DRAFT FOR DISCUSSION

Effects of Energy and Transportation Projects on Soybean Expansion in the Madeira River Basin

By: Maria del Carmen Vera-Diaz, John Reid, Britaldo Soares Filho, Robert Kaufmann and Leonardo Fleck

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Acronyms

ANAPO	Asociación Nacional de Productores de Oleaginosas
CNO	Constructora Norberto Odebrecht
FAO	Food and Agriculture Organization
FURNAS	Furnas Centrais Elétricas S.A.
IBAMA	Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis
IBGE	Instituto Brasileiro de Geografia e Estatística
IIRSA	The Initiative for the Integration of Regional Infrastructure in South America
INEI	Instituto Nacional de Estadística e Informática (Peru)
IPAM	Instituto de Pesquisa Ambiental da Amazônia
ISA	Instituto Socioambiental
IRN	International Rivers Network
LEME	LEME Engenharia
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Modeling
PCE	Projetos e Consultorias de Engenheria
PNUD	Programa de las Naciones Unidas para el Desarrollo
SIFRECA	Sistema de Informações de Fretes
SOTERLAC	A Soils and Terrain Digital Database for Latin and Central America and the Caribbean
WHRC	Woods Hole Research Center
WWF	World Wildlife Fund

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By: Maria del Carmen Vera-Diaz[1], John Reid[2], Britaldo Soares Filho[3], Robert Kaufmann[1] and Leonardo Fleck[2]

Summary

A number of energy and transportation projects have been proposed to promote the physical integration of Peru, Brazil and Bolivia's Amazon territories. The Madeira River Hydroelectric and Navigation Mega-project includes the construction of two hydroelectric power stations (HPS), Jirau and Santo Antônio, in Brazil, a third HPS between Abunã in Brazil and Guayaramerín in Bolivia, and probably a fourth at the Esperanza Falls on the Beni River in Bolivia. Other transportation infrastructure projects proposed in this region include the paving of the Bolivian "Northern Corridor," the Cuiabá-Santarém Corridor, and the "Interoceanic Highway."

One of the main consequences expected from these energy and transportation projects is the expansion of soybean planting, which would involve conversion of several types of Amazonian ecosystems, including forests, grasslands and savannahs. This study predicts potential land use changes as a function of soybean expansion in the regions of Brazil, Bolivia, and Peru affected by the infrastructure projects. We use an interdisciplinary model to estimate soybean yields based on climate, soils, and economic factors. We then use yield predictions to estimate soybean profitability based on variations in transportation costs. The effect of new infrastructure projects is evaluated by estimating changes in the cost of shipping soybeans to the nearest export port under 11 alternative infrastructure scenarios.

Our results indicate that future navigation mega-projects and road improvements in the Bolivia-Brazil-Peru border region in the Southeast Amazon Basin have significant potential to spur soybean expansion by reducing transport costs. The area considered highly profitable for planting would increase by between 6,594 (1 percent) and 142,749 km^2 (17 percent), depending on the projects included in the simulation. In all the scenarios we studied, northwestern Bolivia would be the most heavily impacted in economic and ecological terms. Nevertheless, the state of

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Mato Grosso in Brazil would continue to have the greatest total area classified as highly profitable from soybean cultivation.

These results underscore the potential for natural habitat losses in the southwest Amazon Basin as more infrastructure is constructed. While we draw no conclusions about the feasibility or merits of particular projects, we do conclude that conservation investments are needed in parallel to any new infrastructure projects in this region to minimize the loss of natural values.

1. Introduction

An array of energy and transportation projects has been proposed to promote the physical integration of Peru, Brazil and Bolivia's Amazon territories. Among these is the Madeira River Hydroelectric and Navigation Mega-project. It includes the construction of two hydropower stations (HPS) – Jirau and Santo Antônio – on the Brazilian stretch of the river between Porto Velho and Abunã, a third HPS between Abunã (Brazil) and Guayaramerín (Bolivia), and probably a fourth at the Esperanza Falls on the Beni River in Bolivian territory (Figure 1). The projects also call for the construction of locks and electricity transmission lines. According to official projections, these investments would generate energy at competitive prices and would allow navigation along the Upper Madeira, which shipping is now impeded by waterfalls and rapids (Furnas/Odebrecht/Leme, 2005). More than 4,000 km of waterways upstream from the dams in Brazil, Bolivia, and Peru would become navigable (Table 1). Navigation on the Madeira is considered an important element on the Orinoco-Amazon-Plata hub, one of the twelve proposed by the Initiative for the Integration of Regional Infrastructure in South America (IIRSA).

