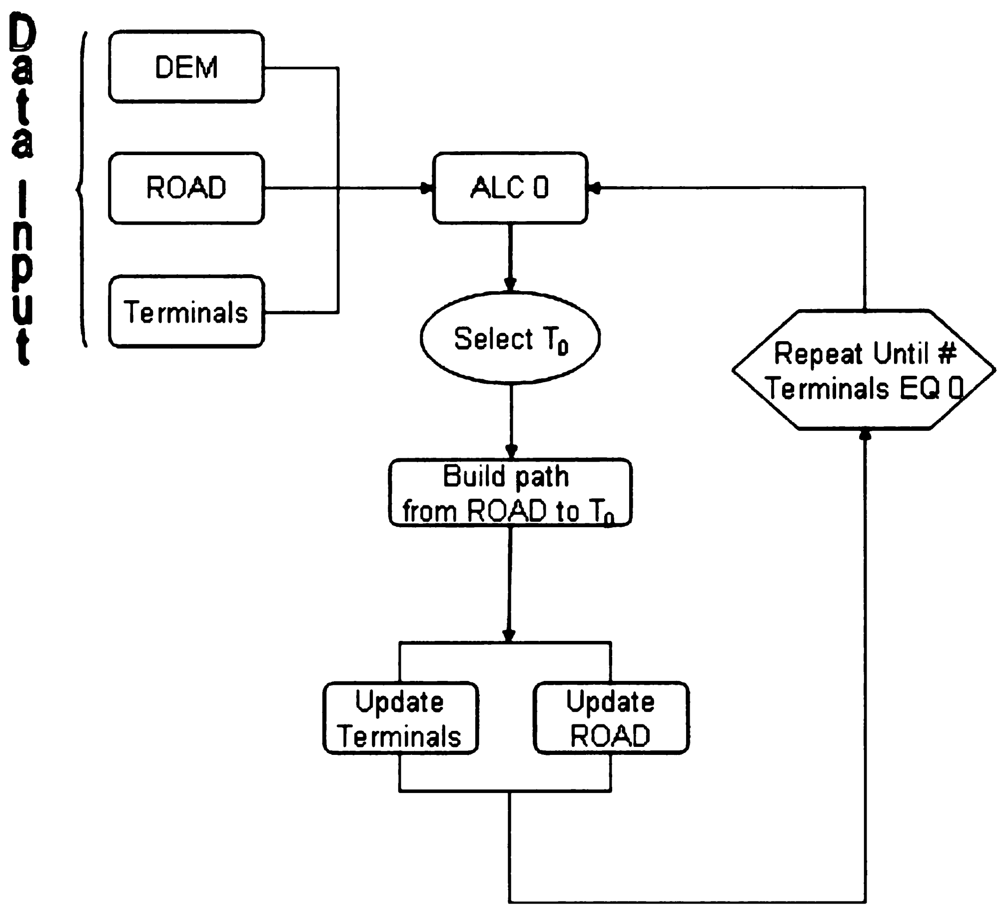


Figure 4.8. Pseudocode for the spanning/rectilinear tree algorithm.

inputs used in the spanning tree algorithm are used in this more complicated algorithm (Figure 4.9). The algorithm begins by calculating the accumulative least cost from the **Road** grid (ALC 0). Then, the terminal with the cheapest cost to be reached is selected (T_0) and a second accumulative least cost from this terminal is calculated (ALC 1). Next, the cheapest terminal to be reached from this first terminal is also selected (T_1). If the cost of reaching this terminal T_1 from T_0 is greater than the cost of reaching T_0 from **Road**, than a simple unique path is build from **Road** to T_0. Otherwise, the algorithm calculates the Steiner point. To this end, it calculates the accumulative least cost from T_1 (ALC 2) and sums the three accumulative costs ALC 0, ALC 1, and ALC 2. The Steiner point (SP) is the smallest value of the sum of these three accumulative grids, as explained in the graph theory section. After this point is selected I calculate another accumulative least cost from this point (ALC 3) and build the skid trails from SP to terminals T_0 and T_1 and to the **Road** grid. Finally, the **Road** grid is updated to include these built skid trail segments, as well as the **Terminals** grid whose T_0 and T_1 values are changed do zero (since they were already reached). If the Steiner point is the same as one of the vertices, then there will be two segments built from **Road** to T_0 and from T_0 to T_1. Otherwise, three segments will be built departing from the Steiner point to T_0, T_1, and the **Road** grid. This process is repeated until all terminals are reached. The resulting network is the logging skid trail network.

In the two algorithms described above, the accumulative least cost surface was calculated using a program I wrote in Iterative Data Language (IDL) that calculates the cumulative least cost by searching each of the eight neighbors separately and choosing the one with the smallest cost (see programs in Appendices B and C). IDL is a powerful matrix oriented computer language that is widely used in remote sensing and visualization applications but has not been used so far, to my knowledge, in GIS applications such as this. The algorithm implemented to calculate the accumulative cost surface combines the search for a least accumulative grid using the Dijkstra algorithm with the anisotropic slope information as described by Collischonn and Pillar (2000) and Yu et al. (2003). Thus, my program overcomes the limitation of assigning a Horn-average slope to each cell as explained in Chapter 3. No slope information is lost due to averaging and the least cost path direction, which is a function of slope, is assigned more precisely. To simplify the calculations, I assigned the friction value, or the cost of traversing a cell, as the absolute difference in height between two cells, since slope can be calculated as $\Delta height/\Delta distance$. The cost of traversing one cell to another adjacent cell is then this slope value multiplied by the distance between the two cells (see equation 4.2), which simplifies to

