

Temporal patterns of road network development in the Brazilian Amazon

Sadia E. Ahmed · Carlos M. Souza Jr. ·
Júlia Riberio · Robert M. Ewers

Received: 17 May 2012 / Accepted: 18 December 2012 / Published online: 6 January 2013
© Springer-Verlag Berlin Heidelberg 2013

Abstract The Brazilian Amazon is a globally important ecosystem that is undergoing rapid development and land-use change. Roads are a key spatial determinant of land-use conversion and strongly influence the rates and patterns of habitat loss and represent a key component of models that attempt to predict the spatio-temporal patterns of Amazonian land-use change and the consequences of such changes. However, the spatio-temporal patterns of road network development are poorly understood and seldom quantified. Here, we used manually digitised satellite imagery at multiple temporal and spatial scales across the Brazilian Amazon to quantify and model the rate at which road networks are proliferating. We found that the road network grew by almost 17,000 km per year between 2004 and 2007. There was large spatial variation in road network density, with some municipalities having road densities as high as 0.5 km/km², and road network growth rates were highest in municipalities with an intermediate road network density. Simulations indicated that road network development within municipalities follows a logistic growth pattern through time, with most of the development occurring within a 39-year time period. This time period is similar to those of other boom and bust development dynamics observed in the Brazilian Amazon. Understanding the temporal patterns of road development will aid the development of better predictive land-use change models for the

Amazon, given the key importance of roads as a predictor of deforestation in many existing models.

Keywords Deforestation · Economic development · Land-use change · Landsat · Logging road

Introduction

Global road networks have been expanding at a rapid rate since the 1900s (Forman et al. 2003). Roads are a distinctive feature in any landscape, with many countries giving 1–2 % of their land surface over to roads and roadsides (Forman 1998). However, the ecological effects of roads spread beyond the physical footprint of the network and may impact 15–20 % of the land or more (Forman and Alexander 1998). In the context of tropical deforestation, roads cause a relatively small amount of direct habitat loss, but exert a huge indirect influence on spatial patterns of deforestation by allowing easier access to new frontiers (Fearnside 2008; Geist and Lambin 2002; Perz et al. 2007, 2008). Roads also encourage extractive industries and further deforestation by settlers, thereby indirectly influencing deforestation rates. As roads are developed to access resources, roads may be seen as a cause of development and it is this causal relationship that led to the Brazilian development policies of the 1970s based around road construction (Alves 2002; Kirby et al. 2006). However, roads may also be a consequence of development, where, as economies grow, they require better infrastructure support and so road networks are developed.

The influence of roads on spatial patterns of deforestation ensures they also exert a strong influence of spatial patterns of biodiversity loss (Fearnside 2005; Finer et al.

S. E. Ahmed (✉) · R. M. Ewers
Department of Life Sciences, Imperial College London,
Silwood Park Campus, Ascot, Berkshire SL5 7PY, UK
e-mail: sa1705@ic.ac.uk; sadia.ahmed05@imperial.ac.uk

C. M. Souza Jr. · J. Riberio
Instituto do Homem e Ambiente da Amazônia,
Caixa Postal 5101, Belém, Pará CEP 66613-397, Brazil

2008; Forman 1998; Maki et al. 2001). Roads influence biodiversity directly through road kill events, but again the largest impact of roads is through indirect processes and 'extended effects'. For example, roads can alter abiotic processes such as surface run-off (Forman and Alexander 1998) and microclimatic conditions including light levels, air and soil temperature, air and soil moisture, soil pH and nutrient levels (Delgado et al. 2007; Gehlhausen et al. 2000; Honu and Gibson 2006). Roads fragment forest habitats, creating new habitat edges and acting as barriers to the movement of animals (Arima et al. 2005; Dyer et al. 2002; Goosem 2007; Keller and Largiader 2003; McGregor et al. 2008; Richardson et al. 1997; Rico et al. 2007). These extended effects alter the abundance, distribution and behaviour of species over large areas (Bee and Swanson 2007; Blom et al. 2005; Eigenbrod et al. 2008; Potvin et al. 2005; Vos and Chardon 1998). Some species do appear to prosper with the presence of roads, benefitting from additional resources such as road-killed carrion (Laurian et al. 2008; Rydell 1992). However, negative effects are five times more prevalent than positive effects (Fahrig and Rytwinski 2009).

The Brazilian Amazon contains approximately one-third of the world's remaining rainforest, covering an area of 4.1 million km². The region is highly biodiverse with 10–20 per cent of the planet's known species, is one of the three most bioculturally diverse areas in the world (Loh and Harmon 2005) and provides many valuable ecosystem services such as water regulation (Bradshaw et al. 2007; Fearnside 2005; Foley et al. 2007), carbon sequestration (Asner et al. 2004; Foley et al. 2007) and local and global climate regulation (Bonan 2008; Foley et al. 2007; Malhi et al. 2008). However, the Brazilian Amazon is also rapidly undergoing extensive development with widespread land-use conversion. Roads are a key spatial determinant of land-use conversion in this region, dictating the spatial pattern of deforestation by regulating access to standing forests which are logged for timber and later clear-cut to make way for agriculture or pasture, which secures land ownership via 'productive use' (Fearnside 2005; Kirby et al. 2006; Perz et al. 2008). This process of deforestation and agriculture following roads has been well documented (Fearnside 2008; Geist and Lambin 2002; Perz et al. 2007; Walker et al. 2004). Given that roads are a key spatial determinant of land-use conversion and that they have extensive impacts on rates and patterns of habitat loss, it is important that we know how many roads are being built, how fast road networks are developing and where they are developing in this globally important ecosystem.

Many studies have investigated temporal patterns of land-use change in the Amazon (e.g. Araujo et al. 2009; Carpentier et al. 2000; Dale et al. 1994; de Barros Ferraz et al. 2005; deKoning et al. 1999; Moreira et al. 2009;

Muller et al. 2010; Soares-Filho et al. 2002; Walker et al. 2004; Walsh et al. 2008; Wassenaar et al. 2007), as well as the temporal patterns of change in the forces that drive land-use change such as economic and agricultural trends (Araujo et al. 2009; Ewers et al. 2008; Morton et al. 2006). However, knowledge of the temporal dynamics of road network development lags far behind, with just one study having examined this in the Brazilian Amazonian state of Para; Brandao and Souza (2006) mapped a total of 25,196 km of roads, of which 15,727 km were constructed in a 10-year time period (1991–2001). This stands in stark contrast to the acknowledged importance of temporal changes in road networks for understanding and predicting deforestation rates and patterns. For example, at least half of the land-use change models based in the Amazon that we are aware of use road networks as either a spatial or temporal predictor of deforestation (Araujo et al. 2009; Etter et al. 2006; Laurance et al. 2001; Mena et al. 2011; Messina and Walsh 2001; Michalski et al. 2008; Soares-Filho et al. 2006; Walker et al. 2004). In Central Africa, Laporte et al. (2007) showed that rates of road building in Central Africa increased over 31 years as a function of industrial logging. Yet no similar study has been carried out for the Amazon or any of its nine constituent countries despite the Amazon being at the forefront of global tropical deforestation.

