Roads, Development and Deforestation: a review

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1. Introduction

Social and economic development has historically been associated with spatial expansion of connection networks. A quick look at any detailed topographic map reveals that more developed countries have denser road and railroad network than less developed ones and that even within a country we are usually confident in identifying the most developed and urbanized regions by the higher density of roads connections. Indeed, as soon as an economy expands it pushes for the development of a rational transportation network, which makes economic specialization and trade more profitable, setting up a virtuous circle between economic and infrastructure development.

Despite this, historical cases indicate that when rural roads are placed in forested areas, it speeds up deforestation, endangering biodiversity and the stability of our planet's climate. This suggests that road construction or rehabilitation poses a trade-off between economic development and environmental damage.

This paper tries to summarize the empirical evidence related to these two impacts of road extension. We do not, however, claim our attempt to be exhaustive given the wide range of issues involved. To keep the size of the work manageable we deliberately reduced the scope of this review, focusing only on developing countries in the tropical region. Most deforestation is concentrated in this region and a large portion of developing countries which probably would benefit the most from transport networks expansion, lay within the tropics. The next section will briefly review the theoretical framework of the impact of roads on rural economics, and some of the issues related to the empirical approach

[1] This is a companion paper to Chomitz et al. (2006), "At Loggerheads", expanding on the author's contributions to chapter 2 of that book. I wish to thank Ken Chomitz for guidance and feedback as well as Piet Buys and Tim Thomas for helpful comments. The findings, interpretations, and conclusions expressed in this paper do not necessarily reflect the views of the Executive Directors of The World Bank or the governments they represent.

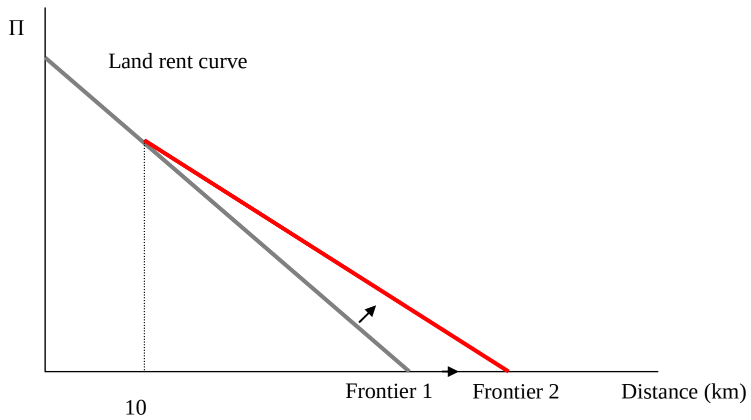
generally adopted in the literature. Sections 3 and 4, the core of the paper, will present the results of our review on the impact of roads on development and deforestation, respectively. Section 5 concludes.

2. The theory: von Thünen and the empirical derivations

In 1826 von Thünen formalized the brilliant intuition that agricultural expansion is closely related to the distance from the market, due to the amount of the transportation costs which shape input costs and produce price. To illustrate this powerful idea simply, we present a basic version of the von Thünen model. For the remainder of this section we will rely on Angelsen (2006).

The model allows only two potential land-uses: agriculture and undisturbed forest. Each hectare of farmed land produces y, and the produce is sold in the nearest market at the price p. Let us denote l and k the labour and capital required per hectare respectively, w the wage rate, r the capital costs, and c the unit transportation costs, i.e. the cost of transporting the production of one hectare for one kilometer and d the distance (in kilometers) from the nearest market.

Figure 1: A basic von Thünen model.



It is intuitive that the farther the land, the less profitable economic activity will be. Formally, the decreasing farming profit per hectare is defined by the following equation:

$$\Pi = py - wl - rk - cd$$

A simple graph allows us to locate the agricultural frontier, i.e. the distance beyond which agricultural profit is negative and unconverted forest persists (see Figure 1).

How does the frontier move with parameter changes? It is straightforward that any change in the parameters that shift or rotate the agriculture curve outwards would move the frontier farther from the market. For the matter of this study we want to address the question of how would the agricultural profit change with the provision of a new road (or upgrading of an existing one). Assuming that a path starting at ten kilometers from the market is upgraded to a paved road, all the economic activities located more than ten kilometers away will benefit from a reduction in the average transportation costs, c. In the graph, the profit curve rotates counterclockwise centered at ten kilometer distance. Consequently, the frontier moves farther from the market.

The consequences of road extension for land use and local/national development depend (among other variables) on the characteristics of demand for agricultural products, of the labour market faced by frontier producers, and on the production function of the good itself. Let us consider different extreme cases. Of course intermediate assumptions produce intermediate results.

Perfectly elastic demand and completely elastic labour supply

A perfectly elastic demand for agriculture ensures that the increase in supply will not decrease prices. Moreover, perfect mobility of labour guarantee that the wage rate is not changing either. Consequently, we expect under these conditions the maximum additional deforestation to occur. Mean local income does not increase, by assumption, since the increase in labour demand is perfectly offset by the increase in labour supply, but at the local and national level employment and production increase. (Implicitly we are assuming some kind of labour market failure, with a migration of 'surplus' labour to the frontier.) The extent of the employment gains depends on the good produced on the deforested land. More labour-intensive agricultural production would imply larger gains as compared with pastures.

Landowners, inframarginal and marginal, also benefit from increased rents in this scenario.

Perfectly elastic demand and fixed local labour force

Clearance of land requires labour and in absence of in-migration from outside the region, the local wage rate increases significantly. If the local workers are capable of working more hours, then clearance takes place and output increases, but workers gain relative to landowners. (In smallholder settings, however, the two groups may be nearly the same.) Less additional deforestation will occur as compared with the previous setting, and less of an output gain at local and national levels.

Inelastic demand and completely elastic labour supply

Here we consider a road extension large enough to depress the market price of the commodity in question. This counteracts to some extent local boosts in farmgate prices in places benefiting from the new roads. In turn, this dampens the impact both on landowner profits and on employment gains.

From this very simple comparative static analysis we can already appreciate the two main outcomes of roads construction and upgrading, which will be the object of this survey. When a new road is built or a poor quality road is upgraded, all potential road users will benefit from the decrease in transportation costs: all farmers located in regions connected to the market through the new or updated road segment will derive higher rents from their activities. On the other hand, however, new areas previously unprofitable for agriculture (the segment between the two frontiers in Figure 1) now become attractive for farming, increasing the incentive to forest clearing (Mäki et al. 2001; Locklin and Haack 2003). In other words, the same factors enhancing economic development also increase deforestation.

Of course, some qualifications are necessary. The simple structure presented does not take into account important factors influencing both economic development and deforestation. To start with, agricultural profits are not only determined by transport costs. Factors such as soil quality, slope, and rainfall heavily influence the returns to farming, shaping the incentive structure of potential farmers about the choice of the location to farm. To capture these, in many of the models featuring in this review, the variable expressing distance to market (or roads) will be a cost-adjusted distance, accounting for accessibility differentials.

Secondly, when a new road is placed a secondary counterbalancing effect on the labour market unfolds: outmigration to reach new off-farm employment opportunities. Transport cost reduction increases mobility and can provide access to new job opportunities either in nearby urban centers and more developed rural regions, or even locally, in case it becomes profitable for manufacturing industries to decentralized part of their production process at the local level. Wherever off-farm employment actually occurs, labour would be diverted from frontier farming, at least partially deterring further clearing.

Third, isolated local producers and workers formerly protected from competition may now face lower price imports – as in the case of porters discussed later on.

Finally, local development and deforestation patterns as presented in the scenarios above will also depend on the distribution of the land among local people (largeowner vs. smallholders) and other institutional variables (e.g. property rights definition and enforcement). In particular, if the new gains are shared among many smallholders the impact in terms of poverty reduction will probably be larger than if they concentrate in the hands of one or few largeholders.

Property rights definition and enforcement are two crucial factors in forest conversion decisions and in the way roads affects development. The effects on deforestation and development are complex. Sometimes deforestation occurs as a means of asserting property rights in anticipation that the land will later have value (Schneider 1995); on the other hand, settlers may be unwilling to invest in land improvement or in higher value crops such as perennials if tenure is insecure. Good definition and enforcement of property rights makes land grabbing and encroachment much more risky and costly, discouraging immigration of potential encroachers even after new roads approach.

We recognize the importance of tenure as well as other social variables (underlying factors as defined by Geist and Lambin 2001) in shaping development and deforestation but we won't address them directly in this work, concentrating instead on the effect of roads on development and deforestation.

Most empirical studies we will consider on the effect of roads on deforestation start from a theoretical structure similar to the one presented above (von Thünen model) and derive a testable equation investigating deforestation rate (or probability) with a set of explanatory variables including distance to roads (in most spatial analysis, see Nelson and Geoghegan 2002 for a review of the theory underlying these models) or road density at the data level (e.g. regional, provincial, communal). The empirical studies exploring the impact of roads on some form of development are much more heterogeneous, both for the kind of "dependent variables" adopted (e.g. access to basic services, transportation costs, agricultural output, poverty rate), and for the general objective and scope of the paper, e.g. project evaluation study, country-specific development analysis, cross-country analysis, infrastructure investment analysis.