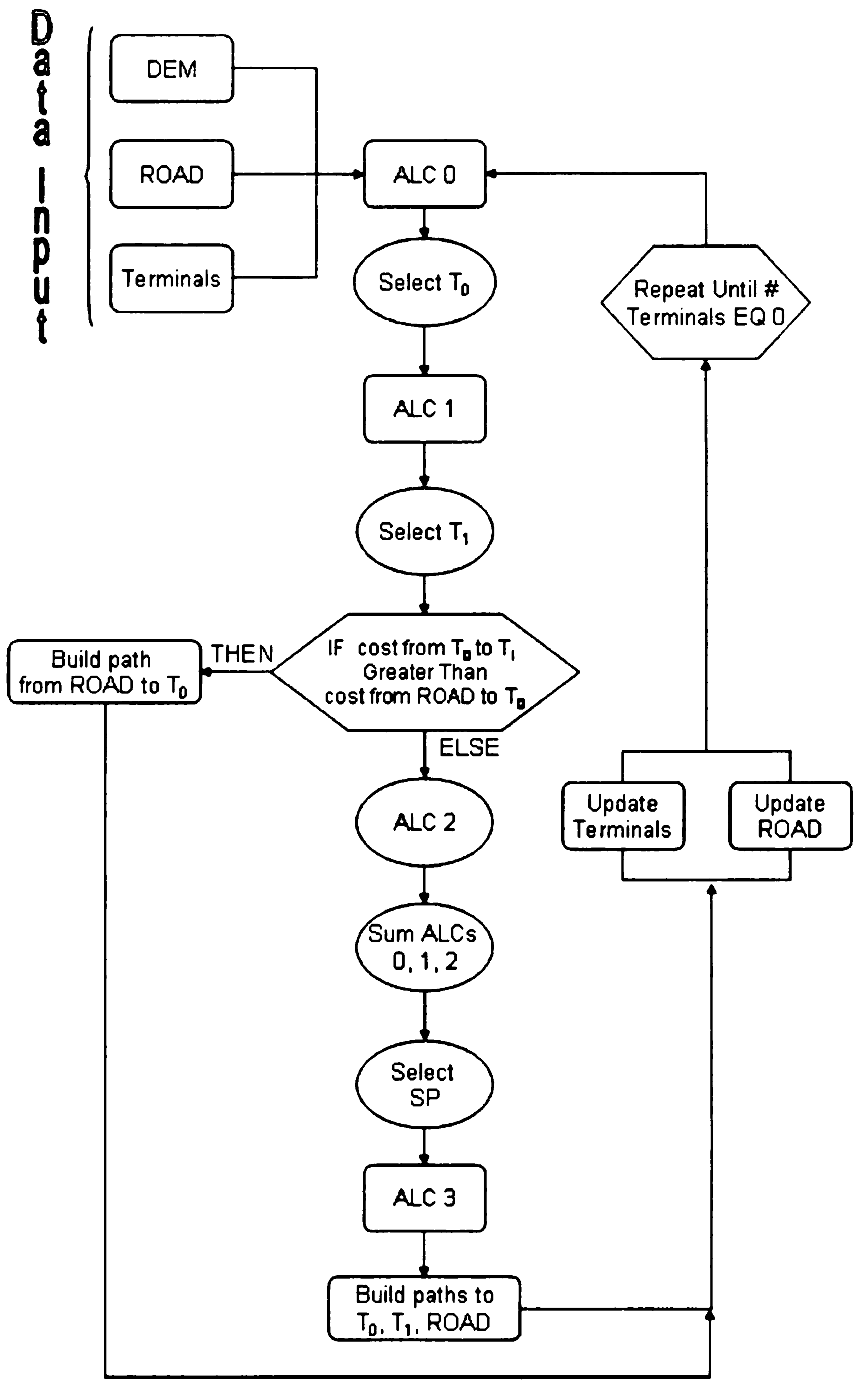


Figure 4.9. Pseudocode for the 3-terminal Steiner problem

difference in height.

4.5 The Dataset

A critical piece of information necessary to model logging skid trails is the location of each tree to be harvested. This information was obtained for a logging site in Acre State, located in the western part of the Brazilian Amazon (Figure 1.4). This site, with an area of approximately 600 hectares, was part of a mahogany forest management experiment conducted by IMAZON (*Instituto do Homem e Meio Ambiente da Amazônia*) and is approximately 30 km off BR-364 highway (Figure 4.10).

This site size is roughly what a logging company would harvest in a year. A typical medium-sized logging firm processes 10,000 m^3 of roundwood annually. The area in forest necessary to supply this amount of roundwood depends on the density of commercially valuable trees. Dense forests in Eastern Amazonia contain 20-60 m^3 of commercial roundwood (5-10 trees) with an average of approximately 38 $m^3 ha^{-1}$ (Verissimo et al., 1992).[10] Less productive forests yield 10-20 m^3 per hectare (Uhl et al., 1991). Hence, a mid-sized sawmill should exploit each year an area of about 500 ha to obtain raw material for processing.

[10] In many cases, loggers return to the same site years later to harvest trees that were not previously accepted in the market and the total volume harvested can be above 50 $m^3 ha^{-1}$.

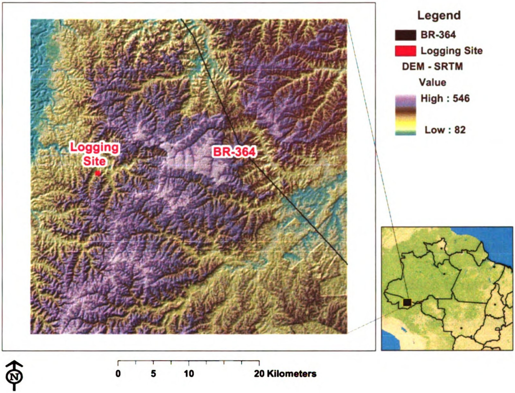


Figure 4.10. Location of the logging extraction site in Acre State, Brazil.

In this analysis, I used two different sources of elevation data. To simulate the first stage of the logging process, or the least cost path from the existing infrastructure to the logging extraction site, I used SRTM data projected to UTM zone 19 south and the official infrastructure in digital format from IBGE (1997) (Figure 4.10). For the second stage, or the simulation of the skid trail network, I used a much more detailed DEM that I created from field measurements conducted by a team of biologists, foresters, and field assistants.

This team ran transects 30-60 m apart in the north south direction and measured the *relative* altitude, with respect to a zero benchmark located near a road, using clinometers and distance tapes (Figure 4.11).[11] These points, with their respective coordinates and height attribute were imported into ArcView®. I used these elevation points to generate a one-meter cell resolution digital elevation model applying the spline or thin plate interpolation method, with 12 points per region for the local approximation. The spline method generates a continuous surface constrained by two conditions. First, the interpolated surface is exact, which means that the surface values and data point values are the same at the data points. Second, the surface must have minimum curvature with a continuous first derivative. This method ensures a smooth (continuous and twice differentiable) interpolated surface and is adequate to represent terrains that do not have abrupt changes in height values (e.g. cliffs) (Burrough & McDonnell, 1998; ESRI, 2002).

The location of each tree was recorded with a handheld GPS set to UTM zone 19 south coordinate system. This area is characterized by open forests with many palm trees and openings in the canopy (ACRE, 2000), which facilitates GPS signal reception from satellites and diminishes measurement errors. No accuracy was reported though.

The resulting DEM grid was 4731 by 1273 one-meter cells. Since

[11] For a detailed description of methods, please refer to Grogan (2001).

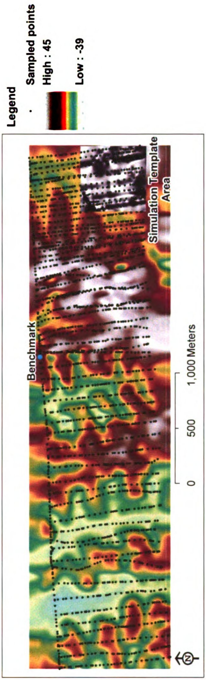


Figure 4.11. Area surveyed and sampled points for height measurement.

the original relative height measurements contained negative values, I shifted all heights by adding 30 meters to each value. Also, in order to capture the point decimal height measurement accuracy and, at the same time, avoid a float data type grid that requires more processing memory, I multiplied all values by 10. The programs I wrote, in particular the three terminals Steiner algorithm, are computationally very demanding. Therefore, in order to diminish the computation time, I clipped a 600 $\times$ 600 m area, located on the southwestern corner of the site (Figure 4.11), and increased the size of the grid cell to 3 m, using cubic convolution (ESRI, 2002), resulting in a final template of 200 by 200 cells or a set of 40,000 nodes or vertices.[12] In this 36 hectares area, 105 trees were tagged by the field work team. The height range for this DEM used in the analysis was between 82 and 546 tenths of meters (Figure 4.12).