Much of the existing literature on road network development in the Brazilian Amazon and elsewhere is qualitative rather than quantitative. For example, Taaffe et al. (1963) described an idealised progression of transport development using Ghana and Nigeria as examples. Perz et al. (2007) investigated the differing development histories of four road networks through interviews with local residents and qualitatively compared the social and spatial processes behind different patterns of unofficial road development. More rigorously, Maki et al. (2001) documented the development of a road connecting two urban centres in Peru (Iquitos and Nauta), and Brandao and Souza (2006) documented the growth rate of roads for an area of 546,000 km² in the state of Para (Brazil), finding that the road network nearly doubled over a period of 10 years. There have also been some recent attempts to model the paths that individual roads take as they are constructed (Arima et al. 2008). Yet there have been no attempts made to understand how rapidly road networks are developed over large spatial scales, despite that knowledge being fundamental to understanding land-use change trajectories in the region (Barlow et al. 2011).

Here, we used pre-existing road maps, satellite imagery and simulations to document the historical, and predict the future, temporal dynamics of road network development in the Brazilian Amazon. We conducted our analysis at two spatial and temporal scales. First, we generated annual road

maps for a 9-year period (2000–2008) from areas of low, medium and high road density to investigate annual patterns of network growth at relatively small spatial and temporal scales. Second, we used pre-existing road maps for the entire Brazilian Amazon from 2004 to 2007 to investigate rates of road network growth within municipalities. Based on our analyses of observed spatial and temporal variation in road network development, we constructed simulations to determine the temporal trajectory of road network growth in this region.

Methods

We manually digitised annual Landsat 5 TM images from 2000 to 2008 at each of three locations (path/row IDs: 231/065, 227/066 and 227/062). Due to the nature of the method, we were unable to distinguish between road types (e.g. official, unofficial or paved, unpaved), thus ‘roads’ refer to all road types aggregated together. Landsat road densities were divided in ArcGIS into three density classes based on natural ‘Jenks’ breaks, low (0.00–0.05 km/km²)-, medium (0.05–0.13 km/km²)- and high-density (0.13–0.23 km/km²) scenes. From within these classes, three Landsat scenes were selected to represent regions of low (0.02 km/km²), medium (0.07 km/km²) and high (0.14 km/km²) road density (Fig. 1), in the expectation that regions with different road density are likely to have different trajectories of road network development. Although digitisation and analysis were carried out at the Landsat scene scale, a similar pattern of road densities was observed at the municipality scale (Fig. 1). There are many automated approaches to digitising road networks (Mena 2003; Brandao and Souza 2006; Li and Briggs 2009; Movaghati et al. 2010), but these are typically less accurate than manual digitisation (Li and Briggs 2009) in which images are observed and visible roads are traced individually and by hand. Subsequently, we manually digitised images in ArcGIS, following the methods described by Brandao and Souza (2006) to create road maps for each year at each location. This method was validated with ground truthing by Brandao and Souza (2006). In addition to the methods detailed by Brandao and Souza (2006), we created the temporal series of maps sequentially based on the previous year’s map. This meant that any gaps in the imagery (e.g. obscured by cloud/canopy cover) in 1 year would be recorded the previous or next year. We validated our digitised satellite images for 2007 against a road map of the whole Amazon from 2007 that was produced using the same methods outlined by Brandao and Souza (2006) (map data provided by IMAZON), by determining the spatial congruence, that is, how much of the digitised roads overlapped between the two maps. We found that in terms of total roads digitised, there was a good similarity between the two maps

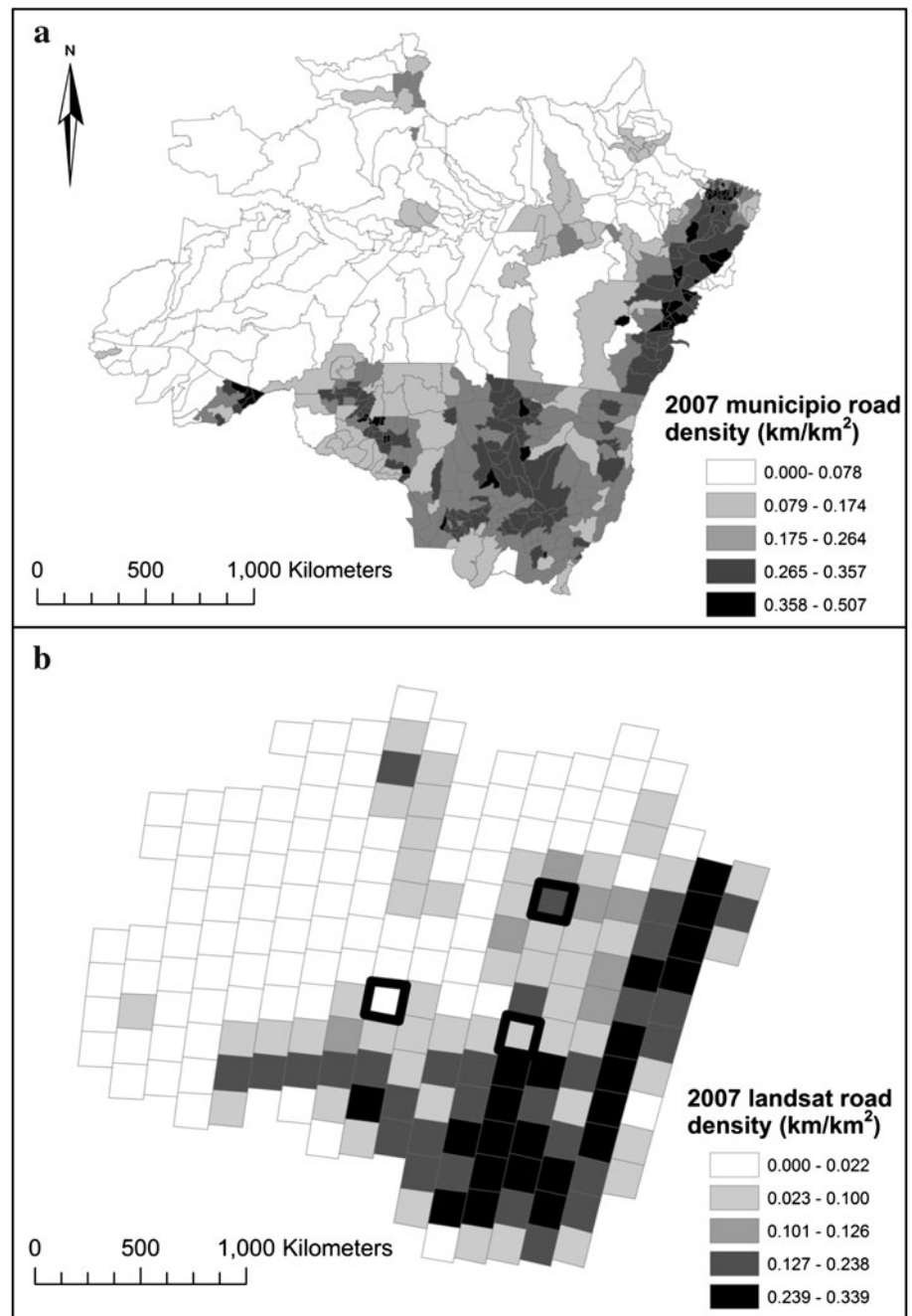
at all three locations (low density = 92 %, mid-density = 79 % and high density = 98 % similarity). Across the three locations, 84 % of our digitised roads fell within 200 m of the Amazon map, and 81 % of the roads on the Amazon map fell within 200 m of our digitised roads. Much of the variation in manually digitised maps arises from variation in judgement calls on irresolute roads, for example, while one person may decide a faint line is a road another may decide it is a boundary line between two patches of land and not a road. Thus, while a spatial congruence of 100 % is not expected, our average congruence of 82.5 % suggests a good degree of accuracy in identifying roads with this method.