Any empirical analysis aiming at quantifying the impact of roads both on economic development and on deforestation face the issue of potential endogeneity of road placement[2]. Indeed, when investigating the effect of roads on development (or agricultural expansion in forested areas – proxying deforestation) we want to be able to control for the intrinsic development potentials of the locations where the roads have been placed. In other words, roads could be placed in that particular location given other factors influencing both development and deforestation (e.g. better soil quality, climate, or higher population density). Development might "push" for road development, which in turn could boost further development. Failing to address this, or at least test for the presence of endogeneity, leads to biased results. For instance we could overestimate the deforesting impact of roads in a certain location, whereas in fact part of (or the entire) effect was to be attributed to intrinsic favorable soil and climate characteristics, which attracted farming development on that site.

There are a set of techniques for dealing with the issue. Spatial studies usually reduce the potential bias adding in the estimated equation controlling factors as soil quality, elevation and slope. In addition, many spatial studies explicitly address the issue with specific econometric techniques (e.g. using a predicted "cheapest way to market" variable as a valid instrument as in Chomitz and Gray 1996). Non-spatial studies deal with endogeneity (when they do at all) with standard econometric techniques (e.g. instrumental variable approach). In the following sections the material is organized first according to the actual aspect of roads impact investigated, and second according to the techniques used to tackle potential endogeneity[3].

3. Survey of the effects of roads proximity on development

A relevant amount of work has been written on the role that road extension can play in shaping economic and social development. Some authors have already tried to summarize the findings in the literature, but the fact that roads can influence in so many different ways the overall development of the environment around them makes it inevitably difficult for any such attempt to be complete. About 30 articles are reviewed in chapter 4 of Fan and Chan-Kang (2005) and a few less are considered by Escobal and Ponce (2002). Overall, these two surveys suggest a positive impact of roads proximity on development in its various aspects (e.g. economic development, poverty reduction, access to basic services). Out of the 55 studies covered by them, only a few focus on the

[2] Spatial studies' specific issues (e.g. spatial autocorrelation) will be briefly addressed before presenting the results of our review in section 4, as spatial studies represent the majority of the studies on deforestation.

[3] We also report in the summary tables whether a study controlled for the potential endogeneity.

shortcomings of roads projects (e.g. lack of maintenance and community participation), even recognizing the presence of benefits of some kind.

We directly reviewed 31 studies, and our conclusions do not diverge significantly from the previous work. In this section the findings will be discussed briefly. and report the results of the studies focusing on agricultural output and poverty alleviation, respectively. All the remaining studies appear in Appendix Table 1.

Agricultural output and productivity

Although road proximity has been found to favor also urban land development (Helmer 2004, focusing on Puerto Rico in the period 1977-1994) most of the studies in the review investigate the impact of roads on agricultural output and productivity. Almost half of them are by the IFPRI research group members[4]. They share the same empirical model (or slightly modified version of the same model) tackling with the potential endogeneity using a system of simultaneous equations.

Fan et al. (2000) estimate the effects of rural infrastructure on agricultural production and poverty reduction on Indian data disaggregated in agro-ecological zones (irrigated area and 13 different rainfed zones). In the first equation the "direct" effects of the different investments are detected, whereas the other equations investigate the "indirect" effects that some infrastructure (e.g. electricity, irrigation, roads) can have on investment decisions. The direct effect (expressed as elasticity) of road density on agricultural production equals 0.189 for irrigated areas, and range from - 0.28 to 1.38 for the rainfed zones (in 7 out of the 9 statistically significant categories elasticities are positive). Roads also have strong indirect effects on rural production giving incentives for technology uptake and other infrastructure investment. Interestingly, a simulation shows that the production returns and the poverty reduction in response to investments in roads are higher in some rain fed zones (including some "lower potential" areas) than in irrigated land (high potential areas). The decreasing returns to investments might explain this finding: the authors suggest that more developed regions of the country may already lie on the flatter section of the investment return's curve. Using a similar theoretical framework Fan et al. (2004) reported for China (1953-2000) an elasticity of agricultural output with respect to road density equal to 0.099, whereas for non agricultural output the elasticity equals 0.173, for wage it is 0.09 and for non agricultural employment 0.1. Returns to roads investment have a geographically quite balanced effect throughout China when we only consider agricultural GDP, but far higher returns for non agricultural GDP have been observed in more developed regions. This pattern is reversed when turning our attention to poverty reduction. In fact, as Fan et al. (2000) reported for India, with the same road investment more people would be lifted above the poverty line in the poorest (western) region in comparison to the more developed (central or coastal) regions.

Interestingly, when the same structure of analysis is run on Ugandan data (Fan and Chan-Kang 2004), returns in terms of poverty reduction are higher in more developed regions, suggesting that high potential areas of Uganda (and most probably other African

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[4] Fan et al. (2000), Fan et al. (2004), Fan and Chan-Kang (2004), Lofgren et al. (2004), Fan and Zhang (2004), Fan et al. (2005).

countries) might have not yet experienced diminishing returns to investment. At the aggregate level, feeder roads turned out to be the second best investment in terms of agricultural output.

Table 1: Impact of rural roads on agricultural output

STUDIES	LOCATION, DATE AND DATA LEVEL	CONTROL FOR ENDOGENEITY	ROAD IMPACT ON AGRICULTURAL OUTPUT
Fan et al. (2000)	India, 1970-1994 (district level)	Y	Elasticity (road density): 0.18** (irrigated) -0.28 to 1.38** (rainfed)
Fan et al. (2004)	China, 1978-2000 (province level)	Y	Elasticity (road density): 0.099*
Fan and Chan-Kang (2004)	Uganda, 1999 (household level)	Y	Returns to government investment in feeder roads: 600% (centre-richest) 870% (east) 490% (north-poorest) 920% (west)
Lofgren et al. (2004)	Zambia, 2001 (household level)	Y	10% increase in feeder roads leads to a +0.2% increase in agricultural GDP growth rate
Fan and Zhang (2004)	China, 1996-1997 (province level)	Y	Elasticity (road density): 0.032**
Binswanger et al. (1993)	India, 1960-1982 (district level)	Y	Elasticity (road length): 0.20***
Jacoby (2000)	Nepal, 1995-1996 (household level)	Y	Elasticity of land value with respect to "time to the market center": -0.26***
World Bank (2001)	Peru, 1994-2000 (household survey)	N	Not significant
Instituto Cuanto (2005)	Peru, 1994-2004 (household survey)	Y	Agricultural land increased by 15.8% in village with improved motorized roads
Zhang and Fan (2001)	India, 1971-1994 (district level)	Y	Elasticity of productivity with respect to road density: 0.043**
De Castro (2002)	Brazil, 1970-1996 (municipal level)	N	Elasticity of agriculture production with respect to road density: 0.33***

Policy makers are often faced with the dilemma, whether to build new roads and extend the existing network or rather upgrade part of the roads already in place. Lofgren et al. (2004) tries to provide some insight on this matter comparing the effects of an increase by 10% of paved road in less remote areas with an increase by 10% of feeder roads in relatively remote rural areas in Zambia. Both construction scenarios would raise GDP and reduce poverty, but effects are different in magnitude and distribution. Feeder roads are predicted to reduce rural poverty by more than 4% and urban poverty by 2%. The paved roads construction scenario leads to a slightly higher increase in GDP but, while urban poverty is reduced by 2% (as in the second scenario), rural poverty would decrease by only 2.5%[5]. Since rural population equals 6.5 million and it represents the 62.6% of the Zambian population, these findings suggest the existence of a trade-off between growth and poverty reduction in roads planning policies.

The last study adopting a system of simultaneous equations to control for endogeneity is by Fan and Zhang (2004), who investigate the specific role of rural infrastructure in explaining the difference in agricultural productivity among Chinese provinces. The elasticity of agricultural output with respect to road density equals 0.032.

A different strategy to control for endogeneity is adopted by Zhang and Fan (2001), which focus on the effects of infrastructure on agricultural productivity growth in 290 Indian districts (1971-1994). They instrument their GMM estimation with historical information for agricultural productivity and road density (up to three lags) and current values of HYV and rainfall, finding an elasticity of productivity growth with respect to road density of 0.043-0.048.

If a data panel is available, adopting a fixed affect specification can be an effective way of reducing potential endogeneity. The idea is skimming away from the analysis all the time-invariant site-specific characteristics, concentrating only on the changes over time in the dependent variable (e.g. agricultural output) associated with changes in the explanatory variables (e.g. road density). This method is adopted by Binswanger et al. (1993) in their study on the interlinkages among government decisions on infrastructure investments, financial institution development and private investment by farmers and the way they jointly influence agricultural output. Mainly due to better market opportunities and reduced transaction costs, roads have a positive impact on agricultural output (estimated elasticity is highly significant and equals 0.20). Moreover, roads are shown to have a positive impact on commercial bank placement and on some private investment.

The same technique is used by Jacoby (2000). Additionally, variables as soil quality, plot size and irrigation are entered in the regression, further controlling for endogeneity. He shows that reducing the distance to roads increases the profitability of agricultural activities (proxied by land value) in Nepal. Wage rate is also shown to decrease with increasing distance to roads.

A panel data cointegration method, which is robust to reverse causation, is adopted by Canning (1999) to investigate the effects of capital investment on productivity in 57 countries from 1960-1990. The elasticity of GDP per capita with respect to physical capital (including roads) per worker equals 0.431 and it is highly significant. When the sample is split according to development level, developed countries show a higher effect.