Table 1. Navigable rivers after dam construction

Dams	Countries Influenced	River	Stretch made navigable	Length (km)
Santo Antônio and Jirau	Brazil	Madeira	Abunã - Porto Velho	270
Abunã – Guayaramerín	Brazil Bolivia	Mamoré/Guaporé	Vila Bela SS Trinidade - Abunã	1565
		Mamoré	Puerto Grether - Costa Marques	780
Esperanza Falls	Brazil Bolivia Peru	Beni	Rurrenabaque - Mamoré	710
		Orthon	Puerto Rico - Beni	200
		Madre de Dios	Puerto Maldonado - Beni	630
Total				**4155**

One of the main consequences expected from this mega-project is the expansion of soybean crops in the Bolivian states of Pando, Beni and part of Santa Cruz as a result of lower transportation costs. According to the Furnas & Odebrecht consortium, these regions contain eight million hectares of land suitable for intensive agriculture. The potential grain output of that land is estimated to be 24 million tons per year (PCE/Furnas/Odebrecht, 2002). However, these predictions are unconfirmed. Further, zoning studies indicate that there may be soil constraints for large-scale grain production in Pando and Beni (Zonisig, 1997). On the Brazilian side, the states of Rondônia and Mato Grosso would reap the greatest benefits from the Madeira waterway, which would affect an area of approximately 350,000 km^2 (PCE/Furnas/Odebrecht, 2002). Currently, the affected regions produce 3 million/tons of soybeans, 6% percent of all Brazilian output (IBGE, 2006). According to the project's estimates, the Madeira waterway would reduce the cost of shipping soybeans from Rondônia and Mato Grosso to Pacific ports and would encourage the expansion of soybean production to 28 million/tons/year (PCE/Furnas/Odebrecht, 2002). At the local level, the economic effects of soy planting could be felt in the form of increased employment, increased productivity (GDP per capita) and welfare gains.

The following road paving proposals also could have large impacts on the expansion of soybean production in the Bolivia-Brazil-Peru border area: 1) The Northern Corridor, connecting La Paz, Guayaramerín and Cobija in Bolivia; 2) The Cuiabá-Santarém Corridor between Guarantã do Norte and Santarém in Brazil, and; 3) The Interoceanic Highway between Rio Branco (Brazil) and Ilo (Peru).

These projects raise a number of environmental and social concerns. The increase in soybean cultivation would cause significant environmental impacts, such as deforestation, loss of biodiversity, soil compaction, erosion, and pollution of rivers due to the use of pesticides and fertilizers. Deforestation has been clearly linked to infrastructure development, particularly roads, in the Amazon Basin (Fearnside 1986, 1987; Kaimowitz and Angelsen, 1998; Nepstad *et al.*, 2001; Alves, 2002; Alencar *et al.*, 2004), and may impose considerable economic losses on society at large (Alencar *et al.*, 2005).

The dams on the Madeira River would also have serious adverse effects on aquatic life by interrupting fish migration routes. In addition, it is anticipated that they would interrupt sediment transport, increase ground water levels, cause flooding, and alter the quality and dynamics of the hydrological resources (Furnas/Odebrecht/Leme, 2005). Social costs are also to be expected as local communities compete with migrants and capitalized land buyers[2] for land and natural resources (Cáceres Vega, 2000). The result can be increased inequity in the distribution of wealth (Fearnside, 1997, 2001). In the last decade, the boom in soybean cultivation in Mato Grosso was accompanied by an increase in the Gini Index (a measure of income inequality) from 0.55 in 1990 to 0.59 in 2000 (UNDP, 2000).

In this study, we predict potential soybean expansion in the tri-national border region shared by Brazil, Bolivia, and Peru as a result of the energy and transportation infrastructure projects mentioned above. The simulations are organized into 12 scenarios – one representing current conditions and 11 with different combinations of new roads and dams. We estimate how much land would be made attractive for soybean agriculture as a result of infrastructure investments, and the potential of soy expansion to affect protected areas, indigenous territories and natural ecosystems in general. The answer depends on rents for soybean production, which are determined mainly by price, yields, and production and transport costs. We use an interdisciplinary model developed by Vera-Diaz *et al.* (2006) to estimate soybean yields based on climatic, edaphic, and economic determinants. We then use soybean yield predictions to estimate a soybean rent (profit) layer in a geographic information system. The effect of the new energy and transportation infrastructure projects is specifically addressed by estimating the cost of shipping soybeans to the nearest export port under each proposed scenario, using spatial analysis techniques. These approaches allow us to assess spatial variations in the economic viability of soybean production and the degree to which expanded planting can be influenced by future infrastructure investments.

2. Study Area

Our study area covers 2.1 million km^2 in the border region of Bolivia-Brazil-Peru, in the Southeast Amazon Basin (Figure 1). This area currently is a mosaic of tropical forest, grasslands, savannas and farmland, with large, meandering rivers. The varied landscapes support a

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[2] Three decades ago, the arrival of soybeans and the coffee eradication program in Southern Brazil drove 2.5 million small-scale farmers from rural areas. Many moved to forest areas in the Center West and Amazon Regions of Brazil (Fearnside, 1986, 1987). Most recently the construction of a new port at Santarém, at the confluence of the Amazonas and Tapajós rivers, has drawn capitalized land buyers from Mato Grosso, Paraná, and Rio Grande do Sul to the municipalities of Santarém and Belterra (Pará State), leading to the expulsion of local communities and encouraging the conversion of forest to soybean fields (Steward, 2004).

considerable diversity of flora and fauna. The human population is characterized by rich cultural diversity due to the convergence of three countries with different historical processes of development.