To examine how road networks change over time and if changes varied in different density classes, we calculated the cumulative amount of road (km) between 2000 and 2008 for each Landsat image. Changes in road length were analysed as a function of year and location using an ANCOVA in the statistics program R 2.10.1 (R Development Core Team 2009).

To investigate the spatio-temporal patterns of road network development at the scale of the entire Brazilian Amazon, we used two complete road maps for the region that were generated using the same manual digitisation methods on Landsat imagery taken in 2004 and 2007 (Brandao and Souza 2006). We used 443 municipalities of the Brazilian Amazon as spatial units for analysis, determining the initial road density in 2004 (km/km²) and the change in road density between 2004 and 2007 (km/km²) for each municipality. We chose to carry out analyses at the municipality level because this is the level at which decisions pertaining to development are made.

Using multiple regression, we tested the effect of the official road density and various socio-economic factors had on road network growth rates. Census data by municipality were obtained for the year 2004 from IPEA (2012) for permanent agricultural area, temporary agricultural area, total agriculture area, cattle head count, credit available for agriculture and credit available for cattle. The percentage of land area protected was also included. Rural and urban population counts for 2000 were used, because data for 2004 were unavailable. Data were log transformed where appropriate and agricultural area measures were converted to density to control for differences in municipality area. Starting with a complete model including all variables, we used model simplification to identify factors relevant to road network growth rates. We also tested for an effect of initial road density on road network growth rates using linear regression, including a quadratic term to allow for a non-linear relationship. Preliminary analyses showed that these models explained little of the variance in the data ($R^2 = 0.06$), but visual inspection of figures suggested that maximum rates of road network development

Fig. 1 Spatial patterns of road network density in the Brazilian Amazon for 2007. Spatial units represent **a** municipality boundaries and **b** at Landsat scenes. The three *dark squares* show the three Landsat scenes in which we analysed annual changes in the road network



varied with initial road density and therefore that initial road density might act as a limiting factor on road network growth rates. The effect of a limiting factor can be quantified using quantile regression (Cade et al. 1999), so we estimated how initial density limits road network growth rates using quantile regression as implemented by the R package ‘Quantreg’ (Koenker 2010).

To investigate the likely temporal trajectory of road network development in the Brazilian Amazon, we constructed a simulation (essentially a Markov chain) based on the relationship we observed between initial road density and road network growth rate. The simulation was

designed to estimate the length of time it would take for a municipality to develop a road network to such a density that new roads are no longer being created. The maximum road density observed in any municipality in 2004 was $0.5 \text{ km}/\text{km}^2$, this municipality showed no development in 2007, and so we assumed that $0.5 \text{ km}/\text{km}^2$ is the density at which road development stops. We assumed that municipalities would have an initial road density of $0.0 \text{ km}/\text{km}^2$. In each annual time step of the simulation, we determined the amount of new road that would be developed in that municipality by creating a window (data bin) around the observed initial density of $\pm 0.05 \text{ km}/\text{km}^2$ and randomly

selecting one observed growth rate that occurred within that window. For example, given an initial density of 0 km/km², the window will subset out all growth rates corresponding to municipalities with densities of between 0 and 0.005 km/km². A random growth rate is selected from the subset rates (e.g. 0.03 km/km²) and is added to 0 km/km², giving the initial density for the next time step (i.e. 0.03 km/km²). All growth rates within a subset have an equal probability of being selected. This method takes into account the non-uniform distribution of growth rates observed among municipalities with similar initial road densities and allows for ‘kick-start’ development, as observed in some municipalities that had very low initial road network densities but very high rates of road network growth. The road network density in a simulation progressively increased through time, and we stopped all simulations when a road density of 0.5 km/km² was reached. For each of 1,000 simulations, we recorded the cumulative increase in road density over time and fitted a logistic model to the simulated data using the R package ‘grofit’ (Kahm et al. 2010). We used the logistic model to quantify the length of the lag and boom phases of road network development. The lag phase tells us the number of years a municipality might take from initial colonisation until it experiences an exponential increase in road network growth. The boom phase, in turn, begins immediately at the end of the lag phase and represents the number of years during which road networks are rapidly growing. We used the second derivative of the logistic model to determine the start and end point of the boom phase. The local maxima and minima points on the second derivative of a logistic model indicate the two time points at which the rate of change in the road network is at its greatest (Ewers and Didham 2006), either accelerating at the end of the lag phase or decelerating at the end of the boom phase.