4.6 Results

As mentioned, the simulation aims to replicate the decision making process of the whole logging operation, which begins with the definition of the logging extraction site. Figure 4.13 display this first step, which

[12] I could have generated this 3 m resolution DEM directly from the spline interpolation of the height measurements but since the objective of this work is to produce a template on which I can test the algorithms, the indirect approach does not pose a serious problem. Moreover, I became aware of the enormous time spent on processing only later on, after the original DEM was already produced.

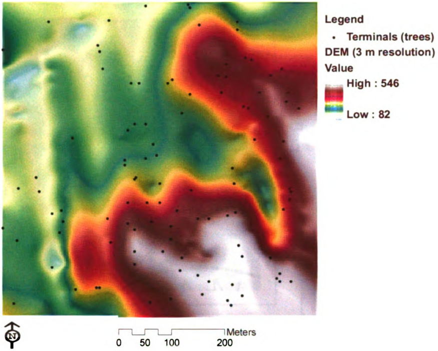


Figure 4.12. Grid DEM template with surveyed trees' locations (terminals)

consists in calculating the least cost convex hull set. The first figure on the left (Panel A) is the first step of such algorithm, where the convex hull set in a Euclidean plane is generated by dissolving the TIN internal lines. The figure on the right panel (B) is the least cost convex hull set that was generated by running the least cost from each vertex that is element of the convex hull boundary W to all other vertices in W.

Once the logging site is defined, the logger builds the main road linking the current infrastructure to the logging site. To this end, I calculated the least cost path from BR-364 to the LCCHS using the

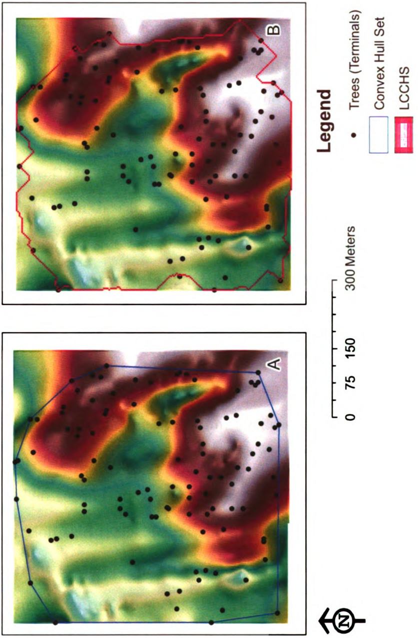


Figure 4.13. A - Convex hull and B - Least cost convex hull set.

program I wrote in IDL, which calculates the accumulative least cost surface using the slope information in all eight directions. Since this least cost path calculation uses the SRTM 90 m resolution data and the LCCHS is at 3 m scale, I converted the latter into a 90 m resolution grid. This conversion created a blunt, coarse LCCHS polygon that served as the destination for the least cost path exercise. Ideally, both datasets should be in the same fine scale but detailed elevation information is not available outside the logging site. Figure 4.14 shows a 3D perspective view (to the east) of the resulting least cost path (red line). The path begins in a higher flat plateau, moves in the site direction, gets to a crest and gently descends to a valley. The path continues to follow the lower terrain until it gets to the extraction site. This path is exactly what I expected from the algorithm because the path makes the necessary turns to avoid steep slopes.

The second step consists of finding the minimum network of extraction skid trails. I first show the ordinary solution provided by the current available software functions, which utilizes the Dijkstra algorithm. Figure 4.15 shows that the ordinary solution generates a great number of unnecessary parallel networks and hence, is not a cost-saving network to build.

I colored each trail segment by its 'hauling traffic.' For example, segments in black are the shared least cost paths to reach 13-105 trees

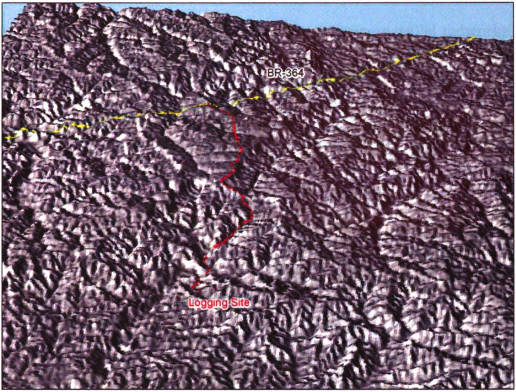


Figure 4.14. 3D shaded view of the least cost path (in red) from BR-364 to the logging extraction site, vertically exaggerated fifteen times.

from the origin where the main road and the LCCHS intersects. These colored trails show that if we utilize Tomlin's approach, the trail in black would be the only clear distinguishable path to select for subsequent interactions (see footnote 5 in Chapter 4). If the second group of most shared segments of 7-11 trees is selected as well (upper middle-left part of figure in dark red), then Tomlin's approach fails because those segments are parallel and consequently at least one of them could be eliminated to diminish building costs. Hence, this figure suggests that Tomlin's approach would generate unnecessary parallel networks, depending on how the hauling traffic cut-off figure is assigned. Moreover, even if dark segments are assigned as 'roads', it does not eliminate the possibility of generating parallel segments in subsequent iterations (light red, magenta segments).

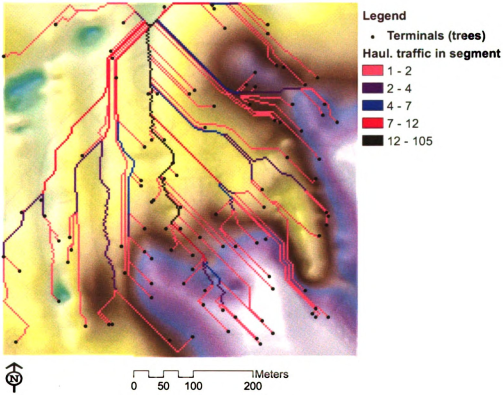


Figure 4.15. Ordinary solution to the least cost path.

The results of the first algorithm I developed, the adaptation of the spanning and rectilinear trees, are shown in figure 4.16. The origin is the green dot on the central upper part of the grid, where the main road coming from BR-364 intersects with the LCCHS calculated in step 1. The result for the second algorithm, which utilizes the idea of finding the Steiner point between three accumulative least cost surfaces, is presented in Figure 4.17.

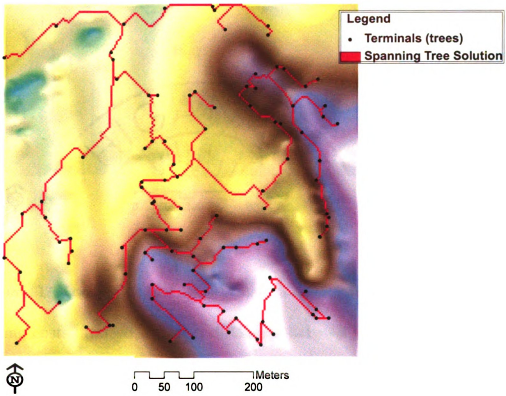


Figure 4.16. The 'spanning tree' network for 105 terminals and one origin.