[5] In the case of feeder roads, benefits are limited to agricultural production. Paved roads benefit both non-agricultural production and export agriculture as it concentrates along the country's main road networks. While paved roads are expected to reduce the transactions costs in both the domestic and export markets, feeder roads reduce only the transactions costs in domestic markets. The analysis seems to disregard the benefit of people living on feeder roads at the edge of the network can derive from main roads upgrading.

Table 2: Impacts of rural roads on poverty alleviation

STUDIES	LOCATION, DATE AND DATA LEVEL	CONTROL FOR ENDOGENEITY	ROAD IMPACT ON POVERTY REDUCTION
Fan et al. (2005)	Tanzania, 2000-2001 (household level)	Y	Marginal effect of distance to public transportation facilities on the probability of being poor: 0.0022 to 0.0033. 30 people lifted above the poverty line each $1,000 invested in roads
Fan et al. (2000)	India, 1970-1994 (district level)	Y	0.25 (in irrigated areas) and 0.03-5.18 (in rainfed areas) people lifted above the poverty line each $1,000 invested in roads
Fan et al. (2004)	China, 1978-2000 (province level)	Y	2.22 (coastal region), 6.94 (central region), and 8.3 (western region) people lifted above the poverty line each $1,000 invested in roads
Fan and Chan-Kang (2004)	Uganda, 1999 (household level)	Y	15.64 (centre), 80.46 (east), 108.77 (north), and 45.45 (west) people lifted above the poverty line each $1,000 invested in feeder roads
Lofgren et al. (2004)	Zambia, 2001 (household level)	Y	10% increase in roads leads to 3-4% decrease in rural poverty
Gibson and Rozelle (2003)	Papua New Guinea, 1996 (household survey)	Y	Roads expansion such that everybody needs at most 2 hours walking to the nearest road reduces the number of poor by 5.77-11.84%
Warr (2005)	Laos, 1997-2003 (household survey and district level)	Y	Roads expansion providing all-weather road access to everybody would reduce by 7% the number of Lao's rural poor (representing 5.6% of Lao's population)
Escobal and Ponce (2002)	Peru, 1994-2000 (household survey)	Y	Roads improvement increased average income by 35% (in motorized road villages)
World Bank (2001)	Peru, 1994-2000 (household survey)	N	Roads improvement had no significant impact on poverty alleviation (short term effect)
Instituto Cuanto (2005)	Peru, 1994-2004 (household survey)	Y	Villages' motorized and non-motorized roads improvement decreased poverty by 4.1% and 5.7%, respectively (mid-long term effect)
Jalan and Ravallion (2002)	4 Chinese provinces, 1985-1990 (household, village and county level)	Y	When road density exceeds 6.5 km per 10,000 individuals, consumption growth is positive

Notes: all results are statistically significant at least at the 5% level unless otherwise indicated.

Income and consumption

A set of articles consider the effect that roads have on consumption growth or income (both agricultural and off farm) and all of them control for endogeneity.

Fan et al. (2005) builds on the same conceptual framework and model (system of simultaneous equations) of Fan, Hazell, and Thorat (2000) but it focuses on income instead of agricultural output. In particular, it investigates the impact of various infrastructures on household income and poverty levels in 7 regions of Tanzania. Distance to facilities (kilometers to public transportation facilities) influences income negatively and is highly significant in 3 of the 7 regions considered (the poorest regions are among the significant). In particular, the elasticities of income, with respect to distance, varies from -0.11 to -0.25. Consequently, reduced distance to public transportation is found to reduce poverty.

Pender et al. (2004) shows that proximity to the nearest *tarmac* road significantly increases the development of non-farm activities in Uganda. Unfortunately, the potential reverse causality is recognized but not addressed properly. This problem was instead reduced with soil quality data in a similar study in East Kalimantan (Dewi et al. 2005), which shows that higher density of provincial roads and district roads are associated with higher value of an "Economic Diversity Index", a measure of the heterogeneity of income sources in the village, confirming that roads proximity enhances off farm employment opportunities.

Gibson and Rozelle (2003) control for endogeneity by adding in the estimated equation geo-climatic variables such as elevation, slope, rainfall, and flooding susceptibility. They show that reducing the travel time to 2 hours for all PNG households that currently need a longer walk to reach the nearest road (17.3% of the population) would determine a fall in the number of poor people by 5.77-11.84%, depending on the model used (reducing also the severity of poverty). Warr (2005) estimates the same relationship for Laos and shows that about 13% of the decline in poverty level which occurred during the studied period can be attributed to roads improvements. Further simulations show that providing with all-weather roads the 50% of the country's population still lacking it in 2002, would have reduced the poverty incidence in rural areas by 7% (250,000 individuals representing about 5.6% of Laos's population). Interestingly, relying on panel data for his estimate, Warr (2005) was able to test for the existence of "endogenous placement" of roads, i.e. whether better off areas received more investment in road construction. A regression of the change in road access on the initial real per capita expenditure yielded a negative and non significant correlation, ruling out endogenous placement of roads, at least in Lao's last decades.

Jalan and Ravallion (2002) developed a micro model of consumption growth starting from an extended version of the classic Ramsey model allowing for constraints on factor mobility and geographic externalities (i.e. geographic capital can influence the productivity of a household's own capital). They test for the existence of "geographic poverty traps" in China. Results show that rural road density generates gains in living standards (elasticity equals 0.015). Moreover, a simulation shows that 6.5 kilometers per 10,000 people represents the critical value of road density below which a poverty trap would occur where consumption does not grow (holding all other variables constant at their mean values).

Transport costs, producer prices

Three studies investigate the impact of roads proximity on transaction costs and/or producer prices. Distance to market was found to increase transportation costs (Renkow et al. 2004), decrease the rice producer price in Madagascar (Minten 1999) and reduce market integration (Moser et al. 2005). The lack of consideration of potential endogeneity of roads placement in the analysis makes the following findings possibly overestimated. Only controlling for factors such as soil quality, climate characteristics, elevation and slope could provide a clean estimate of the impact of roads proximity on transport costs. Nevertheless, it is reasonable to believe that controlling for these effects would not change the sign of the effects reported.

Roads rehabilitation projects' impact evaluations

Three studies analyze the results of a World Bank funded project of rural road improvement in Peru (1995-2000). A local research institution, Instituto Cuanto (2000, as quoted by World Bank 2001), tracking the project development reports weak evidence of rural poverty alleviation and improvement of living standards in targeted areas. After project completion road improvement was associated with a significant travel time reduction, a reduction of transport prices of freight and for passengers, increased reliability of transport services and motorized transport traffic in general, and increased access to health centers (19% comparing with 15% in the control sample). Neither significant impact on the access to education and school attendance, nor noticeable impact on economic production was detected. However, as this survey was carried out relatively close to project completion, it has probably detected only short-term effects of roads improvements. It is reasonable to expect that stronger economic effects would arise in the long run. Escobal and Ponce (2002) adopts a procedure of propensity score matching on the same database to correct for potential bias due to non-random control sample (used by Instituto Cuanto 2000). The idea is to account for the different initial endowment in the two groups, targeted and control villages, in terms of human capital, assets and access to some services, in order to be able to assess the net impact of the project on income level, income composition, and consumption. The results of the analysis are indeed more encouraging than the ones reported by World Bank (2001), confirming strikingly how ignoring potential endogeneity issues can lead to biased results. Households in the villages included in the motorized roads improvement project show a statistically significant increase in annual income of about US$ 120 (representing 35% of the annual income in the control group), mostly from non agricultural activities.

After four years from the project implementation Instituto Cuanto (2005) ran another survey in the same targeted and control villages. That allowed the use of the "difference in differences" method, comparing changes over time within the treated village sample with changes over time found in the control sample in order to assess the net effect of the project. The strongest effects are detected in the transport sector, with a reduction of the travel time by 61.8% due to roads improvement, an important increase in the light vehicles traffic (mainly cars), and a decrease of transport prices of freight and passengers. School matriculation increased by 14% for the villages with improved (non-motorized) paths, and the number of visits to health centers increased by 25-45%. While the area under agricultural use expanded and the price of irrigated land increased, there is no evidence of impact of the project on productivity, crop conversions or increases in marketed output and agricultural prices. Interestingly, an increase in the share of population employed in commerce and services (10-20%) as well as in cattle activities was observed. Male wages increased between 2000 and 2004 by 20%, but female wages did not change significantly. Finally, a positive impact of road improvement on poverty reduction is noticed: in fact, the change in poverty rate over time equals -0.2% for those communities with a rehabilitated motorized road, and +9.4% for communities with an improved non-motorized path, whereas the figures for the control sample are +3.9% and +16.1%, respectively.

A second road improvement project was investigated by Windle and Cramb (1996) in Malaysia. There, road rehabilitation did not change the choice of transport mode very much. Farmers continued to walk to their fields, and their inputs and products were still head-loaded. But new roads made journeys quicker and cheaper. Although it did not lead to an increase in the provision of school and health services, it generally improved the access to the existing ones (particularly to the latter). Interestingly, it increased the proportion of female users of the roads, as they could travel alone, either by bus or private vans.