Results

Road network development showed significant spatial variation across the Amazon (Fig. 2). While some municipalities experienced no network development, others experienced development as high as 0.064 km/km²/year. Interestingly, most road network development was concentrated in the municipalities that form the ‘Arc of Deforestation’ along the south and eastern edges of the Amazon (Fearnside 2005). There was little development ahead of the Arc of Deforestation and almost none behind it to the south.

Significant amounts of new road were added to the road networks in all three Landsat scenes analysed, with road construction occurring in each year × scene combination (Figs. 2, 3). Road network growth rates were fairly

constant through time at all three density scene areas ($R^2 = 0.98$, $p < 0.001$, $df = 21$, Fig. 3), although in the high-density scene, there was a large change in density between 2000 and 2001. The average rate of increase was lowest in the low-density Landsat scene (mean growth rate 76.9 km/year ± 37.3 SE), highest in the mid-density scene (289.7 ± 37.3 km/year) and intermediate in the high-density scene (275.4 ± 26.4 km/year). These differences in road network growth rate were significantly different between the low- and mid-density scenes ($p < 0.001$) and between low- and high-density scenes ($p < 0.001$), but not between the mid- and high-density scenes ($p = 0.705$, Table 1).

At the scale of the Brazilian Amazon, 50,666 km of new roads were constructed between 2004 and 2007 (Fig. 2). We found that change in road density between 2004 and 2007 was significantly negatively related to official road density, permanent agriculture density in 2004 and protected area percentage, however, was significantly positively related to credit available for agriculture (Table 2). Further, there was a significant interaction between official road density and permanent agricultural density, which was significantly positively related to change in road density. Despite the significant relationships observed, the amount of variance in change in road density explained was low, just 18 % ($p < 0.001$, $F_{5,437} = 20.5$, $df = 437$, $R^2 = 0.18$). Other socio-economic variables tested showed no significant relationship with change in road density and were removed during model simplification.

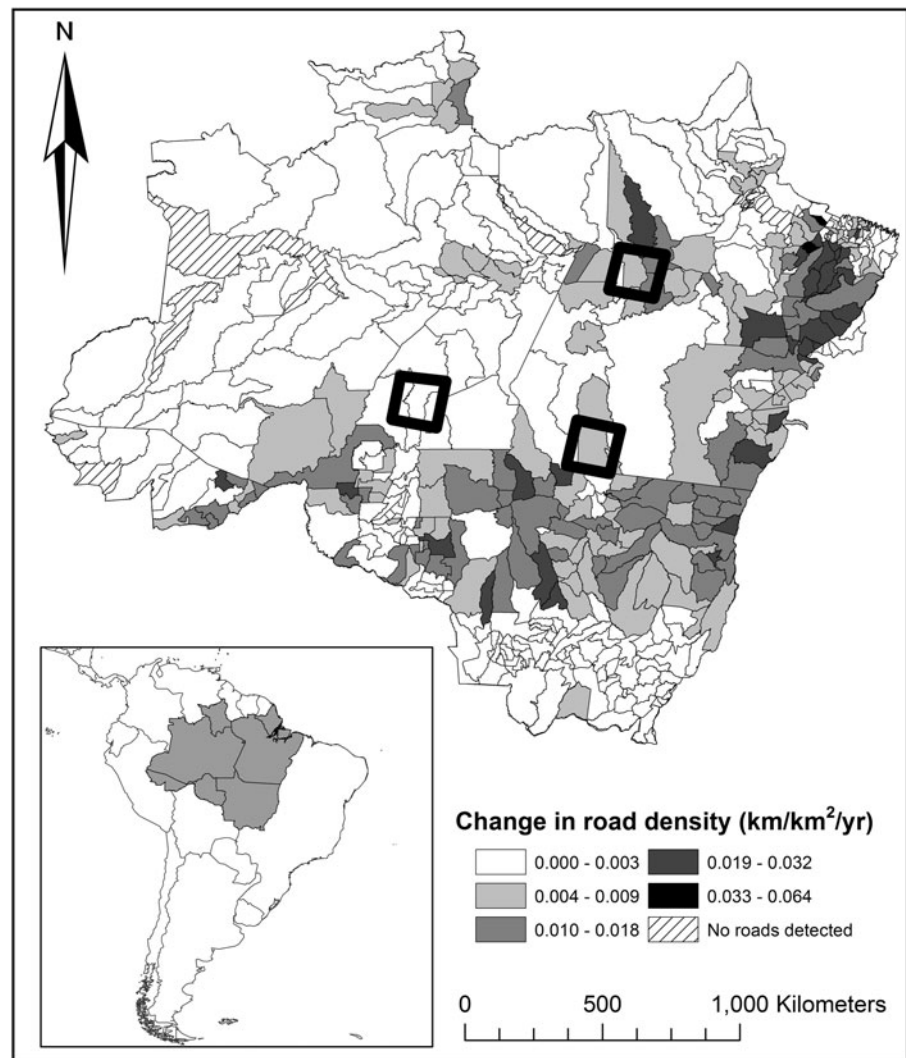
We found a weak, but significant, relationship between initial road density and change in density over three years using linear regression with a quadratic term ($p < 0.001$, $F_{2,440} = 15.28$, $R^2 = 0.06$). Quantile regression revealed that for any given initial road network density, there was a maximum potential increase in road density (90th percentile regression, $p < 0.001$, $F_{7,435} = 29.30$). Many municipalities had road networks that did not grow between 2004 and 2007, regardless of initial road density, whereas the most rapid road network growth rates occurred in municipalities with intermediate road densities (Fig. 4).

Our simulation found that it takes an average of 75 years (95 % CI 58–103 years) for a municipality to fully develop a road network (Fig. 5). The lag phase of road network development typically lasted 15 years (95 % CI 1–34 years), after which the boom period lasted an average of just 39 years (95 % CI 19–71 years).

Discussion

We found that, on average, 16,889 km of new roads are added every year to the Brazilian Amazon road network and that road network development within municipalities is

Fig. 2 Spatial patterns of road network growth rates in the Brazilian Amazon. Spatial units represent municipality boundaries



a process that likely spans around four decades. Road network growth rates varied considerably among municipalities, likely reflecting the different economic and developmental histories of those regions, and the simulated patterns of road network development indicated it follows a boom and bust dynamic in which the majority of roads are built in a short period of time.