The results from both algorithms do not differ considerably. Differences between the networks are difficult to observe visually by comparing both graphics. In Table 4.1, I present the differences in road

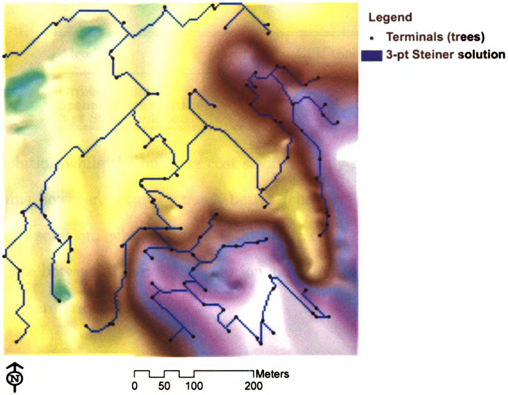


Figure 4.17. Logging skid trail network using the 3-terminal Steiner algorithm.

building costs. Indeed, the cost difference between both algorithms is only 25 units or less than one percent improvement with respect to the spanning tree solution. However, the three-point Steiner spent almost 300 minutes of CPU time to return a solution while the spanning tree algorithm spent only 84 minutes, an almost fourfold difference.[13] At least for this particular instance of the problem, computing cost for the three-point Steiner algorithm are exorbitant relative to the spanning

[13] I used a Xeon Pentium 1.5 GHZ with 512 MB of RAM computer to run the programs.

Table 4.1. Network building cost and processing time spent in each algorithmic solution.

Algorithm	Road Cost	CPU time (min)
Ordinary solution	10.969	< 2
Spanning tree solution	3.520	83.64
3-pt Steiner solution	3.495	289.60

tree solution while the building cost saving is only marginal. Both algorithms however, return a much better (cheaper) network than the ordinary solution, which costs a total of almost 11,000 units.[14] The difference between the ordinary solution and the two algorithms implemented here are obvious.

4.7 Discussion

As I showed in the results section, the two algorithms I wrote return a much cheaper skid trail network than the solution provided by current GIS functions. However, I do not know how these results compare to the actual skid trail network because data on skid trails are not available. Yet, there are reasons to believe that loggers do not design the network carefully to avoid unnecessary trails. Barreto et al. (1998) showed that simply tagging the trail path in the forest before tractors actually open the trails reduces the density of trails by 32.6%, when compared to current unplanned operations. In unplanned operations, the team that

[14] I also programmed a function to calculate these costs so that each segment that is used by more than one terminal is not double counted in the final cost. See equation 4.3.

cuts down the trees does not communicate with the team that builds trails and hauls trees to a patio.[15] Hence, this second team 'guesses' where the fallen trees are by looking for openings in the canopy and obviously are much more prone to build unnecessary trails. In many instances, tractor drivers build trails and reach natural openings in the canopy where no tree are cut down. In other cases, cut trees are simply left behind because drivers are unable to find them. Hence, in this application, my algorithms seems to have a normative use (i.e. how should the trail network be designed) in addition to some predictive capability.

These algorithms can also be used to model roads at different scales. For example, instead of defining trees as terminals, I could define logging landings (or patios) as terminals and design the road network linking those patios. At an even broader scale, I could define different logging sites as terminals and use the algorithms to predict the minimum network of main roads connecting different sites. Therefore, these algorithms could be used to predict forest fragmentation caused by roads at many different scales.

Fragmentation caused by logging extraction trails is different from the fragmentation caused by the other two types of roads (destination determinate and indeterminate). Although logging operations are very

[15] Patios are clearings where loggers pile up tree trunks before loading them onto trucks for transport to sawmills.

selective and take only 5 to 10 trees per hectare, the extraction process damages many nearby trees. For each tree extracted, 27 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 & Uhl, 1997; Gerwing, 2002), which can ultimately lead to a complete change in species composition and in land cover (Cochrane & Schulze, 1999).[16]

On the other hand, the main road linking the current infrastructure to the logging site can be occupied by settlers, just like destination determinate and indeterminate roads. Once such example are the roads built by loggers to access mahogany-rich sites in southern Pará State, described in Verissimo et al. (1995). In that area, loggers in search of mahogany-rich sites opened more than 3,000 km of roads into the forests, branching off the state road PA-279 to the north. Colonists rapidly followed loggers and took possession of 50-100 hectares lots along those roads closer to the official infrastructure up to the border of the Apyterewa Indigenous Reserve. However, according to 2000 Landsat ETM^+ satellite images (not shown), even the southern portion of the Apyterewa reserve seems to be occupied and deforested. Thus, roads connecting official infrastructure to logging sites can generate fragmentation patterns, caused by subsequent clear-cut deforestation,

[16] Intensive logging, such as practiced in Indonesia where 50-120 m^3ha^{-1} are exploited, can be even more damaging (Curran et al., 2004).

similar to destination determinate roads.

CHAPTER 5

Conclusions

This dissertation presents a GIS simulation approach that attempts to replicate different types of logging roads that set the pattern for subsequent forest fragmentation caused by deforestation. In Chapter 2, I presented background information about the development of the transportation system in the Amazon and the different patterns of roads and forest fragmentation. I also provided an overview of the role of roads in determining the overall deforestation pattern. I discussed in particular how the federal road network developed and was designed to link pre-existing population centers, which in turn were dependent on geographical characteristics of rivers. I concluded that federal roads can be considered exogenous to deforestation because bureaucrats did not have a clear intention to route the roads towards fertile soils to reap benefits from future agricultural development.

In Chapter 3, I attempted to model the fishbone pattern of forest fragmentation as a function of the economic behavior of loggers, key agents of land cover change in the Amazon region. Although my success was somewhat limited in generating the observed network, several conclusions can be drawn from the analysis 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 mid-run period of several decades following initial colonization. Consequently, the fishbone pattern most likely arises on the basis of multi-agent 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.

My 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 will probably exert substantial influence on the pattern of fragmentation at a regional scale given their economic importance, although in the study area such effects are only incipient.

In Chapter 4, I reproduced in a GIS the actual two-stage process of logging as described by field informants. I presented two GIS innovations in this chapter. The first is the concept of least cost convex hull set that can be used to define areas encompassing all possible least cost paths between a set of points. This concept was used to define the logging site area. The second innovation were the two algorithms developed to calculate networks interconnecting several points in a raster environment. Although the algorithms do not return the ultimate optimal minimum network, results show that my algorithms do perform much better than current functions available in commercial GIS software that uses the Dijkstra algorithm. Algorithmic improvements could be incorporated to decrease the cost of the total network but, as demonstrated by complexity theorists (i.e. NP-complete problem), at very large computational costs.

These algorithms could have a normative use to help design skid trails that are less damaging to the forest than current unplanned logging operations and hence, could be beneficial to those concerned about sustainable development of the forestry sector. An easy extension of this program would be to include trees that are still small but are valuable for a second cycle harvest. One could simply increase the 'friction cost' surrounding those trees so that least cost trail segments would have to detour and avoid damaging those valuable trees. The same could be done for seed trees that should be kept standing to maintain reproductive/regenerative capacity or trees with edible fruits and seeds that are important for animals' diets.