The HPS projects would be built on the Madeira and along its tributaries, the Mamoré and Beni. This region is composed of extensive humid tropical forest, grasslands, savannas, and crops. The Madeira River is one of the principal tributaries of the Amazon. It accounts for around 15% of the Amazon River's total annual discharge and 50% of all sediments delivered to the Atlantic by the main stem (Goulding et al., 2003). These sediments are a key factor in the biological dynamics of the large expanses of flooded forests (*várzea*) along the Madeira and the Amazon River downstream of the Madeira's mouth. Most of rural Amazonian's population occupies these forests, which are the most biologically productive in the basin due to massive annual sediment deposits (Goulding 1999). The Madeira is also considered a treasure trove of biodiversity, supporting an estimated 750 fish species, 800 bird species, and other, often endangered, wildlife (IRN, 2006).

The Jirau and Santo Antônio HPSs would be located on a 260 km stretch of the Madeira River between Vila de Abunã and Santo Antônio falls in the municipality of Porto Velho - Rondônia State (Brazil). Jirau and Santo Antônio would be located 136 km and 10 km from Porto Velho, respectively. The Abunã-Guayaramerín HPS would be located along the Mamoré and Madeira Rivers[3] between the municipalities of Abunã, Rondônia State (Brazil), and Guayaramerín, Beni Department (Bolivia). The Esperanza dam would be built on the waterfall known as "Cachuela Esperanza" on the Beni River, 30 km upstream of its confluence with Mamoré River, in the Bolivian State of Pando.

The three proposed road projects included in this study are the Northern Corridor, The Cuiabá-Santarém Corridor and The Interoceanic Highway. The Northern Corridor is 1,386 km in length, from La Paz to Guayaramerín, including the stretch from El Chorro to Cobija. This road was built in the late seventies and currently has large impassable stretches during the rainy season (DHV, 2006). The Northern Corridor crosses areas of montane forest, tropical forest, grasslands and the western part of the Beni savannas - the third largest complex of savannas in

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[3] The Mamoré is a large river in Bolivia, which joins the Beni to form the Madeira.

South America. This ecoregion has been identified as a center of plant diversity and endemism (WWF, 2006).

First opened in the 1970s, the Cuiabá-Santarém road stretches 1,750 km, connecting the city of Santarém, located on the banks of the Amazon River, to Cuiabá, the capital of Mato Grosso. Currently, 36 percent of this road is paved and traverses large areas of savannas (*Cerrado*) and, to a lesser extent, transition forests. The remaining 990 km of the Cuiabá-Santarém Corridor between Guarantã do Norte and Santarém are unpaved and cross an inaccessible, sparsely populated tropical forest. The lack of pavement limits passability most of the year.

The Interoceanic Highway is part of the proposed Peruvian extension of Brazil's BR-317 highway that links Rio Branco to the Brazilian frontier town of Assis Brasil in the state of Acre. The Brazilian portion of this road is already paved. The Interoceanic Highway will link the Peruvian frontier town of Iñapari to the Pacific ports of Ilo and Matarani, covering roughly 1,580 km. The portion of this highway between Assis Brasil (Brazil) and Puerto Maldonado (Peru), roughly 600 km, is unpaved and cuts through tropical forest and agricultural lands.

3. Methods

3.1. Model for Soybean Yield

To predict potential land use change, we use an interdisciplinary model for soybean yield that integrates climatic and edaphic determinants of yield with regression models that simulate economic and spatial determinants (Vera-Diaz, *et al*., 2006; Kaufmann and Snell, 1997; Sinclair, 1986). This model was originally developed to forecast soybean expansion in the Brazilian Amazon. The general concept of this model is given by equation (1) and represented in Figure 2.

$$\mathbf{YIELD}_i = \beta_0 + \beta_1 \,\mathrm{MYield}_i + \beta_2 \,\mathrm{TCost}_i + \beta_3 \,\mathrm{Credit}_i + \beta_4 \ln(\mathrm{Fertil})_i + \beta_5 \,\mathrm{Lat}_i + \beta_6 \,\mathrm{Long}_i + u_i \quad (1)$$

in which, *Yield* is the soybean yield (kilograms per hectare), *MYield* is the average soybean yield (kilograms per hectare) simulated by the crop simulation model SOYBEAN, *TCost* is the least-cumulative-cost distance (dollars per ton) to ship soybeans; *Credit* is the total loans obtained for soybean farmers divided by the area planted in soybeans ($/ha), *Fertil* is the cost of fertilizers

(\$/ha), which was estimated using edaphic instrumental variables[4] pH and rooting depth; *Lat* is the latitude used as a proxy of photoperiod, *Long* is the longitude, and *u* is the regression error. We use the coefficients estimated in this equation for Vera-Diaz et al (2006) to forecast soybean expansion on Brazilian Amazon and implement the Yield Model with a new dataset for the entire study area.