Finally, a recent study by the Asian Development Bank (Hettige 2006) analyzes six case studies of roads improvement (two in each of the following countries: Indonesia, Sri Lanka and the Philippines). The initial purpose was using double differences analysis (as in Instituto Cuanto 2005) to assess the effect of roads rehabilitation projects (both as isolated sector projects and as part of Integrated Projects), but practical survey difficulties made it impossible. Some general findings emerge in line with the results so far considered: travel time and costs decreased everywhere for transportation service providers, whereas access to health facilities, electricity and education services improved. Interestingly, further road development (asphalting) was suspiciously considered as it would allow vehicles to come and replace the porters' function, leaving them unemployed.

Summary

The more than 80 studies covered in this short review reveal that roads construction and improvement are strong predictors of development. Road proximity reduces transportation costs, which in turn (recall von Thünen's intuition) increase the price of commodity obtained by local farmer, and reduces the effective costs of inputs (e.g. fertilizer), providing an incentive for agricultural development. However, compared to the theory we found surprisingly low elasticities of agricultural output with respect to road density. This is probably determined by the level of data aggregation adopted by the studies and from the use of road density as a proxy for road proximity, which underestimates the effects of roads at the forest frontier. The study of Jacoby, which explores the benefits of access to the market at the household level adopting a direct measure of road proximity, shows that reducing the distance to roads increases land values significantly in Nepal. Given the importance of the policy implications, more careful spatial analysis is needed. However, those studies which separately evaluate economic benefits of new roads to richer vs. poorer households, found generally the former enjoying a larger share of the new gains. That is due mainly to their initial endowment in capital (and education) which allows them to react quickly to the new economic opportunities. Hettige (2006) illustrates this point well with a series of case studies presenting households story of successful and less successful economic development following road improvement. In the extreme case, roads improvement could even harm some poor section of the society, when it endangers the very existence of their traditional occupation (e.g. porters) without providing a reasonable alternative income source. The several studies which we considered were basically unanimous in their findings (although showing different magnitudes): roads favor poverty reduction. Even more so if we include in our broad definition of poverty the lack of basic services. The fall in transportation and travel costs heavily influence the access to those services, either by reducing the costs of installing new service facilities at the local level (e.g. electricity, better sanitary and toilet facilities, irrigation), or by allowing a much cheaper access to the previously prohibitively distant service providers (e.g. education, health services). Nevertheless the same factors boosting agricultural profits, and consequently relieving poverty, set up incentives to clear forest for conversion to agriculture. The remainder of this work is exploring this nexus in the literature.

4. Survey of the effects of roads proximity on deforestation

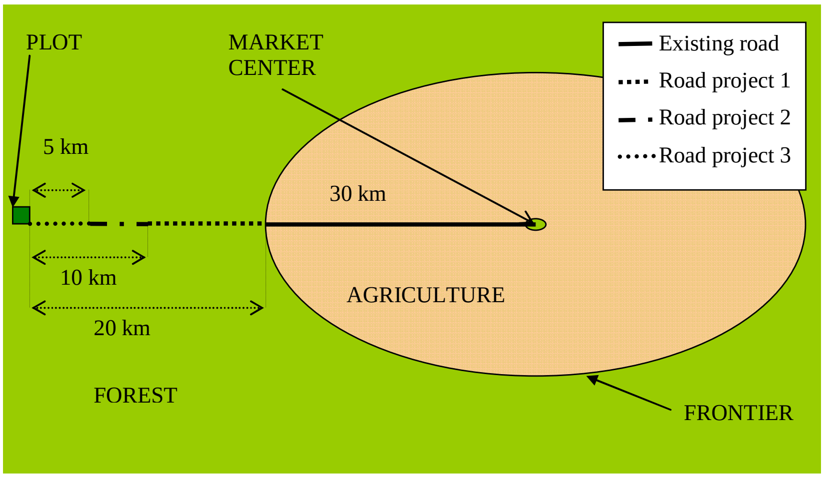
We scanned the literature searching for empirical studies focusing on deforestation having roads proximity (or road density) among the factors of the analysis. We also included in this review those studies entering distance variables in their analysis (e.g. distance to market, village, town) when computed along the existing road network (and not as Euclidean distances[7]). We were able to find thirty-six such studies, most of which use spatial analysis particularly helpful to capture the subject we focus on. Spatial analysis makes use of geographically referenced data in order to visualize the effects under consideration along the spatial dimension, making it possible to analyze a phenomenon (e.g. deforestation) no longer at the state, district or communal level, but at the very plot level.

Quite a clear result emerges from the review. Twenty-two studies (61% of the studies reviewed) revealed an unambiguously positive and significant effect of road proximity on deforestation, i.e. the closer a plot of forest is located to the roads, the more likely its deforestation will be. Two more studies (6%) allegedly support this finding, but unfortunately the statistical significance of the coefficients is not reported in the article. Four studies (11%) find a non significant correlation between roads and deforestation. The remaining eight studies (22%) report mixed results, i.e. some road related variables are associated with more deforestation, whereas some other ones are associated with less deforestation (or non significant); or the same road related variables show a positive effect on deforestation in a time period and the opposite effect in another time period.

[7] Although sometimes we report results for this variable too, Euclidean distances are not expected to capture any roads effect. The same plot at, say, 10 kilometers (Euclidean distance) from the market would have a very different probability of deforestation if connected to the market with a paved road, a narrow path, or nothing at all.

However, notice that no single study consistently supports the opposite claim: roads deter deforestation.

Figure 2: Methodology used for comparing magnitudes



Notes: projects reduce gradually the distance to the paved road.

Spatial studies

Impact magnitude differs significantly across studies. Most of the spatial studies, starting form an empirical derivation of the von Thünen intuition use either a multinomial logit model to assess the impact of a set of independent variables on the probability of various land-use categories, or alternatively a binary probit/logit model assessing the probability of forest as compared to non-forest. Even if using similar econometric techniques, those studies have relevant differences in some underlying assumptions, units of measure, and in the way they model the variable "distance to road". Therefore, to present results in a comparable way, we compute the impact of road proximity on deforestation as the probability of deforestation (or conversion to other land use, usually agricultural) of a hypothetical plot of forest located initially at twenty kilometers, then at ten kilometers, at five kilometers from a paved road and finally directly facing a paved road. The distance to the nearest market will be kept at twenty kilometers and then at fifty kilometers for the studies, which introduce this variable in the analysis. The plot considered is the one identified by the variables' means computed on the sub-sample of forested land only[8] and assigning zero value for the protected areas or any other "special status" dummy variables. This procedure tends to understate the threat of deforestation brought about by road proximity as the variable mean of the forested sub-sample identifies a plot of forest still relatively "safe" in the middle of the forest when compared with a plot at the forest fringe. However, given the information available in the majority of the articles, there was no way to work with a plot located at the forest frontier. shows our proceedings graphically. For each study we asked what the probability of deforestation for the average (forested) plot located at 50 (and 20) kilometers from the market (Euclidean distance)

[8] We used the forest subsample variable means when such information was available. Otherwise, we used the mean of the variable computed on the entire sample.

would be if we implemented, sequentially, the roads projects reducing gradually from twenty to zero the distance in kilometers to the nearest paved road.

Results of this exercise are reported in Table 3. Studies for which only one set of results are reported did not have a variable in the analysis capturing the (Euclidean) distance to the market. For all other studies the first set of probabilities refers to a plot located at 50 kilometers form the market, whereas the second set of probability refers to a plot 20 kilometers away from the market. The last column expresses the absolute change is deforestation probability after the implementation of the three road projects (which put the plot 20 kilometers closer to the roads). The table also reports whether the paper explicitly controls for endogeneity[9] and spatial autocorrelation[10].

Except Müller and Munroe (2005) where the coefficients were not statistically significant, the other studies, for which the necessary information was provided[11], identify an increase in the absolute probability of deforestation due to the progressive road proximity. Reducing the distance to the nearest paved road by 20 kilometers, keeping fixed the distance to the market, increased the probability of deforestation at least by 1% and all the way up to 100%!

We tend to consider those studies directly addressing spatial autocorrelation and endogeneity more reliable in their estimate processes. Eleven such studies[12] have been found in the literature, and all but one (again Müller and Munroe 2005) found non negligible impacts of roads on deforestation.

Chomitz and Gray (1995; 1996) was the first such study and found that both categories of agricultural land use considered in the analysis in Belize (semisubsistence and commercial agriculture) become less prevalent as distance to markets increases; commercial agriculture being much more sensitive to that variable. At a market, middle quality land has a 34% chance to be cleared for commercial agriculture purposes whereas only 1.4% chance to be used for subsistence agriculture. Moving away from the market rapidly decreases the likelihood for land to be used for commercial purposes, less so for semisubsistence agriculture. On high quality land (although at relatively high elevation) the likelihood of a plot to be used for commercial agriculture is 5% at the market,

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[9] Keep in mind that as all studies presented in Table 3 are spatial studies entering in the analysis variable on soil quality, slope and elevation, the potential road endogeneity is at least partially controlled for, even for those studies that did not explicitly control for endogeneity.

[10] Spatial autocorrelation occurs when values of a variable sampled at nearby locations are more similar than those sampled at locations more distant from each other. The presence of spatial autocorrelation often violates the assumption of independence that is implicit in many statistical analyses, leading to biased estimates or inaccurate standard errors. Bias due to spatial autocorrelation is usually addressed with some form of sampling procedure (Besag, 1974) in order to include only observation separated by sufficient distance such that the autoregressive effect is absent; and with the introduction in the analysis of spatial lagged variables and geographic coordinates (for a more extensive treatment of the issue, see Nelson and Geoghegan 2002).