I could also use these algorithms and programs to model, in a positive sense, logging roads in a broader scale by linking different potential logging sites. If some kind of tree density surface grid were available, I could define potential logging sites by assessing their profitability and then connect these sites by a minimum network. As such, I might be able to explain many logging road patterns observed on satellite images throughout the Amazon basin.

The conservation community can benefit from the findings of this dissertation as well. This dissertation provides a better understanding of the behavior of actors engaged in road building construction and the results can help policy makers and conservationists better formulate policies to avoid further landscape fragmentation. In particular, my research showed that once an area is opened for colonization, local agents take upon themselves to develop the region, even without further governmental support. Local agents, and loggers in particular, have the financial capital and local political support to keep building and improving the initial infrastructure set in place by the government. Hence, the lack of new official investments in infrastructure is not a constraint for the expansion of the road network. My findings suggest the opposite: governmental institutional presence is necessary in the one hand to provide the infrastructure so badly needed in those areas and, on the other hand, to curb undesirable expansion of the frontier that can have damaging and long lasting consequences to the conservation of biodiversity.

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 dissertation provided an initial attempt to do so for an old colonization frontier in the Amazon basin.

I 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 my focus on loggers as spatial agents, and the use of GIS software to model their spatial decision-making processes. Although my 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. Finally, my dissertation showed that the combination of theory, applied field work, and computational GIS can be a powerful combination to understand the social processes that generate patterns in the landscape.

APPENDIX A

Field Interviews

The field interviews were conducted during the period 07-21 July 2004 in Uruará and were part of a larger project supported by NASA's Large Scale Biosphere and Atmosphere Program (Project: A Basin-Scale Econometric Model for predicting future Amazonian landscapes; PI: Dr. Robert Walker). The field work team applied a formal survey questionnaire, including questions regarding road construction, road's segments expansions, choice of route, and maintenance. I participated in interviews in seven different *travessões* that spur off the Transamazon. In each travessão, I interviewed three to four colonists. These colonists were selected using the 'snowball' sampling approach as follows. In each travessão, I first obtained information about the oldest colonists currently living in the area as well as directions on how to find their lot, by informally chatting with any person I met. I also asked for people that might be knowledgeable about the opening/extension of a particular travessão. Next, I proceeded to interview those subjects that were appointed to be long time residents. Each person interviewed was also asked to suggest other names for further interviews.

In the case of the Transtutuí, I interviewed the logger that build it and the colonist that participated in the conflict over a detour on his former property. In the case of the Transiriri, I interviewed colonists along the whole stretch of the road as well as old residents in the village at the destination point where a port, used to transport logs in barges, still exists and is currently operational.

The information about the two stages of the logging operation in the skid trail case, was obtained from a interview with another logger who is very knowledgeable about road construction since he is specialized in road building.

Other interviews that provided contextual information included: INCRA's (Institute for Agrarian Reform) supervisor in Uruará, city council members, and municipal secretary of infrastructure.