3.2. Motivation

The effect of the climate and edaphic environment on soybean yield is represented in equation (1) using the yield *(MYield)* that is forecast by the crop simulation model SOYBEAN[5]. The relationships among climatic and edaphic variables and yield are probably highly nonlinear and vary over the phenological development of the soybean plant. Therefore, using the *MYield* model to capture the climate influence on soybean yields is more effective than specifying climatic and edaphic variables in equation (1). The SOYBEAN model was simulated with daily data for precipitation (mm/day), maximum and minimum temperature (degrees K), and net downward solar radiation flux (Watts per meter squared) from 1950 to 2001. Edaphic conditions and management practices also are included in this model and represented by the variables rooting depth[6] and planting date. An average of the outputs from the SOYBEAN MODEL, that is, soybean yields (*MYield)* was estimated to be included in equation (1).

Transportation costs have an indirect effect on soybean yield. High transportation costs reduce the price of soybeans that farmers receive, which reduces the economic viability of applying inputs such as fertilizers and herbicides, ultimately leading to lower yields. Local prices for these agricultural inputs also are affected by high transportation costs. Together, these effects suggest that yield should be negatively related to transportation costs. These data were estimated using spatial analysis techniques (Section 3.3).

The availability of credit issued by grain companies and national banks is a decisive factor on soybean production. Increasing credit increases the quality and quantity of purchased inputs and promotes investment in modern farm machinery, which, in turn, has a positive effect on soybean yields.

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[4] More details about the instrumental variables for estimating fertilizers can be found in Vera-Diaz et al (2006).

[5] More details about the crop simulation model SOYBEAN can be found in Vera-Diaz et al (2006).

[6] Rooting depth is the estimated depth to which root growth is unrestricted by physical or chemical impediments as classified by the FAO (1990).

The effect of fertilizers on yield is straightforward - increasing fertilizer applications increases yield. However fertilizer use and yield are jointly determined. The rate of fertilizer application depends on its marginal effect on rent, which is determined by the marginal effect on yield, the price of soybeans, and the price of fertilizers. Based on this economic calculus, farmers only apply fertilizer to areas where the value of the increased yield is greater than the cost of the additional fertilizer. This simultaneity between yield and fertilizers is addressed using the instrumental variables pH and rooting depth to estimate fertilizers values (Vera-Diaz et al, 2006).

Soybean yield is also affected by the photoperiod or day length. Recent soybean expansion into low-latitudes (< 25°), including areas near to the Equator, is possible due to cultivars that include long-juvenile genes, which delay flowering and maturity (Hartwig and Kiihl, 1979; Sinclair *et al.*, 2005). Despite these advances, soybeans are naturally short-day plants that are less productive in low latitudes, so we include latitude to capture the effect of photoperiod on soybean yield. Finally, the model specifies longitude to represent omitted variables that vary systematically in an east-west direction, such as slope[7] or the effect(s) of spatially biased estimates for variables that are included in the SOYBEAN model.

3.3. Transportation Costs

A least-cumulative-cost approach is proposed used to estimate transportation costs and simulate the impact on soybean expansion of future navigable waterways and the paving of roads. Using this method we calculate the cost of shipping a ton of soybeans from each place in the study area to the most accessible soybean export port, as defined by the lowest cost path, using ArcGIS software.

Two layers were used to calculate soybean transportation costs: *the export ports layer* and *the land use cost layer*. The *export port layer* includes the ports of Itacoatiara, Santarém, São Luis, Paranaguá, Santos, and Rio Grande, in Brazil; Arica in Chile; Ilo and Matarani in Peru; and Buenos Aires in Argentina. These ports represent the main market channels for soybeans.

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[7] The slope variable was omitted from the soybean yield model due to endogeneity problems between slope and fertilizers. Amazon farmers use fertilizers primarily in mechanized agriculture, which is practiced in flat areas. Therefore, we considered that variables related to fertilizer capture the influence of slope on soybean yields.

The *land use cost layer* was built by overlapping maps of land cover, road networks, railroads, and rivers (Eva *et al.*, 2002; WHRC/IPAM/ISA, 2000). The land cover map consists of six categories; (1) forest, (2) flooded forest, (3) montane forest, (4) barren and desert, (5) agriculture, and (6) grassland and savanna. The road network map classifies roads as either paved or unpaved. The railroad map includes the main railroads used to ship soybeans. The river map classifies rivers as either navigable or non-navigable. Each category of land cover, roads, railroads, and rivers was assigned cost values or friction coefficients[8] (Table 2), which represent the cost per unit of distance (US$/ton/km) to move soybeans. These costs are based on the notion of friction; some cells in the digital maps are more difficult and costly to traverse than others. For instance, paved roads are relatively easy to travel and have a low coefficient of friction as compared to unpaved roads (Stone, 1998). Next, this friction map (the land use cost layer*)* was used in combination with the *export port layer* to calculate the lowest cost path from each location in the study area to reach an export port, producing the transportation cost map (Figure 3). This procedure was computed using cost-distance and cost-allocation functions available within ArcGIS software.