There is an evident spatial pattern of road density observed, with high road densities observed in the eastern and southern Amazon (Fig. 1), particularly in the states of Rondonia, Mato Grosso and Para. This pattern is likely associated with settlement and economic development of the municipalities within these states. In the 1970s, the Brazilian government instigated several policies to encourage the development and colonisation of the Amazon. Government incentives to encourage colonisation and cattle ranching projects (Kirby et al. 2006), as well as private colonisation projects via companies and co-operatives, were utilised to encourage settlement particularly in

the frontier states of Mato Grosso, Rondonia and Para (Jepson 2006). At the centre of the colonisation initiatives was the building of road networks, notably the Cuiaba-Porto Velho (BR-364), Trans-Amazonian (BR-230) and Cuiaba-Santarem (BR-174) highways (Alves 2002; Kirby et al. 2006). Between 1970 and 1990, almost 700,000 families were relocated to the Amazon (Ludewigs et al. 2009), and it is unsurprising that road densities were highest in these states.

Within a given Landsat scene, we found that the road network growth rate was relatively constant through time over the 9-year period during which we tracked annual changes to the road network. There are two main causes of road network development: government initiatives to link populations and economies, and private sector development to aid the extraction of natural resources (Brandao and Souza 2006; Perz et al. 2007). Both causes have considerable momentum behind them, in that constructing roads require expensive machinery and personnel. If these

resources are both limiting and used with the same level of efficiency among years, it follows that the rate of road construction in any given year will be similar to the rate the year before. This potentially explains why networks grew at remarkably constant rates within Landsat scenes, and the same momentum suggests that the rates of road network development we observed are likely to continue into the immediate future.

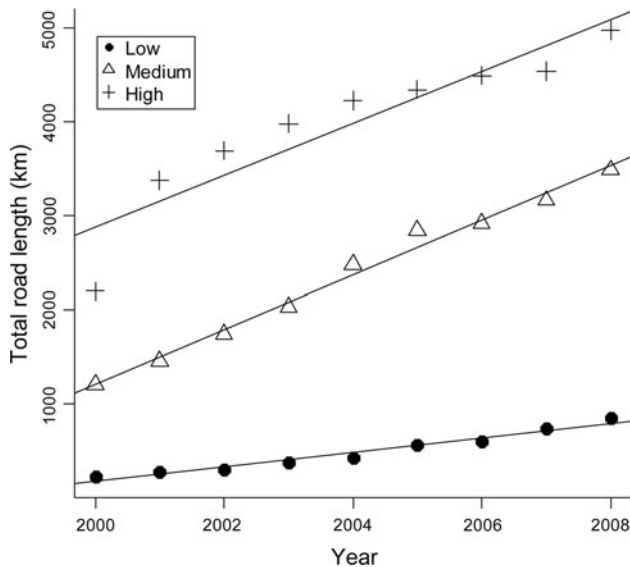


Fig. 3 Annual cumulative growth in the road network in three regions of the Brazilian Amazon. The three regions correspond to the Landsat scenes shown in Fig. 1 and varied in the degree of initial road density: low (0.02 km/km²); medium (0.07 km/km²); and high (0.14 km/km²)

Table 1 ANCOVA comparing differences in road development, in terms of total length (km) in three Landsat scene locations over a 9-year period (2000–2008)

Density scene	Slope	Standard error	t value	p value	df	R ²
High	275.39	26.43	10.42	<0.001	21	0.98
Low	76.90	37.38	-5.31	<0.001		
Medium	289.7	37.38	0.38	0.705		

Table 2 The effect of socio-economic factors and official road density on the change in road density between 2004 and 2007, across the Brazilian Amazon

Factor	Slope	Standard error slope	t value	p value
Log official road density	-0.223	0.054	-4.12	<0.001
Log permanent agriculture density	-0.024	0.005	-5.22	<0.001
Log credit available for agriculture	0.001	0.0001	4.56	<0.001
Log protected area per cent	-0.001	0.001	-2.13	<0.05
Log official road density interaction with log permanent agriculture	0.621	0.072	8.65	<0.001

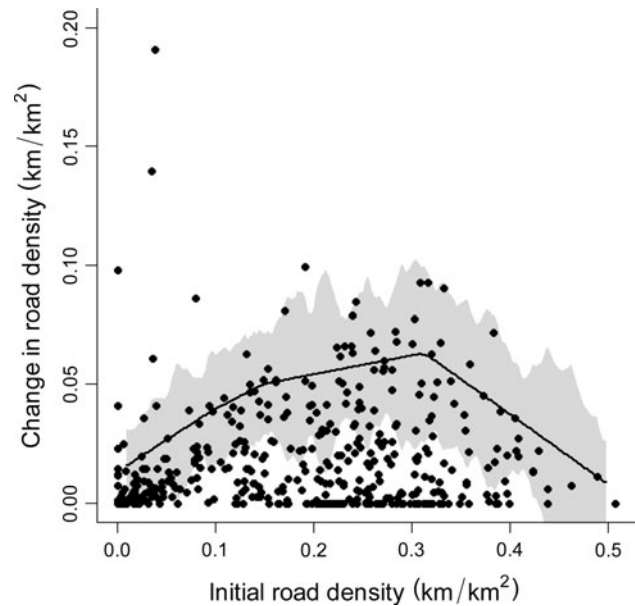


Fig. 4 Relationship between initial road density on change in road network density over a 3-year period (2004–2007) in 443 municipalities of the Brazilian Amazon. The *black line* shows the 90th percentile regression and represents the maximum likely road network growth rate for a municipality with a given road density. The *grey shaded area* represents the 95 % confidence interval around the 90th percentile regression

While road networks appear to grow at relatively stable rates within a region, we detected significant differences in road network growth rates among regions. Average growth rates were low in regions with low initial road density, increased in regions with medium road density and then reduced again in regions with high initial road density. This general pattern was defined largely by an apparent upper limit to road network growth rates at any given initial road density, with the most rapid rates of network growth occurring at intermediate road densities. By contrast, at all initial road densities, there were municipalities that experienced no road network development. Across the Brazilian Amazon, road networks were rapidly expanding in the set of municipalities that collectively form the ‘Arc of Deforestation’ along the south and eastern edges of the Amazon (Fearnside 2005). This is where most deforestation is concentrated in the Brazilian Amazon, and the level

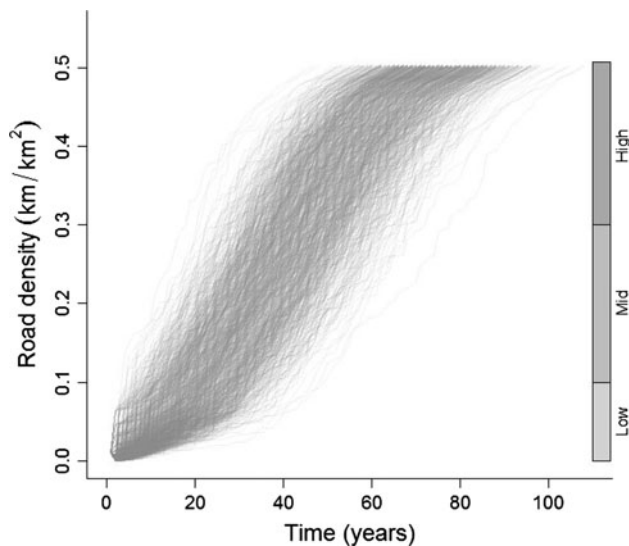


Fig. 5 Simulated trajectories of road network development in the Brazilian Amazon. *Each line* represents the trace from one of 1,000 simulations, estimating the road density within a municipality as a function of municipality road network age. The *bar* shows the delineation of low-, mid- and high-density municipalities. Delineation is based on natural ‘Jenks’ breaks

of congruence between road network growth rates and the Arc of Deforestation further reinforces the link between roads and deforestation (Fearnside 2005; Kirby et al. 2006).