APPENDIX B

IDL Program to Calculate Directional Dependent Slope Least Cost Surfaces

```
;*******************************************************************************
;+
; NAME:
;    LCDEM
;
; PURPOSE:
;      Calculates the accumulative least cost surface and the "back link grid"
;      Needs four inputs: a dem grid, a grid determining the origin from which
;        the cost will be accumulated and a destination grid. NO FRICTION GRID
;        IS USED. SEE <LCGRID> FUNCTION
;
; OUTPUT:
;     A structure in which the first element is the accumulative cost grid
;        and the second element is the back link grid
;
; AUTHOR:
;      EUGENIO ARIMA
;      Imazon & Michigan State University
;
; CREATED:
;    Jan 06 2005
;
```

```
; USAGE: FUNCTION
;     IDL> lcpath = lcdem(demgrid, origin, destination, csize)
;      where
;      demgrid is the dem grid
;      origin = origin grid
;      destination = destination grid
;      csize is the cellsize
;
; MODIFICATION HISTORY:
;
;       Jan 12, 2005:
;           Ccost is no longer the whole matrix total sum but an array
;             multiplication (faster).
;
;       Jan 18, 2005:
;           Include a nodata check
;
;       Feb 14, 2005:
;          Include fourth input grid of destination. Program runs until
;           the accumulative cost to destination are calculated. All other
;           non assigned cells are given a no-value. Saves computation time.
;
; GENERAL COMMENTS:
;
;
;       I use the Dijkstra algorithm concept to create this program
;        (see Dijkstra 1959).
;       The advantage of this program is that you can define your own cost
;         functions, i.e. can use for example anisotropic cost surfaces.
;
;       This program is still much slower than ArcInfo costdistance functions
;         because of the many IF statements and the loop REPEAT UNTIL.
;       This program returns approx. 200 values per second.
;       Any suggestion on how to improve the code is welcome...
;-
;********************************************************************************
function lcdem, dem, orig, dest, csize
T = SYSTIME(1)
csize = csize
SourceGrid = temporary(orig)
nDims = size(SourceGrid, /dimensions)
;
;
; This program handles the bordering cells a little oddly.
; I create an extra row and column on each side (four) to avoid
;    checking whether the cell exist or not. Of course, those
;    bordering cells are not included in the processing
;    (are assigned a fake 'already searched.')
;
```

```
ncol = ndims[0]+2
nrow = ndims[1]+2
;print, 'Number of columns: ', ncol
;print, 'Number of rows: ', nrow
sg = temporary(make_array(ncol, nrow, /byte, value=0))
;
; Plugging the original source grid into the expanded matrix
sg[1:ncol-2, 1:nrow-2] = temporary(SourceGrid)
SourceGrid = temporary(sg)
;
;
; Next, import the dem cost grid file

CG = temporary(dem)
;
cgtmp = temporary(make_array(ncol,nrow, /integer))
;
; Plug the original dem grid into the expanded matrix
cgtmp[1:ncol-2, 1:nrow-2] = temporary(CG)
CostGrid = long(cgtmp)
;
;print, 'Max elevation is: ', max(CostGrid)
;print, 'Min elevation is: ', min(CostGrid)
;
;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; This is the major change implemented in version 10.
; See bottom of Repeat Until loop.
DestGrid = temporary(dest)
dg = temporary(make_array(ncol, nrow, /integer))
dg[1:ncol-2, 1:nrow-2] = temporary(DestGrid)
DestGrid = temporary(dg)
Dest = temporary(where(DestGrid GT 0))  ; see the repeat loop
nDest = n_elements(Dest)
;print, '# of trees is: ', nDest
;DestArray = make_array(nDest, /byte, value = 1)
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;
;
noval = where(CostGrid EQ 0)
;
;Print, '# of novalue data is: ', n_elements(noval)
;
origin = where(SourceGrid GE 1)
origin1 = origin
;
; Define the matrix of already searched cells
JaSearch = make_array(ncol, nrow, /byte, value = 0)
JaSearch[origin] = 1
```

```
; Set the boarders as already searched
JaSearch[0,*] = 1
JaSearch[*,0] = 1
JaSearch[ncol-1, *] = 1
JaSearch[*, nrow-1] = 1
;
; Set novalue data as already searched
if noval NE [-1] then JaSearch[noval] = 1
;
; Define the back link grid
BackLink = make_array(ncol, nrow, /integer)
;
; Define the accumulative cost grid
AccumCost = make_array(ncol, nrow, /float, value= -1)
AccumCost[origin1] = 0
;
; To initialize the program, we first calculate the least
; cost from the origin to the neighborhood of the origin
;
nOrigin = n_elements(origin)
;Print, '# of origin points: ', nOrigin
;Print, ''
; Define positions
; For the DEM, I want the difference in height
; Assign -1 relative to central position
;
pos0 = fltarr(9)
pos0[4] = 1
pos1 = pos0
pos1[3] = -1
pos2 = pos0
pos2[0] = -1
pos3 = pos0
pos3[1] = -1
pos4 = pos0
pos4[2] = -1
pos5 = pos0
pos5[5] = -1
pos6 = pos0
pos6[8] = -1
pos7 = pos0
pos7[7] = -1
pos8 = pos0
pos8[6] = -1
;
;
; Loop over each cell considered to be the origin
for i =0, nOrigin-1 do begin
;
```

```
; Mask is the 3x3 neighborhood matrix of indexes
mask = lon64arr(9)
;
tmp = origin[i]; this is the cell in the middle (positive)
tmp1 = origin[i] - 1
tmp2 = origin[i] - ncol - 1
tmp3 = origin[i] - ncol
tmp4 = origin[i] - ncol + 1
tmp5 = origin[i] + 1
tmp6 = origin[i] + ncol + 1
tmp7 = origin[i] + ncol
tmp8 = origin[i] + ncol - 1
;
; This position assignment is very important
; Look at ArcInfo help to understand why.
; Search for costbacklink in grid - Online Help.
;
mask[0] = tmp2
mask[1] = tmp3
mask[2] = tmp4
mask[3] = tmp1
mask[4] = tmp
mask[5] = tmp5
mask[6] = tmp8
mask[7] = tmp7
mask[8] = tmp6
;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;
; These are the functions that determine the cost of traversing the cells
; You can basically change it to whatever you want.
;
; Example for the origin:
;        ccost1 = transpose(CostGrid[mask]) # pos1
;        ccost2 = transpose(CostGrid[mask]) # pos2
;
; Example for other cells:
;      ccost1 = transpose(CostGrid[mask]) # pos1 + AccumCost[smallercost[0]]
;      ccost2 = transpose(CostGrid[mask]) # pos2 + AccumCost[smallercost[0]]
;
;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; The basic formula is (rise/run)
; For cells in diagonal: [(H1-H2) / (csize*sqrt(2))]
; For the 'rook' case, the formula is: (H1-H2) / (csize)
; I used the absolute height difference. For certain applications
;   moving downslope is easier than upslope (should remove the abs fct)
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Since we have to multiply for the distance travelled, the csize
```

```
;   cancels out (no division by csize or csize*sqrt(2))
; I add a value of 1 just to eliminate the possibility of zero cost for
;   flat areas
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
ccost1 = abs(transpose(CostGrid[mask]) # pos1) + 1
ccost2 = abs(transpose(CostGrid[mask]) # pos2) + 1
ccost3 = abs(transpose(CostGrid[mask]) # pos3) + 1
ccost4 = abs(transpose(CostGrid[mask]) # pos4) + 1
ccost5 = abs(transpose(CostGrid[mask]) # pos5) + 1
ccost6 = abs(transpose(CostGrid[mask]) # pos6) + 1
ccost7 = abs(transpose(CostGrid[mask]) # pos7) + 1
ccost8 = abs(transpose(CostGrid[mask]) # pos8) + 1
print, ''
;
; plug values on AccumCost
; position 1
if ( Accumcost[origin[i] - 1] EQ -1 ) AND ( JaSearch[origin[i] - 1] EQ 0 ) $
        then begin
     Accumcost[origin[i]- 1]= ccost1
     BackLink[origin[i] - 1] = 1
     endif else begin
     if (ccost1 LT Accumcost[origin[i] - 1]) AND ( JaSearch[origin[i] - 1] EQ 0 ) $
      then begin
     Accumcost[origin[i] - 1] = ccost1
     BackLink[origin[i] - 1] = 1
     endif
endelse
; position 2
if ( Accumcost[origin[i] - ncol -1] EQ -1 ) AND $
       ( JaSearch[origin[i] - ncol -1] EQ 0 ) then begin
     Accumcost[origin[i] - ncol -1]= ccost2
     BackLink[origin[i] - ncol - 1] = 2
     endif else begin
     if (ccost2 LT Accumcost[origin[i] - ncol -1]) AND $
      ( JaSearch[origin[i] - ncol - 1] EQ 0 ) then begin
     Accumcost[origin[i] - ncol -1] = ccost2
     BackLink[origin[i] - ncol - 1] = 2
     endif
endelse
; position 3
if ( Accumcost[origin[i] - ncol] EQ -1 ) AND $
      ( JaSearch[origin[i] - ncol] EQ 0 ) then begin
     Accumcost[origin[i] - ncol]= ccost3
     BackLink[origin[i] - ncol] = 3
     endif else begin
     if (ccost3 LT Accumcost[origin[i] - ncol]) AND $
       ( JaSearch[origin[i] - ncol] EQ 0 ) then begin
     Accumcost[origin[i] - ncol] = ccost3
     BackLink[origin[i] - ncol] = 3
```

```
     endif
endelse
; position 4
if ( Accumcost[origin[i] - ncol + 1] EQ -1 ) AND $
      ( JaSearch[origin[i] - ncol + 1] EQ 0 ) then begin
     Accumcost[origin[i] - ncol + 1]= ccost4
     BackLink[origin[i] - ncol + 1] = 4
     endif else begin
     if (ccost4 LT Accumcost[origin[i] - ncol + 1]) AND $
     ( JaSearch[origin[i] - ncol + 1] EQ 0 ) then begin
     Accumcost[origin[i] - ncol + 1] = ccost4
     BackLink[origin[i] - ncol + 1] = 4
     endif
endelse
; position 5