Table 2. Cost (friction) of traversing different land surfaces

Land use Category	Friction coefficients - $/ton/km
Paved road	0.05
Unpaved road	0.15
Navigable river	0.02
Non-navigable river	3.00
Railroad	0.03
Grassland and savannas	0.30
Forest	3.00
Flooded forest	3.00
Montane forest	3.00
Barren and desert	3.00

Sources: Stone (1998); Guimarães and Ulh (1998); Nelson et al. (1999)

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[8] For this study, the friction coefficients are based on previous estimates for the cost of transporting products over various land use surfaces (Barros and Uhl, 1995; Barros and Verissimo, 1996; Stone, 1998; Guimarães and Uhl, 1998; Nelson et al., 1999; Veríssimo et al., 1992, 1995; and Vera-Diaz et al., 2006). The friction coefficients are derived largely from the logging industry. Using these values we assume that timber can serve as a proxy for all transported goods because timber is similar to other agricultural products in weight and volume. We calibrated these cost estimates to reflect soybean sector conditions, based on published information (Sifreca, 2006).

To assess the effect of the infrastructure projects on soybean transportation costs, we simulate: 1) the building of the Jirau and Santo Antônio (Brazil), Abunã-Guayaramerín (Brazil-Bolivia), and Esperanza Falls (Bolivia) HPSs and; 2) the paving of the Northern Corridor (Bolivia), the Cuiabá-Santarém Corridor (Brazil), and the Interoceanic Highway (Brazil-Peru). The simulations were based on alternative infrastructure scenarios shown in Table 3. The infrastructure improvements under each scenario were implemented on the river map by changing the relevant pixels from non-navigable to navigable after the construction of the HPSs[9] and on the road network map by changing the relevant pixels from unpaved to paved. These new layers were used to generate a new minimum cumulative cost maps for the twelve proposed scenarios using the techniques described above.

Table 3. Alternative Infrastructure Scenarios

	Scenarios											
Infrastructure Projects	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Current conditions	√											
Santo Antônio dam		√	√	√	√	√	√			√		√
Jirau dam		√	√	√	√	√	√			√		√
Abunã-Guayamerín dam			√	√		√	√					
Esperanza dam				√			√					
Northern Corridor					√	√	√	√	√	√	√	√
Cuiabá-Santarém Corridor									√	√		
Interoceanic Highway											√	√
Scenario likelihood (**H**igh - **M**edium - **L**ow)		H	M	L	H	M	L	H	H	H	H	H

- **Scenario I** represents conditions with the current transportation infrastructure.
- **Scenario II** includes the building of Jirau and Santo Antônio HPSs, which would make the Madeira River navigable between Porto Velho and Abunã.
- **Scenario III** includes the construction of Jirau, Santo Antônio, and Abunã-Guayaramerín dams, which would permit navigation on the Madeira River (between Porto Velho and Abunã), on the Mamoré/Guaporé (between Vila Bela da Santíssima Trindade and Abunã) and, on the Mamoré (between Puerto Grether and Costa Marques).

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[9] We assume that the HPS projects also would include the construction of locks and channels for fluvial navigation.

- **Scenario IV** adds the Esperanza HPS to Scenario III. This fourth dam would make the Beni River navigable (between Rurrenabaque and the Mamoré), the Orthon (between Puerto Rico and Beni), and the Madre de Dios (between Puerto Maldonado and the Beni).
- **Scenario V** adds the paving of the Northern Corridor to Scenario II.
- **Scenario VI** adds the paving of the Northern Corridor to Scenario III.
- **Scenario VII** adds the paving of Northern Corridor to Scenario IV.
- **Scenario VIII** includes just the paving of the Northern Corridor.
- **Scenario IX** considers the paving of the Northern Corridor and Cuiabá-Santarém Corridor.
- **Scenario X** is Scenario II plus Scenario IX.
- **Scenario XI** considers the paving of the Northern Corridor and the Interoceanic Highway.
- **Scenario XII** is Scenario II plus Scenario XI.

The proposed infrastructure scenarios were classified into three groups according to their likelihood of implementation. These categories were defined taking into account the current status of each infrastructure project and a subjective assessment of their chances of being carried out in the medium term. Scenarios II, V, VIII, IX, X, XI, and XII are considered the most probable, while Scenarios III and VI are assigned medium probability, and Scenarios IV and VII are given a low probability.

3.4. Soybean Rent Scenarios

Soybean rent is the profit obtained by planting soybeans. At a simple level, rent is the difference between the revenues generated by soybean cultivation and the production and transportation costs[10]. To estimate the profitability for planting soybeans, we use the yield values predicted by the Yield Model and average soybean prices (USDA-WASDE, 1983-2005). Due to a limited availability of production cost data, we included only transportation costs in the estimate of soybean rent. Since the local price of the agricultural inputs and the price of soybeans that farmers receive are severely influenced by transportation costs, we assume that this variable is a reasonable proxy for the variation in the cost of production. Therefore, yield predictions

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[10] *Rent* = (yield * price) – (production cost + transportation cost)

from equation (1) and transportation cost maps from section (3.3) were used to estimate twelve scenarios of soybean rent for every pixel within the study area. Transportation cost is the variable changing in each soybean rent layer according to the simulation of the alternative infrastructure scenarios.