A very small number of municipalities with very low initial road densities had road network growth rates that were much higher than the general pattern observed in the remaining municipalities (Fig. 4). Similarly, we detected a rapid jump in road construction between 2000 and 2001 in the high-density Landsat scene (Fig. 3). These apparently sporadic events of rapid road construction at particular places and times suggest that the general pattern of road network development can be accelerated under exceptional circumstances, perhaps through significant government investment in roads as part of regional development initiatives devised to kick-start economic development (Carvalho et al. 2002), or possibly through the establishment of new industries. The number of these exceptions was, however, very low, indicating that there is a general pattern by which road networks develop.

The observed pattern of road network development in the Brazilian Amazon likely reflects the economic trajectory of municipalities. The first new roads created in a municipality increase access to the region for extractive industries and colonisers, who further expand the road network by constructing unofficial roads to move their products to markets (Fearnside 2008; Geist and Lambin 2002; Perz et al. 2007, 2008). These unofficial roads are financed by the profits arising from exploiting resources and land in a previously unexploited region. This process of increasing economic returns within a municipality can

stimulate further development in the region, generating a positive feedback loop that leads initially to exponential growth and maximum network growth rates as resource extraction and land development reaches the highest levels the region can support. Once resources begin to be depleted and the majority of the land had either had its resources removed or has been converted to other uses such as agriculture, the rate of road network growth might slow for one of two reasons. First, the economic impetus to expand and develop might be reduced, leading to slower road network growth rates. Alternatively, the road network might have approached a density that is high enough to provide access to all parts of the municipality. In this case, a sufficient road infrastructure already exists and would render further expansion unnecessary. This likely explains why the majority of observed road development is concentrated along the Arc of Deforestation (Fig. 2); new roads are developed in front of the arc to aid timber extraction, and once the ‘arc’ passes the rate of new road construction will slow and eventually stop as resources are exhausted and road networks are developed to such an extent that the entire municipality is well connected.

The relationship between initial road density and change in road density (Fig. 4) provided a good relationship upon which to model the temporal trajectory of road development. The official road network has been used in the past to predict future road networks for use in land-use land cover change modelling (Messina and Walsh 2001; Soares-Filho et al. 2006). Here, we found that the density of official roads to be inversely related to change in road density, likely because the official road network has not changed much over the years and much of the development associated with official roads has already taken place. Thus, while areas with high official road densities are likely to be areas of high road density in general, they are unlikely to be areas of high changes in road density. Arable agriculture was also inversely related to change in road density, such that areas of high road development have less agricultural area, and this seems feasible if we consider roads to be a cause of development. In locations where roads have already developed (i.e. low changes in road density), we see high levels of agriculture (behind the Arc of Deforestation) but where they are developing, agriculture has yet to fully expand. Credit for agriculture is positively related to road density development, and it is possible that this positive relationship is linked to the amount of capital available generally for development; thus, in areas where there is high credit for agriculture, there are also capital resources available for road development. The negative relationship between the percentage of land area protected and road development highlights the role that protected areas play in determining road network development, with highly protected areas experiencing less network growth. While we

found that official roads, in conjunction with agriculture, have a significant relationship with road development, they explain little variance in observed road growth over the study period. Further, the majority of socio-economic factors tested showed no significant relationship with road development. This, in addition to the fact that socio-economic factors are extremely difficult to predict, they, unlike initial density, do not form a suitable basis upon which to model future road development trajectories.

The temporal dynamics of road network development we describe above and simulated (Fig. 5) are similar to those of economic boom and bust development trajectories that have previously been observed in the Brazilian Amazon. The development of the Amazon has been economically dependent on boom and bust cycles of extractive industries (Godfrey 1990), with that dependence mirrored in many development indices in the Amazon, including life expectancy, literacy and standard of living (Rodrigues et al. 2009). It is thought that the boom in development and improvement in living standards occur as a result of people taking advantage of resources that become available in frontier areas where new roads have been laid (Fearnside 2008; Perz et al. 2008; Rodrigues et al. 2009). The temporal scale of economic boom and bust cycles appears to match the temporal scale of road network development that emerged from our simulations. For example, the rubber boom of the late eighteenth century lasted approximately 50 years (Godfrey 1990), cacao booms lasted between 20 and 40 years (Clough et al. 2009) and a boom in animal skins from Rio Preto lasted 20 years (Macedo and Anderson 1993). By comparison, our simulations suggested that the boom period of road development lasts for an average period of 39 years. Our model, then, appears to have generated realistic temporal trajectories of road network development for the Brazilian Amazon.

On average, it was found that it takes 75 years for an area to reach 'maximum' road density. Maximum is a relative term, as some areas may, in reality, ultimately reach marginally higher densities than those predicted by the simulation. Also, the simulation assumes that all areas will eventually reach the maximum density, whereas many places will not for various reasons including areas that may be protected or where resources are depleted quickly with little investment and thus little road development. Our simulation, then, reflects a scenario in which development continues unhindered until the maximum road density is attained. Further, the rate at which the road network is developed is likely to be highly variable because of differences in geographic environments and economic investment. Our simulation is based on empirical growth rates and as such implicitly takes into account such variable conditions. This is reflected in the range of length of time for road networks to develop (58–103 years).

The Amazon is an ecosystem that provides a multitude of ecosystem services that are globally important (Foley et al. 2007), but is undergoing rapid transformation as forests are progressively cleared for agriculture. As such, it is unsurprising that many models have been developed to predict future land uses of the Amazon. However, a key aspect of these models that has been largely ignored is the rates and patterns of road network development (Barlow et al. 2011). We have used a combination of spatial and temporal data to explore this issue, revealing the remarkable rate at which road networks are expanding and modelling the temporal trajectory of road networks. We anticipate these analyses will form a base for generating integrated land-use models that incorporate the economic development of the region, with a view to gaining a more comprehensive understanding of how this globally important ecosystem is changing.