if ( Accumcost[origin[i] + 1] EQ -1 ) AND $
     ( JaSearch[origin[i] +1] EQ 0 ) then begin
     Accumcost[origin[i] + 1]= ccost5
     BackLink[origin[i] + 1] = 5
     endif else begin
     if (ccost5 LT Accumcost[origin[i] + 1]) AND $
       ( JaSearch[origin[i] + 1] EQ 0 ) then begin
     Accumcost[origin[i] + 1] = ccost5
     BackLink[origin[i] + 1] = 5
     endif
endelse
; position 6
if ( Accumcost[origin[i] + ncol + 1] EQ -1 ) AND $
     ( JaSearch[origin[i] + ncol + 1] EQ 0 ) then begin
     Accumcost[origin[i] + ncol + 1]= ccost6
     BackLink[origin[i] + ncol + 1] = 6
     endif else begin
     if (ccost6 LT Accumcost[origin[i] + ncol + 1]) AND $
       ( JaSearch[origin[i] + ncol + 1] EQ 0 ) then begin
     Accumcost[origin[i] + ncol + 1] = ccost6
     BackLink[origin[i] + ncol + 1] = 6
     endif
endelse
; position 7
if ( Accumcost[origin[i] + ncol] EQ -1 ) AND $
    ( JaSearch[origin[i] + ncol] EQ 0 ) then begin
     Accumcost[origin[i] + ncol]= ccost7
     BackLink[origin[i] + ncol] = 7
     endif else begin
     if (ccost7 LT Accumcost[origin[i] + ncol]) AND $
      ( JaSearch[origin[i] + ncol] EQ 0 ) then begin
     Accumcost[origin[i] + ncol] = ccost7
     BackLink[origin[i] + ncol] = 7
     endif
```

```
endelse
; position 8
if ( Accumcost[origin[i] + ncol - 1] EQ -1 ) AND $
     ( JaSearch[origin[i] + ncol - 1] EQ 0 ) then begin
     Accumcost[origin[i] + ncol - 1]= ccost8
     BackLink[origin[i] + ncol - 1] = 8
     endif else begin
     if (ccost8 LT Accumcost[origin[i] + ncol - 1]) AND $
     ( JaSearch[origin[i] + ncol - 1] EQ 0 ) then begin
     Accumcost[origin[i] + ncol - 1] = ccost8
     BackLink[origin[i] + ncol - 1] = 8
     endif
endelse
;
;
endfor
;
CropAcCost = temporary(where((AccumCost GE 0) AND (JaSearch NE 1)))
MinCost = temporary(min(AccumCost[CropAcCost]))
smallercost = temporary(where((AccumCost EQ Mincost) AND (JaSearch NE 1)))
JaSearch[smallercost[0]] = 1
;
;print, 'Program running up to here'
;print, ' '
;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Begin Loop on other cells of the matrix
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;

Repeat Begin
;
origin = smallercost[0]
tmp = origin
tmp1 = origin - 1
tmp2 = origin - ncol - 1
tmp3 = origin - ncol
tmp4 = origin - ncol + 1
tmp5 = origin + 1
tmp6 = origin + ncol + 1
tmp7 = origin + ncol
tmp8 = origin + ncol - 1
;
mask[0] = tmp2
mask[1] = tmp3
mask[2] = tmp4
mask[3] = tmp1
mask[4] = tmp
mask[5] = tmp5
```

```
mask[6] = tmp8
mask[7] = tmp7
mask[8] = tmp6
;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;
; These are the functions that determine the slope cost of traversing the
; cells. You can basically change it to whatever you want.
; The way its written, calculates the slope (rise/run) as cost
; Up or down is the same. See comments in the ccost calculation for
;   the origin cells
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;
ccost1 = abs(transpose(CostGrid[mask]) # pos1)
ccost2 = abs(transpose(CostGrid[mask]) # pos2)
ccost3 = abs(transpose(CostGrid[mask]) # pos3)
ccost4 = abs(transpose(CostGrid[mask]) # pos4)
ccost5 = abs(transpose(CostGrid[mask]) # pos5)
ccost6 = abs(transpose(CostGrid[mask]) # pos6)
ccost7 = abs(transpose(CostGrid[mask]) # pos7)
ccost8 = abs(transpose(CostGrid[mask]) # pos8)
;
;
;
ccost1 = ccost1 + AccumCost[smallercost[0]] + 1
ccost2 = ccost2 + AccumCost[smallercost[0]] + 1
ccost3 = ccost3 + AccumCost[smallercost[0]] + 1
ccost4 = ccost4 + AccumCost[smallercost[0]] + 1
ccost5 = ccost5 + AccumCost[smallercost[0]] + 1
ccost6 = ccost6 + AccumCost[smallercost[0]] + 1
ccost7 = ccost7 + AccumCost[smallercost[0]] + 1
ccost8 = ccost8 + AccumCost[smallercost[0]] + 1
;
; Must check whether the neighbor was already searched or if its the origin
; position 1
if ( Accumcost[origin - 1] EQ -1 ) AND ( JaSearch[origin - 1] EQ 0 ) then begin
     Accumcost[origin - 1]= ccost1
     BackLink[origin - 1] = 1
     endif else begin
     if (ccost1 LT Accumcost[origin - 1]) AND $
      ( JaSearch[origin - 1] EQ 0 ) then begin
     Accumcost[origin - 1] = ccost1
     BackLink[origin - 1] = 1
     endif
endelse
; position 2
if ( Accumcost[origin - ncol - 1] EQ -1 ) AND $
     ( JaSearch[origin - ncol -1] EQ 0 ) then begin
     Accumcost[origin - ncol - 1]= ccost2
```

```
     BackLink[origin - ncol - 1] = 2
     endif else begin
     if (ccost2 LT Accumcost[origin - ncol -1]) AND $
      ( JaSearch[origin - ncol - 1] EQ 0 ) then begin
     Accumcost[origin - ncol - 1] = ccost2
     BackLink[origin - ncol - 1] = 2
     endif
endelse
; position 3
if ( Accumcost[origin - ncol] EQ -1 ) AND $
    ( JaSearch[origin - ncol] EQ 0 ) then begin
     Accumcost[origin - ncol]= ccost3
     BackLink[origin - ncol] = 3
     endif else begin
     if (ccost3 LT Accumcost[origin - ncol]) AND $
      ( JaSearch[origin - ncol] EQ 0 ) then begin
     Accumcost[origin - ncol] = ccost3
     BackLink[origin - ncol] = 3
     endif
endelse
; position 4
if ( Accumcost[origin - ncol + 1] EQ -1 ) AND $
   ( JaSearch[origin - ncol + 1] EQ 0 ) then begin
     Accumcost[origin - ncol + 1]= ccost4
     BackLink[origin - ncol + 1] = 4
     endif else begin
     if (ccost4 LT Accumcost[origin - ncol + 1]) AND $
      ( JaSearch[origin - ncol + 1] EQ 0 ) then begin
     Accumcost[origin - ncol + 1] = ccost4
     BackLink[origin - ncol + 1] = 4
     endif
endelse
; position 5
if ( Accumcost[origin + 1] EQ -1 ) AND $
     ( JaSearch[origin + 1] EQ 0 ) then begin
     Accumcost[origin + 1]= ccost5
     BackLink[origin + 1] = 5
     endif else begin
     if (ccost5 LT Accumcost[origin + 1]) AND $
     ( JaSearch[origin + 1] EQ 0 ) then begin
     Accumcost[origin + 1] = ccost5
     BackLink[origin + 1] = 5
     endif
endelse
; position 6
if ( Accumcost[origin + ncol + 1] EQ -1 ) AND $
    ( JaSearch[origin + ncol + 1] EQ 0 ) then begin
     Accumcost[origin + ncol + 1]= ccost6
     BackLink[origin + ncol + 1] = 6
```

```
     endif else begin
     if (ccost6 LT Accumcost[origin + ncol + 1]) AND $
     ( JaSearch[origin + ncol + 1] EQ 0 ) then begin
     Accumcost[origin + ncol + 1] = ccost6
     BackLink[origin + ncol + 1] = 6
     endif
endelse
; position 7
if ( Accumcost[origin + ncol] EQ -1 ) AND $
    ( JaSearch[origin + ncol] EQ 0 ) then begin
     Accumcost[origin + ncol]= ccost7
     BackLink[origin + ncol] = 7
     endif else begin
     if (ccost7 LT Accumcost[origin + ncol]) AND $
      ( JaSearch[origin + ncol] EQ 0 ) then begin
     Accumcost[origin + ncol] = ccost7
     BackLink[origin + ncol] = 7
     endif
endelse
; position 8
if ( Accumcost[origin + ncol - 1] EQ -1 ) AND $
    ( JaSearch[origin + ncol - 1] EQ 0 ) then begin
     Accumcost[origin + ncol - 1]= ccost8
     BackLink[origin + ncol - 1] = 8
     endif else begin
     if (ccost8 LT Accumcost[origin + ncol - 1]) AND $
     ( JaSearch[origin + ncol - 1] EQ 0 ) then begin
     Accumcost[origin + ncol - 1] = ccost8
     BackLink[origin + ncol - 1] = 8
     endif
endelse
;
; Find next min cost
;
;ToGo = temporary(n_elements(where(JaSearch EQ 0)))
CropAcCost = temporary(where((AccumCost GE 0) AND (JaSearch NE 1)))
    MinCost = temporary(min(AccumCost[CropAcCost]))
    smallercost = temporary(where((AccumCost EQ Mincost) AND (JaSearch NE 1)))
    JaSearch[smallercost[0]] = 1
; End of loop
; Repeat until all cells in the JaSearch are assigned as searched.
;print, ToGo
;
DestSearch = temporary(where(JaSearch[Dest] EQ 0))
; Change in Version 10
; Check the JaSearch cost at destinations
EndRep until (DestSearch EQ [-1])
;
; Old repeat until...
```

```
;EndRep until (ToGo EQ 1)

BackLink[origin1] = 0
;
; Writing the files
; Writing the accumulated least cost grid
;
noval2 = where(AccumCost EQ -1.0)
if noval NE [-1] then AccumCost[noval] = -9999
if noval2 NE [-1] then AccumCost[noval2] = -9999
;
; Clip the border out
OutAc = AccumCost[1:ncol-2, 1:nrow-2]
;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; ATTENTION: if you want to correct the AccumCost for the cell size
; unit, you have to multiply the AccumCost matrix by csize.
; If you simply want to know the least cost path, not the monetary
; values, you do not have to correct for cell size since this
; is a constant that multiplies all values and therefore does not
; affect optimization.
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;
; Putting the two grids into one single structure
; First, create a structure to store first grid
AC = {grid, name: 'acost', inten: OutAc}
;
; Then, replicate this structure to store the other grid
acgrid= replicate(AC, 2)
acgrid[0] = AC
;
;
; Writing the back link grid into the structure
if noval NE [-1] then BackLink[noval] = -9999
if noval2 NE [-1] then BackLink[noval2] = -9999
OutBk = fix(BackLink[1:ncol-2, 1:nrow-2])
BK = {grid, name: 'bklk', inten: OutBk}
acgrid[1] = BK
;
Return, acgrid
End
;*******************************************************************************
```