4. Data Sources and Data Manipulation

Daily climate data (precipitation, temperature and, solar radiation) from 1950 to 2001 used in the SOYBEAN Model were obtained from the NCEP- NCAR reanalysis project, which uses climate models to interpolate spatially and temporally sparse ground-based measures (NASA/NCEP/NCAR, 2004). Rooting depth data were obtained from a soil map at SOTERLAC whose original scale is 0.5 degrees for four depth categories (very shallow < 30cm; shallow 30-50 cm; moderately deep 50-150 cm; very deep > 150 cm) (ISRIC, 1998). These categories were converted to values (e.g. 15 cm, 40 cm, 100 cm, and 150 cm) for use in the SOYBEAN model.

To estimate the ln(Fertil) parameter, data on rooting depth were reclassified as 1 = effective rooting depth (> than 50 cm) and 0 = no-effective rooting depth (< than 50 cm)[11]. Data on soil pH were derived from a soil map at SOTERLAC at 0.5^{o} resolution, with values changing from 4.5 (strongly acidic) to 6.6 (basic). The values for ln(Fertil) predicted by the variables rooting depth and pH were used as instruments to estimate equation (1).

Data for estimating transportation cost layers were obtained from a spatial dataset assembled by WHRC, ISA and IPAM. The dataset includes layers of land cover, roads, railroads, rivers, and ports. Data on land cover at one km^2 of resolution were derived from Eva *et al.* (2002). The original land cover map has more than forty classes, which we reclassified into the six categories: forest, flooded forest, montane forest, barren/desert, agriculture, and grassland/savanna. Data on the road network, rivers, and ports were obtained from WHRC/IPAM/ISA (2000). The road network is classified as dirt or paved. Rivers are categorized as either navigable or non-navigable. The map of ports complied by the same institutions includes the main export ports of South America, from which we selected the primary ports used to export soybeans in Brazil, Bolivia, and Peru: Itacoatiara, Santarém, São

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[11] These categories are based on empirical studies, which indicate that rooting depth goes beyond 50 centimeters as the plant enters the reproductive flowering phase (Jones *et al.,* 2005).

Luis, Paranaguá, Santos, and Rio Grande in Brazil; Arica in Chile; Ilo and Matarani in Peru; and Buenos Aires in Argentina.

Data for credit and planting date at the census tract and state level were obtained from the 1995-1996 Brazilian Agricultural Census (IBGE, 1996), ANAPO (2004), and INEI (1994). These data were spatialized using ArcGIS software, with each polygon transformed to centroide and depicted by its X and Y coordinates. Then, credit and planting date surfaces were estimated using interpolation techniques.

All original data were converted to raster format at two km^2 of spatial resolution.

5. Results

5.1. Transportation Cost Scenarios for Soybeans

Soybean transportation costs vary greatly across the study area, ranging from US$14 to 576 per ton. Low transportation costs predominate in Mato Grosso (Brazil) and Santa Cruz (Bolivia) due to better road networks. These regions are characterized by large extensions of agricultural and pasture lands, factors that reduce the friction to the movement of freight. Under current infrastructure conditions, an area equal to one million km^2 has transportation costs lower than $100 per ton[12] (Table 4). Most of this area (67%) is located in Mato Grosso State, Brazil's main soybean producer.

Table 4. Area with transportation costs <= $100/ton/km

Scenarios	Total area	Increase	
	km^2	km^2	%
I	1,068,521		
II	1,070,336	1,815	0%
III	1,079,986	11,465	1%
IV	1,113,200	44,679	4%
V	1,132,106	63,585	6%
VI	1,153,130	84,609	7%
VII	1,237,467	168,946	15%
VIII	1,129,323	60,802	5%
IX	1,144,146	75,625	7%
X	1,146,929	78,408	7%
XI	1,192,183	123,662	11%

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[12] According to the Brazilian National Association of Grain Exporters (ANEC), the cost of transporting a ton of soybeans in Brazil from farms to export port averages US$37. This values show high variability across Brazilian territory, reaching in some cases up to $100 per ton. In our study, we assume $100 per ton as threshold for "low" transport costs, above which costs are considered prohibitive.

XII	1,194,905	126,384	11%

Infrastructure investments simulated in the 11 alternative scenarios lower transportation costs and increase the area attractive for soybean planting to varying degrees (Table 4). This increase would range from 1,815 km^2 (Scenario II) to 168,946 km^2 (Scenario 7), or less than 1 percent to 16 percent, respectively. In all proposed scenarios except for Scenario II, Bolivia would see more than 60 percent of the increase in the area made attractive for planting[13]. Most of the new area with transportation costs lower than \$100 per ton would be located in the department of Beni.

In spite of the fact that Bolivian territory would be the most affected by transport cost reductions, Brazil would still have roughly 80% of the total area with low transportation costs in all scenarios, varying from 894,281 km^2 (Scenario II) to 935,330 km^2 (Scenario VII). These areas would be located mainly in Mato Grosso and Pará states where there are already vast plantations.