[11] We are grateful to the authors, who provided supplementary information needed for this simulation.

[12] Chomitz and Gray (1996); Nelson and Hellerstein (1997); Nelson, Harris and Stone (2001); Müller and Zeller (2002); Müller and Munroe (2005); Munroe et al. (2002); Pfaff (1999); Mertens et al. (2002); Mertens et al. (2004); Nelson et al. (2004); Vance and Geoghegan (2002).

whereas for semisubsistence the figure equals 45%. Moving away from the market reduces that probability, although much more gradually for the latter category. Serneel and Lambin (2001) find similar patterns in Kenya. Smallholder deforestation is more likely to happen close to villages but at more distant location from the district capital, with mechanized agriculture more likely to occur near the district capital and farther from small villages (at least for the period 1985-1995). At a first sight these findings are puzzling. Two main explanations can restore the trust on von Thünen's theory. First, as smallholders sometimes practice subsistence or semi-subsistence agriculture (e.g. in Belize), they are less concerned about the transportation costs. When they do sell their product, the relevant market is most probably the local and not the regional one. Second, small-scale farmers often face credit constraints, which do not allow them to invest in fertilizers. Consequently, they are more sensitive to soil quality; therefore if it means better soil, they are ready to farm further away from roads and markets. On the other hand, mechanized agriculture needs easy access for the use of heavy machinery and fertilizers and also since the entire product is generally marketed (as Chomitz and Gray results confirm).

Surprisingly, Mertens et al. (2002) and Naidoo and Adamowicz (2006) report the opposite finding. The former study investigates the effect of roads on deforestation by different producer types in Pará (Brazil) and argues that smallholder directed colonization is particularly sensitive to road proximity. The latter shows that only smallholders caused deforestation is associated significantly with road proximity in Paraguay. Again, probably the crucial factor is represented by the degree of integration in the market of the various farmers, and which market (local, regional,global) is relevant for each of them. Mertens et al. (2002) is among the studies not fully supporting our von Thünen derived predictions as the variable "distance to village" is found to be positively associated with deforestation by both small and large farmers, at least in the first model considering the period from 1986 to 1992. A closer look at the specific situation provided by the authors helps interpret these results. Quoting directly, "most villages existing before 1986 are remote mining centers, located far from the towns and main roads, and did not lead to further forest conversions" (Mertens et al. 2002). Again, von Thünen survives.

In the analysis of Nelson and Hellerstein (1997) focusing on central Mexico, increasing the cost of access to the nearest road by two times the maximum value in the sample would increase forested area by 20% and reduce irrigated area by 16%. Similarly, in the Brazilian Amazon "paved road density" increases the likelihood of deforestation (Pfaff 1999). Distance from primary and secondary roads deterred deforestation in the Bolivian Amazon, although the magnitude of the effect decreased overtime (Mertens et al. 2004)[14]. This relation is solid also in the Yucatan region (Mexico), as shown by Vance and Geoghegan (2002), who however warn on the danger of looking only at the potential deforesting effect of road placement. They argue that roads usually also increase access to off-farm income sources, which can reduce the pressure on forests, decreasing labour on the frontier farms.

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[14] Secondary roads have a systematically lower impact on deforestation (see also Fujisaka et al. 1996).

Table 3: Probability of deforestation at different distance from roads (spatial studies)

STUDY	COUNTRY	CONTROL ENDOG-ENEITY	CONTROL SPATIAL AUTOCOR-RELATION	PROBABILITY OF DEFORESTATION (at difference distances from the nearest paved road; when distance to market was provided we computed the three probability at 50 km (top) and 20 km (bottom) for the relevant market)				
				20 km	10 km	5 km	0 km	P(0 km)-P(20 km)
Chomitz and Gray (1995)	Belize	Y	Y	0 [1]	0.00028	0.0014	0.01	0.01
				0 [1]	0.00065	0.003	0.02	0.02
Cropper et al. (2001)	Thailand	N	Y	0.11	0.129	0.154	0.26	0.15
				0.1	0.13	0.156	0.3	0.2
Deininger and Minten (2002)	Mexico	N	N	0.51	0.56	0.58	0.603	0.093
Müller and Munroe (2005) [2]	Vietnam	Y	Y	0	0	0	0	0
Müller and Zeller (2002)	Vietnam	Y	Y	0.012	0.033	0.048	0.063	0.051[3]
				0.0001	0.0007	0.0014	0.003	0.0029
Munroe et al. (2002)	Honduras	Y	Y	n.a.	n.a.	n.a.	n.a.	0.50[4]
Naidoo and Adamowicz (2006)	Paraguay	N	Y	0.1028	0.2146	0.3237	0.491	0.39
				0.08[5]	0.197[5]	0.323[5]	0.52	0.44
Nelson and Hellerstein (1997)	Mexico	Y	Y	n.a.	n.a.	n.a.	n.a.	0.068 [6]
Nelson et al. (2001)	Panama	Y	Y	0	0	0	0.999	0.999
				0	0	0	1	1
Southworth et al. (2004)	Honduras	N	Y	n.a.	n.a.	n.a.	n.a.	0.08
Vance and Geoghegan (2002)	Mexico	Y	Y	n.a.	n.a.	n.a.	0.05 [7]	n.a.
				n.a.	n.a.	n.a.	0.2 [7]	n.a.

Notes:
(1) Converted roughly 30 kilometers on paved roads in 18 minutes travel time
(2) The coefficients were not statistically significant
(3) In the same interval the probability of forest degradation increases from 0.4 to 0.86
(4) Computed as the marginal effect of the probit model reported in the article times the cost reduction implied by substituting 20 kilometers off-roads with a paved road
(5) The joint probability of deforestation decreases when closer to market. The reduction of probability of ranching more than offset the increase in probability of smallholder and soybean agriculture.
(6) We adopted the costs used by one of the author in Nelson et al. (2004) and Nelson et al. (2001) to simulate the road construction's effect
(7) As only "on-road distance to market" is provided we can only compute the probability of deforestation of a plot at 50 and 20 kilometers from the market but directly close to a road.

Munroe et al. (2002) capture the effect of market remoteness on deforestation with two aggregate cost variables “maize price + distance to nearest village” and “coffee price + distance out of region”. The idea is that maize is associated with local consumption whereas coffee is mainly for export. The variable “maize price + distance to nearest village” shows a negative marginal effect whereas “coffee price + distance out of region” has a small but positive effect on the probability of deforestation. The authors do not explain the interpretation of these results further. In particular, the choice of the variables for capturing the distance to market does not seem convincing. Indeed, at least theoretically, increases in the price of agricultural outcomes should constitute an incentive to more deforestation, whereas more remote location (increasing the costs of access to markets) would lead to a lower incentive to deforestation.

Our simulation in Table 3, for the study by Müller and Zeller (2002), shows that when the distance to paved road decreases by 20 kilometers, deforestation is predicted to increase in absolute terms by 5.1%. Yet, the interpretation of the results by the authors is less pessimistic: they argue that access to all-year roads improved agriculture (better access to markets, infrastructure, agricultural inputs and public services), and contributed to intensification in agricultural production, determining a higher productivity on existing farmed land and reducing the need for land for shifting cultivation in central Vietnam. In other words, after a first period (1975-1992) where road development was associated with more forest clearing, better access to market along with better enforcement of protected areas and policies discouraged shifting cultivations, reduced agriculture expansion, decreased pressure on forested lands and caused forest regeneration mainly on grasslands previously used for shifting cultivation (Müller and Zeller 2002, p.347-348).

As already mentioned Müller and Munroe (2005) is the only study (among the ones controlling for both endogeneity and spatial autocorrelation), which found no significant impact of roads on deforestation in their analysis in Dak Lak province (Vietman). Interestingly, however, the authors question their finding and recognize that this result is probably driven by the fact that large areas used for agricultural purposes at the time of the study (1992-2000) are too far from the all-year road network used as a valid instrument for road distances in the empirical estimation (roads network at the French colonial time).

Six more studies[17] explicitly correct for spatial autocorrelation and even if they do not explicitly address the potential endogeneity of roads placement, their spatial analysis implicitly corrects for it (at least partially), as it includes variables such as soil quality, slope and elevation in the analysis. All of them find a significant (positive) impact of roads proximity on deforestation.

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[17] Cropper et al. (2001); Serneels and Lambin (2001); Kirby et al. (2006); Naidoo and Adamowicz (2006); Southworth et al. (2004), Tucker et al. (2004).

In particular, Cropper et al. (2001) found in Thailand that reducing the distance to the nearest paved road (from 2.5 to 1 km away) of a plot at 6 km from the nearest market center (on-road distance) by 1.5 km increases the likelihood of deforestation by 5% (from 0.18 to 0.23).

As already mentioned before, Serneels and Lambin (2001) found for Kenya that for mechanized agriculture the variables that seem to matter the most are accessibility to market and agro-climatic potential. In particular, low altitude plains where heavy machinery has easy access are preferred and accessibility is even more important than soil quality. Smallholder settlements are common near the border with a nearby National Reserve farther from roads and markets, given the exception which permits them temporary access to the permanent water of the Park during times of drought. Moreover, they are more sensitive to soil quality and to the distance from the village where they can access social services (e.g. health centers, schools, local markets).