APPENDIX C

IDL Program to Record the Paths in a raster grid

```
;***************************************************************************
;+
; NAME:
;     ALLPATHS
;
; PURPOSE:
;     Selects the least cost path once the accumulative cost grid
;      and the direction-to-origin grid are generated by the program
;       <leastcost.pro> or <lcdem.pro>
;
; USAGE: FUNCTION
;     IDL> trails = allpaths(accumcostgrid, bklinkgrid, destgrid)
;
; AUTHOR:
;     E. Arima
;
; CREATED:
;     Feb 25 2005
;
; MODIFICATION HISTORY:
;
;
;
; COMMENTS:
;     Need three inputs: accumulative cost grid, back link grid
;       and the destination grid
```

```
;-
;*************************************************************************
;:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
; First, import destination grid
;
function allpaths, acost, bklink, dest
Dest = dest
nDims = size(Dest, /dimensions)
ncol = ndims[0]
nrow = ndims[1]
;
; Create the path grid to be filled with ones
;   if part of path, otherwise zero
; Path array should be long to accomodate -9999
;
; Read the Backlink grid
BkLk = bklink
;
; Read the accumulative cost grid
AcCost = acost
;
; Destinations should be numbered from 1 to N
;
;DestLab = label_region(Dest, /all_neighbors)
;Dest = DestLab
; For some reason, the label_region command is creating
;  many regions (infrastructure) that were supposed to be
;  only one.
NumTrees = max(Dest) ; number of trees or destinations
;
tree = 1 ; counter
Path = make_array(ncol, nrow, /Long, value=0)
;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Begin Loop
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;
While tree LE NumTrees do begin
;
Pathtmp = temporary(make_array(ncol, nrow, /Long, value=0))
DestReg = temporary(where(Dest EQ tree)) ; destination id
MinDestCost = temporary(min(AcCost[DestReg])) ; acc. value at destination id
PossDest = temporary(where((Dest EQ tree) AND (AcCost EQ MinDestCost[0])))
;
if MinDestCost[0] EQ 0 then begin
    tree = tree + 1
    DestReg = temporary(where(Dest EQ tree)) ; destination id
    MinDestCost = temporary(min(AcCost[DestReg])) ; acc. value at destination id
    PossDest = temporary(where((Dest EQ tree) AND (AcCost EQ MinDestCost[0])))
```

```
endif
;
; There might be more than one least possible destinations,
;   select the first one
;
TheDest = temporary(PossDest[0])
;
; Now, we will select the path from destination
;   back to the origin (thats how it works...backwards)

; Create another index variable to loop
;
ind = TheDest
;
; Now, read the backlink grid value
; Begin loop
; Remember that origin must be assigned a value of zero
;
direction = Bklk[ind]
;
repeat begin
;print, 'Current direction :', direction
;print, 'Current index :', ind
;print, ' '
    ;
    case direction of
    1: Pathtmp[ind + 1] = 1
    2: Pathtmp[ind + ncol + 1] = 1
    3: Pathtmp[ind + ncol] = 1
    4: Pathtmp[ind + ncol - 1] = 1
    5: Pathtmp[ind - 1] = 1
    6: Pathtmp[ind - ncol - 1] = 1
    7: Pathtmp[ind - ncol] = 1
    8: Pathtmp[ind - ncol + 1] = 1
    endcase
    ;
    case direction of
    1: ind = ind + 1
    2: ind = ind + ncol + 1
    3: ind = ind + ncol
    4: ind = ind + ncol - 1
    5: ind = ind - 1
    6: ind = ind - ncol - 1
    7: ind = ind - ncol
    8: ind = ind - ncol + 1
    endcase
    ;
    direction = Bklk[ind]
    ;
```

```
EndRep until (direction EQ 0.00)
;
; Summing the last path to the current
; Number indicates how many trees "use" the path
;
Path = Path + Pathtmp
;
tree = tree + 1 ; counter
;
EndWhile
;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; End loop
;
Return, Path
End
```

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