The infrastructure scenarios with road paving (VIII, IX, and XI) would result in substantially greater reductions in transportation costs than those that include only the construction of navigation works (II, III, and IV), and would affect an area up to two times greater than navigation infrastructure.

5.2. Soybean Rent Scenarios

Under current conditions, approximately 853,474 km^2 (40%) of the study area has high soybean rent potential (greater than \$300/ha/year)[14]. Of the area with a high rent potential, 57 percent is located in forest lands, 25 percent in agriculture lands, and 15 percent in grasslands and savannas. MAP Most of areas with the highest economic rents are located in Mato Grosso (60%) and Santa Cruz (14%), where road networks are more developed. An area of 166,405 km^2 with high rent potential is located on indigenous lands and protected areas of Bolivia (52

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[13] Brazil would be the most affected by the planned infrastructure projects in Scenario II, specifically Rondônia state.

[14] In practice, soybean farmers spend on average \$250/ha in production costs for raising soybeans (Embrapa, 2002). These production costs are not accounted in our estimate. Consequently, we chose \$300/ha as threshold for high soybean rent potential assuming a profit greater than 15% after deducing these production costs.

percent), Brazil (46 percent), and Peru (1 percent) MAP. Most of these areas are legally off limits to soybean production, but nonetheless subject to growing pressure from soybean planters.

With new infrastructure, the area with high potential rents could range from 860,068 km^2 (Scenario II) to 996,223 km^2 (Scenario VII), that is, an increase of between 1 percent and 17 percent, respectively (Table 5, Figure 5).

Table 5. Area of high soybean rents (>= $300/ha)

Scenarios	Total area km^2	Increase km^2	%
I	853,474		
II	860,068	6,594	1%
III	875,738	22,264	3%
IV	927,526	74,052	8%
V	912,733	59,259	6%
VI	929,401	75,927	8%
VII	996,223	142,749	15%
VIII	906,441	52,967	5%
IX	930,914	77,440	9%
X	937,206	83,732	9%
XI	974,685	121,211	13%
XII	976,803	123,329	13%

Considering only the scenarios with a high probability of medium-term implementation (II, V, VIII, IX, X, XI, and XII), we observe that the construction of the Jirau and Santo Antônio HPSs and the pavement of Northern Corridor and Interoceanic Highway (both projects included in Scenario XII) would cause the greatest increase, 123,329 km^2, in the area with high soybean rents. Eighty percent of this increase would be located in forest lands, 11 percent in grasslands/savannas, and 7 percent in agricultural areas. MAP Under this scenario, 63 percent of the total increase would be located in Bolivia, 29 percent in Brazil, and 8 percent in Peru. MAP More than 80 percent of the new potential area in Bolivia would be located in the departments of Pando and Beni. For Brazil and Peru, the principal states influenced by the infrastructure initiatives would be Acre and Madre de Dios, respectively. The increased area under Scenario XII would encompass 37,692 km^2 of protected areas and indigenous lands in Bolivia (73%), Brazil (22%), and Peru (5%).

Individual appraisals of the Jirau and Santo Antônio HPSs (Scenario II) and the Northern Corridor and Interoceanic Highway (Scenario XI) reveals that the road projects would account for more than 90 percent of the 123,329 km^2 increase in the area with high potential rent and would mainly affect the state of Acre and the departments of Pando, and Beni. The construction of the two HPSs would do little to facilitate soybean transport and therefore have a minimal impact on the increase in area attractive to soybean planting (less than 1 percent). The dams would mainly affect expansion in the Brazilian states of Rondônia and Acre.

The low probability scenario VII (construction of 4 HPSs and the pavement of the Northern Corridor), could be the most environmentally catastrophic if areas made attractive to soybean cultivation are effectively converted. It would expand the area with soybean potential from 853,474 km^2 to roughly one million km^2, that is, an increase of 17 percent, 23 percent of which would be located in protected areas and 12 percent in indigenous lands.

In general terms, road improvements would have more potential to expand the agricultural frontier than the Madeira navigation projects. For instance, the potential area for raising soybeans would be increased seven times more by paving the Northern Corridor (Scenario VIII) than building the Jirau and Santo Antônio HPSs (Scenario II). Paving the Northern Corridor and the Interoceanic Highway (Scenario XI) would increase the potential soybean area by 114,617 km^2, that is, 64 percent more than building the four HPSs in the study area (Scenario IV). Previous studies indicate that road infrastructure is the single most robust predictor of frontier expansion and accompanying deforestation in tropical forest regions (Kaimowitz and Angelsen, 1998). More than two-thirds of Amazon deforestation takes place within 50 km of major paved roads, where agriculture, cattle ranching, and logging activities are economically feasible (Nepstad *et al.*, 2001; Alves, 2002).

5. Conclusions

Our results indicate that future navigation mega-projects and road improvements in the Bolivia-Brazil-Peru border region in the Southeast Amazon Basin have significant potential to spur soybean expansion by reducing transport costs. In all scenarios[15] we constructed, northwestern Bolivia would be the most heavily impacted in economic and ecological terms by

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[15] Except for Scenario II, which would affect mainly the states of Rondônia and Acre in Brazil.

the new infrastructure projects. Nevertheless, the state of Mato Grosso (Brazil) would continue to have the greatest total area with high potential rents from soybean cultivation.