Acknowledgments We would like to thank the Grantham Institute for Climate Change and Microsoft Research for funding this work, and IMAZON (Instituto do Homem e Ambiente da Amazônia) for providing the Amazon wide road maps.

References

- Alves DS (2002) Space-time dynamics of deforestation in Brazilian Amazon. *Int J Remote Sens* 23:2903–2908
- Araujo C, Bonjean CA, Combes J, Motel PC, Reis EJ (2009) Property rights and deforestation in the Brazilian Amazon. *Ecol Econ* 68:2461–2468
- Arima EY, Walker RT, Perz SG, Caldas M (2005) Loggers and forest fragmentation, behavioural models of road building in the Amazon basin. *Annu Assoc Am Geogr* 95:525–541
- Arima EY, Walker RT, Sales M, Souza C, Perz SG (2008) The fragmentation of space in the Amazon basin, emergent road networks. *Photogramm Eng Remote Sens* 24:699–709
- Asner GP, Nepstad D, Cardinot G, Ray D (2004) Drought stress and carbon uptake in an Amazon forest measured with space borne imaging spectroscopy. *PNAS* 101:6039–6044
- Barlow J, Ewers RM, Anderson L, Aragao LEOC, Baker TR, Boyd E, Feldpausch TR, Gloor E, Hall A, Malhi Y, Milliken W, Mulligan M, Parry L, Pennington T, Peres CA, Phillips OL, Roman-Cuesta RM, Tobias JA, Gardner TA (2011) Using learning networks to understand complex systems, a case study of biological, geophysical and social research in the Amazon. *Biol Rev* 86:457–474
- Bee MA, Swanson EM (2007) Auditory masking of anuran advertisement calls by road traffic noise. *Anim Behav* 74:1765–1776
- Blom A, van Zalinge R, Heitkonig IMA, Prins HHT (2005) Factors influencing the distribution of large mammals within a protected central African forest. *Oryx* 39:381–388
- Bonan GB (2008) Forests and climate change, forcings, feedbacks and the climate benefits of forests. *Science* 320:1444–1449
- Bradshaw CJA, Sodhi NS, PehK SH, Brook BW (2007) Global evidence that deforestation amplifies flood risk and severity in the developing world. *Glob Change Biol* 13:2379–2395
- Brandao AO, Souza CM (2006) Mapping unofficial roads with Landsat images, a new tool to improve the monitoring of the Brazilian Amazon Forest. *Int J Remote Sens* 27:177–189