Access to paved roads turns out to be the mayor driving force of deforestation in Amazon, followed by population density, and unpaved road access in a recent study by Kirby et al. (2006). Consequently, the authors warn on the effects of the implementation of “Avanca Brasil”, a Brazilian infrastructure improvement project, which would significantly increase the pressure on protected areas and indigenous reserves.

Tucker et al. (2004) try to capture the effect of roads on secondary forest as well. They run a comparative land-use change analysis between two sites: La Campa, Honduras and Camotán, Guatemala. As usual remoteness is associated with less deforestation, but interestingly, road proximity is also associated with forest regrowth[18]. Abandonment of marginal agricultural plots, “apparently in order to pursue agricultural intensification and coffee expansion” (Tucker et al. 2004), and the presence of community organization for forest protection, concurred in determining the overall trend of forest regeneration in Honduras. This result is confirmed in Munroe et al. (2004) and echoes the warning from Vance and Geoghegan (2002) not to forget the potential advantages of roads proximity even for forests. In Guatemala, however, the observed regrowth does not offset ongoing deforestation.

Finally, even if they do not explicitly control for spatial autocorrelation, it is worth presenting the results of two further spatial studies. Etter et al. (2006) study deforestation in Colombia. Roads proximity is among the most important predictors of deforestation both at the national and the regional level. The Amazon region is by far the most crucial factor. Interestingly, more than 90% of the country’s commercial agriculture and 80% of smallholder agriculture is located within five kilometers from a road. A significant exception regards deforestation for illegal coca cultivation, which is located for obvious reasons in less accessible areas.

In their study on two Mexican states Deininger and Minten (2002) show that increasing the distance from the next paved road by 68 kilometers would reduce the probability of deforestation by 18 percentage point. Moreover, they show the importance of physio-

[18] The finding by Pendleton and Howe (2002) that distance to roads significantly decreases the amount of old-grown forest cleared for agriculture, but does not affect smallholders’ clearing of secondary forest also seems to supports this.

geographic variables in deforestation analysis, usually adopted in spatial analysis. Omitting those variables is shown to even reverse the sign of the effect of the some variables on deforestation, for example poverty.

Non spatial analysis

The rest of the studies for which it was possible to compute the effect of the roads proximity on deforestation in terms of elasticity are reported in . All but two studies (Lombardini 1994; and Osgood 1994) confirm the positive correlation of roads and deforestation. Only two among these studies controlled for endogeneity.

Table 4 Impact of roads on forests (elasticities)

STUDY	COUNTRY	ENDOGENEITY	DEPENDENT VARIABLE	TYPE OF ROAD VARIABLE	ELASTICITY DEPENDENT VARIABLE WITH RESPECT TO ROADS VARIABLE
Andersen and Reis (1997)	Brazil	N	Proportion of cleared forest	Road length in the region	0.047***
Cropper et al. (1999)	Thailand	Y	Proportion of cleared forest	Road density	0.427*** [(a)]
Panayotou and Sungsuwan (1994)	Thailand	N	Forest cover	Rural roads extension	-0.11*
Lombardini (1994)	Thailand	N	Forest cover	Paved and unpaved roads length	-0.0012
Osgood (1994)	Indonesia	N	Forest cover	Road length in the region	-0.041
Pendleton and Howe (2002)	Bolivia	N	Old-grown forest clearing	Walking time to nearest road	-0.132**

[(a)] The elasticity reported is for the entire kingdom. When the analysis is run on two sub-samples (North vs. South) the coefficient is significant (and roughly conserves the same magnitude) only for the South.

Cropper et al. (1999) adopted a two-stage-least-squares estimation and entered information about soil quality and slopes to control for endogeneity. They found an elasticity of forested area with respect to road density of -1.5 in the South/Central Thailand, but for North and Northeast Thailand the variable had no explanatory power for deforestation.

Similarly Pichón (1997) reduces the potential endogeneity adding in the estimated equation information on soil quality and hilliness. After reporting the usual deterring effect of distance from roads on deforestation in the Ecuadorian Amazon, the author strongly supports an intensive approach to road construction; i.e. improving the existing road network as a measure for increase economic activities and development without constructing new roads (see also Guimaraes and Uhl 1997).

An original analysis by Andersen et al. (2002) found interesting and somehow puzzling results. The method adopted to tackle endogeneity of roads is by lagging road density variables[20]. In addition to road density, interaction terms ("road*cleared land") are entered in the estimation to detect if there is any significant change in the way roads affect deforestation, depending on the share of already cleared forest in the neighborhood. This turned out to be crucial. During the first period (1980-1985) paved roads were not affecting deforestation. Unpaved road shows instead an unexpected sign, i.e. they reduce the growth of agricultural land. However, when summing up this effect and the interaction term's effect, deforestation is actually increasing in places with a relatively high proportion of cleared land. In the 1985-1995 period, both paved and unpaved roads are positively associated with growth in agricultural land, but interestingly, the interaction term "paved road*cleared land" has a negative sign, implying that paved roads reduce farmed land growth in already highly deforested areas. Since the latter effect is larger than the former, the authors argue that road paving in Brazil (the bulk of the "Avanca Brasil" program) would, in fact, reduce deforestation!

These results need to be better qualified. In fact, if the simulation on the consequences of road paving is based on the crucial assumption that the total extension of roads is not changing (simply converting unpaved to paved roads), the policy advice is not credible and can be misleading. Road paving is expected to decrease transportation costs and increase profitability of agriculture for the entire region connected to the relevant market through the upgraded road. Paving roads may not *directly* increase deforestation in the already heavily farmed wings of the targeted road, but it will very likely *indirectly* increase deforestation along the unpaved roads off-shooting from the main highway. Furthermore, it will possibly push for the spontaneous creation of such new roads heading to a region not yet deforested, bringing about dramatic environmental consequences. These latter indirect effects could possibly more than offset the beneficial impact of paving reported by Andersen et al. (2002).

Finally, Bray et al. (2004) make an important point in their study of the 'Mayan Zone', in Mexico. Even if roads were found to increase deforestation probability during the period 1984-2000 (although not significant for the period 1976-1984), a very low annual net forest cover loss resulted (0.1% per year). The authors claim that efficient institutional innovations for sustainable forest management, starting back in the 1930s with the reservation of large chunk of forest for *chicle* (NTFP used to produce chewing gum) harvesting under *ejidos* (common property rights titles) and reinforced with the institutions of permanent forest estates under community management, effectively

[20] It is not entirely convincing, as the effect under consideration can manifest in the long term.

reduced immigration, and allowed secondary forest regrowth where mature forest was gone. The message is that, as mentioned in the theoretical section, roads might not be inescapably linked with high deforestation. When efficient institutions are in place it is possible to get some of the benefits we reported without necessarily paying the price in terms of biodiversity loss and potential climate change.

All remaining studies providing the results of econometric analysis are listed in Appendix Table 2, which also includes the studies discussed so far.

Summary

The diagnosis of this short review is reasonably clear: roads proximity is among the crucial proximate factors of deforestation. Even if the studies considered differ in the econometric techniques used, with regards to the variables entered in the analysis and in the definition of the road variable, almost all of them could not entirely reject the hypothesis that roads do influence deforestation incentives, at least for part of the time period considered. The rule is found to be valid throughout the tropics at least. The reduction in transportation costs generally attracts newcomers and gives incentives to the local population to increase economic activities, which in turn usually directly affect the nearby forest. However, few encouraging trends emerge from the literature. Firstly, protected areas have a mitigating effect on deforestation, suggesting that when a new road is planned, a previous consideration on the biodiversity of the region should be done, and the more fragile areas should be protected. Secondly, a clear definition of property rights as well as providing the means for enforcing them effectively, even if it does not guarantee forest conservation, can at least reduce the deforestation impact of migration, usually following road construction.

Finally, the studies which tried to separate the effect of roads proximity on deforestation from the one of reforestation, found that forest regrowth usually occurs first close to the roads. The reduced number of studies focusing of both forest trends do not permit us to take it as a general rule, but if confirmed by future analysis this result would further support the Boserupian intuition, i.e. modern technology progress reduces agricultural land necessity as it leads to agricultural intensification. In other words, road proximity, ensuring on one hand cheaper access to new technologies, fertilizers, and heavy machinery, and on the other hand easier access to off-farm employment opportunities, can reduce the demand for land and allow marginal lands to regenerate as forest (see literature on forest transition, e.g. Mather 1992; Rudel et al. 2005).

5. Conclusions

Roads represent a crucial factor of development. When asked about their development priorities, it is not unusual that local poor villages set road development among the first projects they would like to see implemented (see Ford and McConnell (2001); for example in Madagascar, and Hettige (2006) in three Asian countries). Given the results found in the literature it is easy to understand why: roads allow isolated population to get easier access to basic health centers and schools; increase mobility of people and goods, reducing transport costs and boosting through that mechanism economic development (although the effects on agricultural output were surprisingly small).

This study also shows that roads represent a crucial factor of deforestation. Roads allow farmers to break even at farther locations, inevitably increasing deforestation when that occurs in remote forested regions.

This suggests the existence of a trade off between economic and social development and forest conservation. The reduction in transportation costs implied by road expansion leads to both more development as well as more deforestation. Despite this rather pessimistic conclusion, the literature reviewed also identifies some factors which might mitigate the trade off, at least partially.