Of the scenarios classified as having a high probability of medium-term implementation, Scenario XII would cause the greatest economic and ecological impacts. Construction of the Jirau and Santo Antônio HPSs and the paving of the Northern Corridor and Interoceanic Highway, all considered under this scenario, would expand the area with potential for high soybean rents from 853,474 km^2 to 976,803 km^2 a change of 13 percent. Lowland rain forest would be the land-use category most affected.

While our study shows roads having greater potential than dams to stimulate the spread of soybeans, the Madeira projects would have other environmental impacts not addressed in this paper. Although still in the licensing phase, expectations of the Jirau and Santo Antônio dams' construction have already caused impacts such as illegal deforestation and disorderly migration and occupation[16] in the Jaci-Paraná district of Porto Velho[17] (Derivi, 2006). The projects would impact the Karitiana indigenous lands. There would be losses of migratory fish species, and aquatic and terrestrial habitat. As noted earlier in this paper, other impacts would include interruption of sediment transport, flooding, rising groundwater, and changes in water quality, among others (Furnas/Odebrecht/Leme, 2005; IRN, 2006). Some of the most dramatic river level fluctuations in the Amazon Basin take place downriver of the Madeira rapids, between Porto Velho and the mouth of Manicoré River (Goulding, 2003), and this dynamic could be completely modified by the dams. Impacts would also extend upstream into Bolivia, because the Madeira River drains almost all of its Amazonian territory, an area of 724,000 km^{2,} or 66 percent of the country. The magnitude and range of these impacts could make the Madeira dams more environmentally damaging then the roads analyzed, and therefore deserve other complementary studies.

Most of the scenarios (except for II) indicated that infrastructure investments could provoke high levels of indirect impact on Bolivia's ecosystems, including permanent threats to protected areas and indigenous lands. It should be noted that our projections of potential soybean expansion do not stop at the boundaries and protected areas. These areas have legal

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[16] Furnas and Odebrecht, the companies proposing the construction, declared that the project would create some 20,000 direct jobs at each plant. Their representatives have pointed out they would give priority to local labor in all communities that might be affected by the power plants (Furnas/Odebrecht/Leme, 2005; Derivi, 2006).

[17] Porto Velho is the capital of the Rondônia state.

safeguards against conversion of natural ecosystems and have been shown to be effective – in varying degrees – in forestalling deforestation (Nepstad *et al.* 2006). In theory, therefore, the effective area of expansion would be smaller than that which we project. Even if outright deforestation is avoided, however, these areas would, at the very least, risk ecological isolation as surrounding lands are converted, and experience more illegal logging and hunting. These pressures will also tend to raise the costs of enforcing boundaries and regulations.

Species conservation outside of protected areas also requires attention as new infrastructure is considered. For example, there are still unprotected endemic primate and macaw species with highly restricted distributions along the Northern Corridor. Some live in small forest patches interspersed in the Beni savannas, and would be particularly vulnerable to habitat loss as a function of soybean expansion. If the road is paved, their conservation would require intensive and well coordinated measures, including the creation of new protected areas before construction begins (Fleck, pers. comm.). Other key species and habitats that would be particularly threatened by soybean expansion should be identified and appropriate conservation measures put in place.

There are important limitations with respect to the data set and analysis that may affect the precision of our results. For example, the simulations show high current profitability for soybeans in parts of Northeast Bolivia where there are currently no plantations at all. This may be an artifact of incomplete road data. We lacked comprehensive road network information, which would ideally include all categories of roads, surface conditions and the type of relief cut by each road. We were limited to using average transport cost values for paved and unpaved roads. Also, we estimated soybean transport costs assuming that they reflect distance in a reasonably consistent way. In reality, transport rates rarely are based on a strict distance principle. The structure of freight rates are complex and are shaped by several factors other than distance, such as tapering fares, grouping, and competition.

The coarse resolution of soil and climate maps also could have affected our predictions. For example, soil restrictions associated with the pH level and rooting depth are difficult to capture in the model due to the lack of a dataset with fine resolution. These limitations notwithstanding, the present study provides an important indication of the potential magnitude of impacts of infrastructure development across a large area of the Amazon Basin.

Finally, it is important to point out that this study is not a cost-benefit analysis. We have not calculated the costs of infrastructure projects and weighed them against the benefits in a common currency. Therefore, our results do not indicate whether or not particular projects are financially or economically feasible, and certainly don't indicate whether or not any particular project should be built. The study does, however provide a conceptual, mathematical and cartographic framework to understand the potential extent of increased soybean production and environmental impacts as a result of infrastructure investments. Further, it gives some indication of potential social impacts of the land-ownership consolidation that usually accompanies soybean farming. This information can be used by policymakers and development agencies as they consider new investments and by conservation organizations as they attempt to project future environmental threats.

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