Some authors argue that intensive road construction, instead of an extensive approach, would indeed provide similar advantages in terms of development without putting the precious forest which remains, under pressure. Instead of roads penetrating in the remote forest, they would improve and strengthen the existing network of roads in order to offer more economic opportunities to the population already connected to the market (reducing migration to the "frontier") and set an incentive for those living isolated from the market to move closer to it where the services are regularly provided.

Strengthening property rights enforcement and tenure security would also reduce the damaging effects of roads on forests. Throughout the studies of section 4 all dummies representing both protected areas but also any kind of community forest management institution (e.g. *ejido* in Mexico) were usually found to decrease deforestation, keeping fixed the distance to roads (see among others Chomitz and Gray 1996; Nelson, Harris and Stone 2001; Mueller and Zeller 2002; Mertens et al. 2002; Deininger and Minten 2002). This suggests that creating an adequate legislative framework able to guarantee and protect forestland tenure would reduce deforestation even in the presence of roads placement. Despite that, if we recall von Thünen one last time, it is not at least theoretically guaranteed that the forest owners, whoever they are, will find it more profitable to manage forest instead of converting it to agriculture once the latter becomes more profitable. Careful mechanisms should be put in place to safeguard at least the most fragile forest environments.

6. Appendix

Appendix Table 1: Compilation of studies on the effects of roads on development

STUDIES	LOCATION, DATE AND DATA LEVEL	CONTROL FOR ENDOGENEITY	DEPENDENT VARIABLE	ROADS IMPACT ON DEPENDENT VARIABLE
Jacoby (2000)	Nepal, 1995-1996 (household level)	Y	Land value Wage rate	Elasticity of land value w.r.t. “time to the market center”: -0.26*** Elasticity of wage w.r.t. “time to the market center”: -0.048***
Ghosh and De (2005)	India, 1971-1998 (state level)	N	Per capita income	Effect of roads as part of “Economic Overhead Capital”: (+)*** (n.s for 1991-1992 model)
Renkow et al. (2004)	Kenya, 1999 (household and village level)	Not applicable	Fixed transaction costs in the market of maize	Effect of distance to nearest village by truck (road): (+)***
Canning (1999)	57 countries, 1960-1990 (country level)	Y	GDP per worker	Elasticity of GDP w.r.t physical capital: 0.431*** (higher in developed countries)
Jalan and Ravallion (2002)	4 Chinese provinces, 1985-1990 (household, village and county level)	Y	Consumption growth	Elasticity w.r.t. of road density: 0.015***
Gibson and Rozelle (2003)	Papua New Guinea, 1996 (household survey)	Y	Ln (consunmp./poverty line)	Marginal effect of travel distance to nearest road (hours): -0.04**
Warr (2005)	Laos, 1997-2003 (household survey and district level)	Y	Real per capita expenditure	“District built road during 1997-2002” dummy: 0.188*
Minten (1999)	Madagascar, 2000-2001 (commune census data)	N	Producer price of rice	Reduction of price in US$/kg/km: 0.001-0.0016

STUDIES	LOCATION, DATE AND DATA LEVEL	CONTROL FOR ENDOGENEITY	DEPENDENT VARIABLE	ROADS IMPACT ON DEPENDENT VARIABLE
World Bank (2001)	Peru, 1994-2000 (household survey)	N	 Travel time Freight transport costs Passenger transport costs Student registered Student dropouts Visit to health centers	Change due to roads rehabilitation (short term effects): -21.8% to -33.4% -7.9% to -13.6% -6.6% to 19.6% +6.9% (significant only for non-motorized road villages) -9% to +24.7% (the latter for non-motorized road villages) -3% to +4.1% (the latter for motorized road villages)
Instituto Cuanto (2005)	Peru, 1994-2004 (household survey)	Y	 Travel time Freight transport costs Passenger transport costs Student registered Visit to health centers Male wage	Change due to roads rehabilitation (medium-long term): -61.8% -5.7% to -46.4% -8.8% to -40.6% -0.4% to +14.1% (the latter for non-motorized roads villages) +25.4% to +45.6% (the latter for motorized road villages) +20.6% (only for motorized road villages)
Dewi et al. 2005	East Kalimantan, Indonesia, 1992-1997 (spatial data, village level)	N	Economic diversity index [1] (heterogeneity of income sources)	Density of provincial and district road: +***
Pender et al. (2004)	Uganda, 1999-2000 (community level)	Y	Increase in nonfarm activities	Elasticity (reduction in distance to tarmac road): 0.089***
Hettige (2006)	Sri Lanka, Indonesia, Philippines, 1993-2001 (households level)	N	Travel time Access to electricity Increase in non-farm income	At least 50% less than control villages 17% more households than in control villages 9% more households than in control villages

Notes: [1] positively associated with a well-being index (VDI), similar to the World Bank's HDI.

Appendix Table 2: Compilation of studies considering the effect of roads proximity on deforestation

STUDIES	LOCATION AREA (km²), AND DATE	VARIABLE CAPTURING ROAD EFFECT	IMPACT ON DEFORESTATION	CORRECT FOR SPATIAL AUTO-CORRELATION	CORRECT FOR ENDO-GENEITY	CONTROL VARIABLES (IMPACT ON DEFORESTATION) Soil quality	Slope	Altitude
Andersen et al. (2002)	Amazon-(BR) (~5 Million) 1980 to 1985	Unpaved road density	- (at least **)	N	Y	n.i.	n.i.	n.i.
		Unpaved road *cleared land	+ (at least **)					
		Paved road density	n.s.					
	1985 to 1995	Paved road density	+ (at least **)					
		Unpaved road density	+ (at least **)					
		Paved roads * cleared land	- (at least **)					
		Unpaved road *cleared land	+ n.s					
Andersen and Reis (1997)	Amazon-(BR) (~5 Million) 1970 to 1985	Road length	+***	Y	N	n.i.	n.i.	n.i.

STUDIES	LOCATION AREA (km²), AND DATE	VARIABLE CAPTURING ROAD EFFECT	IMPACT ON DEFORESTATION	CORRECT FOR SPATIAL AUTO-CORRELATION	CORRECT FOR ENDO-GENEITY	CONTROL VARIABLES (IMPACT ON DEFORESTATION) Soil quality	Slope	Altitude
Bray et al. (2004)	Mexico (7,300) 1976 to 1984 & 1984 to 2000	Distance to roads	n.s. (1976-1984) -*** (1984-2000)	Y	Y	n.i.	n.i.	n.i.
Chomitz and Gray (1996)	Belize (11,712) 1989-1992	Distance to market	-***	Y	Y	+***	±	n.i.
Chomitz and Thomas (2003)	Amazon-(BR) (4.86 Million) 1970 to 1985	Proportion of land within 50 km from main federal roads Distance to cities with populations > 25,000 Distance to cities with populations > 100,000	+*** -*** - (n.r.)	N	Y	n.r.	n.i.	n.i.
Cropper et al. (1999)	Thailand (514,000) 1976 to 1989	Road density	+***	n.a.	Y	+	-***	n.a.

STUDIES	LOCATION AREA (km²), AND DATE	VARIABLE CAPTURING ROAD EFFECT	IMPACT ON DEFORESTATION	CORRECT FOR SPATIAL AUTO-CORRELATION	CORRECT FOR ENDO-GENEITY	CONTROL VARIABLES (IMPACT ON DEFORESTATION)		
						Soil quality	Slope	Altitude
Cropper et al. (2001)	N Thailand (n.i.) 1986	Cost to nearest market	-***	Y	N	+***	-***	-***
Deininger and Minten (2002)	Mexico (160,000) 1980-1990	Distance to the nearest paved road	-***	N	N	+*	-***	-***
Etter et al. (2006)	Colombia (1.1 million) 1998	Distance to roads, town	-***	N	N	+***	±	n.i.
Geoghegan et al. (2001)	Mexico (22,000) 1988 to 1992 & 1992 to 1995	Distance to roads Distance to market Distance to village	-*** (1988-1992) -*** (1992-1995) +** (1988-1992) +*** (1992-1995) +*** (1988-1992) -*** (1992-1995)	N	N	+***	+***	-***
Kirby et al. (2006)	Amazon-(BR) (5 Million) 1999	Distance to roads	-**	Y	N	(n.s.)	n.i.	n.i.
Lombardini (1994)	Thailand (514,000) 1986 to 1992	Extension of unpaved and paved roads	+ (n.s.)	n.a.	N	n.i.	n.i.	n.i.

STUDIES	LOCATION AREA (km²), AND DATE	VARIABLE CAPTURING ROAD EFFECT	IMPACT ON DEFORESTATION	CORRECT FOR SPATIAL AUTO-CORRELATION	CORRECT FOR ENDO-GENEITY	CONTROL VARIABLES (IMPACT ON DEFORESTATION) Soil quality	Slope	Altitude
Mahapatra and Kant (2005)	Cross-national study 1980 to 1995	Percentage of paved road on the total road length	+*	n.a.	N	n.a.	n.a.	n.a.
McConnell et al.(2004)	Madagascar (940) 1957 to 2000	Distance from village	- n.r.	Y	N	n.i.	- n.r.	- n.r.
Mertens et al. (2004)	Bolivia (364,000) <1989 & 1989 to 1994	Distance to roads, and to Santa Cruz	-***	Y	Y	±	n.i.	n.i.
Mertens et al. (2002)	Pará, Brazil (56,300) 1986 to1992	Distance to main road Distance to secondary road Distance to village	- *** (planned colonization, 1) +*** (small-scale coloniz., 2) -*** (medium, 3) -*** (large, 4) -** (1) -*** (2) +* (3) + (n.s.) (4) +** (1) -*** (2) +*** (3, 4)	Y	Y	n.i.	n.i.	±

STUDIES	LOCATION AREA (km²), AND DATE	VARIABLE CAPTURING ROAD EFFECT	IMPACT ON DEFORESTATION	CORRECT FOR SPATIAL AUTO-CORRELATION	CORRECT FOR ENDO-GENEITY	CONTROL VARIABLES (IMPACT ON DEFORESTATION) Soil quality	Slope	Altitude
		Distance to main road	- *** (1) +*** (2, 3) + (n.s.) (4)					
	1992 to 1999	Distance to secondary road	-*** (1, 2, 3, 4)					
		Distance to village	-*** (1, 2, 3, 4)					
Müller and Munroe (2005)	Vietnam (~1,390) 2000	Distance to nearest all-year road	+ (n.s.)	Y	Y	+***	±	±
Müller and Zeller (2002)	Vietnam (~2,390) 1975 to 1992 & 1992 to 2000	Distance to nearest all-year road	-*** (1975-1992) -*** (1992-2000)	Y	Y	+***	-***	-***
		Distance to district capital	+*** (1992-2000) n.i. (1975-1992)					
		Travel time to all-year road	+*** (1992-2000; n.s. for paddy) +*** (1975-2000; n.s. for mixed agriculture)					

STUDIES	LOCATION AREA (km²), AND DATE	VARIABLE CAPTURING ROAD EFFECT	IMPACT ON DEFORESTATION	CORRECT FOR SPATIAL AUTO-CORRELATION	CORRECT FOR ENDO-GENEITY	CONTROL VARIABLES (IMPACT ON DEFORESTATION)		
						Soil quality	Slope	Altitude
Munroe et al. (2002)	Honduras (1,015) 1987 to 1996	Maize price + distance to nearest village Coffee price + distance out of region	- n.r. + n.r.	Y	Y	n.i.	-n.r.	-n.r.
Munroe et al. (2004)	Honduras (1,015) 1987 to1996	Distance to the nearest village Distance out of region	-*** -(n.s.) (Market proximity is found to increase the probability of forest regrowth)	Y	N	n.i.	+***	-***
Naidoo and Adamowicz (2006)	Paraguay (2,920) 1991 to 2004	Distance to roads	-* (by smallholders) -(n.s.) (by ranchers) +(n.s.) (for soybean)	Y	N	+***	-***	±
Nelson et al. (2004)	Panama (16,100) 1987 to1997	Cost of wood transport to market (via road or river)	- n.r.	Y	Y	n.i.	n.i.	n.i.

STUDIES	LOCATION AREA (km²), AND DATE	VARIABLE CAPTURING ROAD EFFECT	IMPACT ON DEFORESTATION	CORRECT FOR SPATIAL AUTO-CORRELATION	CORRECT FOR ENDO-GENEITY	CONTROL VARIABLES (IMPACT ON DEFORESTATION)		
						Soil quality	Slope	Altitude
Nelson and Hellerstein (1997)	Mexico (n.i.) 1973	Least-cost route: to nearest road/village	-**	Y	N	n.s.	-***	-***
		to near large population center	+(n.s.)					
Nelson, et al. (2001)	Panama (15,995) 1987 to1997	Cost to border or El Real	-(n.s.)	Y	Y	+***	-***	-***
		Cost to Puerto Pina	+***					
		Cost to village	-***					
		Cost to nearest town	-***					
Osgood (1994)	Indonesia (n.i.) 1972 to 1988	Extension of roads	+ (n.s.)	n.a.	N	n.i.	n.i.	n.i.

STUDIES	LOCATION AREA (km²), AND DATE	VARIABLE CAPTURING ROAD EFFECT	IMPACT ON DEFORESTATION	CORRECT FOR SPATIAL AUTO-CORRELATION	CORRECT FOR ENDO-GENEITY	CONTROL VARIABLES (IMPACT ON DEFORESTATION) Soil quality	Slope	Altitude
Pan et al. (2004)	Ecuador (~1,000) 1990 & 1999	Road access to *finca*	-*** (1990) + n.s. (1999)	Y	N	(n.s.)	(n.s.)	n.i.
		Road/boat distance to community	+* (1990) - n.s. (1999)					
		Euclidean distance to reference community	-*** (1990) + n.s. (1999)					
Panayotou and Sungsuwan (1994)	Northeast Thailand (169,000) 1973 to 1982	Rural roads extension	+*	n.a.	N	n.i.	n.i.	n.i.
		Distance to Bangkok	-***					
Pender et al. (2004)	Uganda (n.i.) 1990 to 1999	Change in distance to *tarmac* roads	-**	N	N	n.i.	n.i.	n.i.
		Change in distance to market	- (n.s.)					

STUDIES	LOCATION AREA (km²), AND DATE	VARIABLE CAPTURING ROAD EFFECT	IMPACT ON DEFORESTATION	CORRECT FOR SPATIAL AUTO-CORRELATION	CORRECT FOR ENDO-GENEITY	CONTROL VARIABLES (IMPACT ON DEFORESTATION)		
						Soil quality	Slope	Altitude
Pendleton and Howe (2002)	Bolivia (n.i.) 1995	Walking time to roads	-** (primary forest) + (n.s.) (secondary f.)	N	N	n.i.	n.i.	n.i.
		Walking time to the closest market	+*** (primary forest) +** (secondary f.)					
Pfaff (1999)	Amazon-(BR) (n.i.) 1975 to 1988	Density of unpaved roads	+***	Y	Y	+***	n.i.	n.i.
		Density of paved roads	- (n.s.)					
Pichón (1997)	Ecuador (~70,000) 1990	Distance to road, distance to nearest marketplace	-***	n.a.	Y	+***	-***	n.i.

STUDIES	LOCATION AREA (km²), AND DATE	VARIABLE CAPTURING ROAD EFFECT	IMPACT ON DEFORESTATION	CORRECT FOR SPATIAL AUTO-CORRELATION	CORRECT FOR ENDO-GENEITY	CONTROL VARIABLES (IMPACT ON DEFORESTATION) Soil quality	Slope	Altitude
Reis and Guzman (1994)	Amazon-(BR) (5 Million) 1983-1987	Extension of unpaved roads	+**	Y	Y	n.i.	n.i.	n.i.
		Extension of paved roads	+ (n.s.)					
		Distance to state capital	- (n.s.)					
Southgate (1991)	Ecuador (130,000) 1982	Extension of all-weather roads	+ (n.s.)	n.a.	N	+***	n.i.	n.i.
Southworth et al. (2004)	Honduras (1,015) 1987 to 2000	Distance to roads and regional market	-**	N	N	n.i.	+*	-**

STUDIES	LOCATION AREA (km^2), AND DATE	VARIABLE CAPTURING ROAD EFFECT	IMPACT ON DEFORESTATION	CORRECT FOR SPATIAL AUTO-CORRELATION	CORRECT FOR ENDO-GENEITY	CONTROL VARIABLES (IMPACT ON DEFORESTATION)		
						Soil quality	Slope	Altitude
Serneels and Lambin (2001)	Kenya (10,694) 1975 to 1985 & 1985 to 1995		*Mechanized agriculture*:	Y	N	+***	n.i.	-***
		Distance to roads^2	-*** (1975-1985) -*** (1985-1995)					
		Distance to roads	+*** (1975-1985) +*** (1985-1995)					
		Distance to village	-*** (1975-1985) +*** (1985-1995)					
		Distance to Narok (district seat)	-*** (1975-1985) -*** (1985-1995)					
			Smallholders (1975-1985 model only):					
		Distance to roads (log)	-***					
		Distance to village (log)	-***					
		Distance to Narok	+***					

STUDIES	LOCATION AREA (km²), AND DATE	VARIABLE CAPTURING ROAD EFFECT	IMPACT ON DEFORESTATION	CORRECT FOR SPATIAL AUTO-CORRELATION	CORRECT FOR ENDO-GENEITY	CONTROL VARIABLES (IMPACT ON DEFORESTATION)		
						Soil quality	Slope	Altitude
Tucker et al. (2005)	Guatemala (1,053) 1987 to 1996	Distance to nearest town (local market) Distance out of region (capital city or regional market centre)	-** +** (Market proximity also increases probability of forest regrowth)	Y	N	n.i.	-**	+**
Vågen (2006)	Madagascar (476) 1972-2001	Distance to roads, village	-***	N	N	n.a.	+*** (u)	+*** (u)
Vance and Geoghegan (2002)	Yucatan (22,000) 1984-1987 to 1994-1997	Distance to market	-***	N	N	+***	-***	-***
Wilson et al. (2005)	Chile (42,000) 1995-1996	Distance to roads and town	-***	N	N	+**	-***	-***

Notes: dates (x-y indicates a single cross section analysis based on composite forest cover data for the period x-y; x & y indicates separate cross section analyses for periods x and y; x to y indicates an analysis of forest cover change between x and y).
n.a.: not applicable; n.i: variable not included; n.s.: not significant; n.r.: significance not reported; ± effect differs for different types of land uses
*, **, *** represent 10%, 5%, and 1% significance level respectively.

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