- Cade BS, Terrell JW, Schroeder RL (1999) Estimating effects of limiting factors with regression quantiles. *Ecology* 80:311–323
- Carpentier CL, Vosti SA, Witcover J (2000) Intensified, production systems on western Brazilian Amazonian farms, could they save the forest? *Agric Ecosyst Environ* 82:73–88
- Carvalho GO, Nepstead D, McGrath D, del Carmen Vera Diaz M et al (2002) Frontier expansion in the Amazon. *Environment* 44:34–45
- Clough Y, Faust H, Tschardt T (2009) Cacao boom and bust, sustainability of agro forests and opportunities for biodiversity conservation. *Conserv Lett* 2:197–205
- Dale VH, O'Neill RV, Southworth F, Pedlowski M (1994) Modelling effects of land management in the Brazilian settlement of Rondonia. *Conserv Biol* 8:196–206
- de Barros Ferraz S, Vettorazzi CA, Theobald DM, Bellester MVR (2005) Landscape dynamics of Amazonian deforestation between 1984 and 2002 in central Rondonia. *Brazil Assess Future Scenarios For Ecol Manag* 204:67–83
- deKoning GHJ, Veldkamp A, Fresco LO (1999) Exploring changes in Ecuadorian land use for food production and their effects on natural resources. *J Environ Manag* 57:221–237
- Delgado JD, Arroyo NL, Arevalo JR, Fernandez-Palacios JM (2007) Edge effects of roads on temperature, light, canopy cover and canopy height in laurel and pine forests Tenerife, Canary Islands. *Landsc Urban Plan* 81:328–340
- Dyer S, O'Neill JP, Wasel SM, Boutin S (2002) Quantifying barrier effects of roads and seismic lines on movements of female woodland caribou in northeastern Alberta. *Can J Zool* 80:839–845
- Eigenbrod F, Hecnar SJ, Fahrig L (2008) The relative importance of road traffic and forest cover on anuran populations. *Biol Conserv* 141:35–46
- Etter A, McAlpine C, Wilson K, Phinn S, Possingham H (2006) Regional patterns of agricultural land use and deforestation in Colombia. *Agric Ecosyst Environ* 114:369–386
- Ewers RM, Didham RK (2006) Continuous response functions for quantifying the strength of edge effects. *J Appl Ecol* 43:527–536
- Ewers RM, Laurance WF, Souza CM Jr (2008) Temporal fluctuations in Amazonian deforestation rates. *Environ Conserv* 35:303–310
- Fahrig L, Rytwinski T (2009) Effects of roads on animal abundance, an empirical review and synthesis. *Ecol Soc* 14 (article 21)
- Fearnside PM (2005) Deforestation in Brazilian Amazonia, history, rates and consequences. *Conserv Biol* 19:680–688
- Fearnside PM (2008) The roles and movements of actors in the deforestation of Brazilian Amazonia. *Ecol Soc* 13:23–45
- Finer M, Jenkins CN, Pimm SL, Keane B, Ross C (2008) Oil and gas projects in the Western Amazon, threats to wilderness, biodiversity, and indigenous people. *PLoS ONE* 3:e2932
- Foley JA, Asner GP, Costa MH, Coe MT, DeFries R, Gibbs HK, Howard EA, Olsen S, Patz J, Ramankutty N, Snyder P (2007) Amazonia revealed, forest degradation and the loss of ecosystem goods and services in the Amazon basin. *Frontiers Ecol Environ* 5:25–32
- Forman RTT (1998) Road ecology, a solution for the giant embracing us. *Landsc Ecol* 13:3–5
- Forman RTT, Alexander LE (1998) Roads and their major ecological effects. *Annu Rev Ecol Syst* 29:207–231
- Forman RTT, Sperling D, Bissonette JA, Clevenger AP, Cutshall AP, Dale VH, Fahrig L, France R, Goldman CR, Heanue K, Jones JA, Swanson FJ, Turrentine T, Winter TC (2003) Road ecology science and solutions. Island Press, Washington
- Gehlhausen SM, Schwartz MW, Augspurger CK (2000) Vegetation and microclimatic edge effects in two mixed-mesophytic forest fragments. *Plant Ecol* 147:21–35
- Geist HJ, Lambin EF (2002) Proximate causes and underlying driving forces of tropical deforestation. *Bioscience* 52:143–150
- Godfrey BJ (1990) Boom towns of the Amazon. *Am Geogr Soc* 80:103–117
- Goosem M (2007) Fragmentation impacts caused by roads through forests. *Curr Sci* 93:1587–1595
- Honu YAK, Gibson DJ (2006) Microhabitat factors and the distribution of exotic species across forest edges in temperate deciduous forest of southern Illinois, USA. *J Torrey Bot Soc* 133:255–266
- IPEA (2012) www.ipea.gov.br
- Jepson W (2006) Private agricultural colonization on a Brazilian frontier, 1970–1980. *J Hist Geogr* 32:839–863
- Kahm M, Hasenbrink G, Lichtenberg-Frate H, Ludwig J, Kschischo M (2010) Grofit, fitting biological growth curves with R. *J Stat Softw* 33:1–21. URL: <http://www.jstatsoft.org/v33/i07/>
- Keller I, Lurgiader CR (2003) Recent habitat fragmentation caused by major roads leads to reduction of gene flow and loss of genetic variability in ground beetles. *Proc R Soc* 270:417–423
- Kirby KR, Laurance WF, Albernaz AK, Schroth G, Fearnside PM, Bergen S, Venticinque EM, da Costa C (2006) The future of deforestation in the Brazilian Amazon. *Futures* 38:432–453
- Koenker R (2010) Quantreg, quantile regression. R package, version 4.53. <http://CRAN.R-project.org/package=quantreg>
- Laporte NT, Stabach JA, Grosch R, Lin TS, Goetz SJ (2007) Expansion of industrial logging in central Africa. *Science* 316:1451
- Laurance WF, Cochrance MA, Bergen S, Fearnside PM, Delamonica P, Barber C, D'angelo S, Fernandes T (2001) The future of the Brazilian Amazon. *Science* 291:438–439
- Laurian C, Dussault C, Ouellet J, Courtois R, Poulin M, Breton L (2008) Behaviour of moose relative to a road network. *J Wildl Manag* 72:1550–1557
- Li Y, Briggs R (2009) Automatic extraction of roads from high resolution aerial and satellite images with heavy noise. *World Acad Sci Eng Technol* 54:416–422
- Loh J, Harmon D (2005) A global index of biocultural diversity. *Ecol Ind* 5:231–241
- Ludewigs T, De Oliveira D'Antona A, Brondizio ES, & Hetrick S (2009) Agrarian structure and land-cover change along the lifespan of three colonization areas in the Brazilian Amazon. *World Dev* 37:1348–1359
- Macedo DS, Anderson AB (1993) Early ecological changes associated with logging in an Amazon floodplain. *Biotropica* 25:151–163
- Maki S, Kalliola R, Vuorinen K (2001) Road construction in the Peruvian Amazon; processes, causes and consequences. *Environ Conserv* 28:199–214
- Malhi Y, Roberts T, Betts RA, Kelleen TJ, Li W, Nobre CA (2008) Climate change, deforestation and the fate of the Amazon. *Science* 319:169–172
- McGregor RL, Bender DJ, Fahrig L (2008) Do small mammals avoid roads because of the traffic? *J Appl Ecol* 45:117–123
- Mena JB (2003) State of the art on automatic road extraction for GIS update a novel classification. *Pattern Recogn Lett* 24:3037–3058
- Mena CF, Walsh SJ, Frizzelle BG, Xiaozheng Y, Malanson GP (2011) Land use change on household farms in the Ecuadorian Amazon, design and implementation of an agent based model. *Appl Geogr* 31:210–222
- Messina JP, Walsh SJ (2001) 2.5D morphogenesis, modelling landuse and landcover dynamics in the Ecuadorian Amazon. *Plant Ecol* 156:75–88
- Michalski F, Peres CA, Lake IR (2008) Deforestation dynamics in a fragmented region of southern Amazonia, evaluation and future scenarios. *Environ Conserv* 35:93–103
- Moreira E, Costa S, Aguiar AP, Camara G, Carneiro T (2009) Dynamical coupling of multiscale land change models. *Landsc Ecol* 24:1183–1194

- Morton DC, DeFries R, Shimabukuro YE, Anderson LO, Arai E, Espirito-Santo FDB, Freitas R, Morisette J (2006) Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. *Proc Natl Acad Sci USA* 103:14637–14641
- Movaghati S, Moghaddamjoo A, &Tavakoli. A (2010) Road extraction from satellite images using particle filtering and extended Kalman filtering. *IEEE Trans Geosci Remote Sens* 48: 2807–2817
- Muller R, Muller D, Schierhorn F, Gerold G (2010) Spatiotemporal modelling of the expansion of mechanised agriculture in the Bolivian lowland forests. *Appl Geogr* 31:631–640
- Perz SG, Caldas MM, Arima E, Walker RJ (2007) Unofficial road building in the Amazon, socio-economic and biophysical explanations. *Dev Change* 38:529–551
- Perz S, Brilhante S, Brown F, Caldas M, Ikeda S, Mendoza E, Overdevest C, Reis V, Reyes JF, Rojas D, Schmink M, Souza C, Walker R (2008) Road building, land use and climate change, prospects for environmental governance in the Amazon. *Philos Trans R Soc B* 363:1889–1895
- Potvin MJ, Drummer TD, Vucetich JA, Beyer DE, Peterson RO, Hammill JH (2005) Monitoring and habitat analysis for wolves in upper Michigan. *J Wildl Manag* 69:1660–1669
- R Development Core Team (2009) R, a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna
- Richardson JH, Shore RF, Treweek JR, Larkin SBC (1997) Are major roads a barrier to small mammals? *J Zool* 243:840–846
- Rico A, Kindlmann P, Sedlacek F (2007) Barrier effects of roads on movements of small mammals. *Folia Zool* 56:1–12
- Rodrigues ASL, Ewers RM, Parry L, Souza C Jr, Verissimo A, Balmford A (2009) Boom-and-bust development patterns across the Amazon deforestation frontier. *Science* 324:1435–1437
- Rydell J (1992) Exploitation of insects around streetlamps by bats in Sweden. *Funct Ecol* 6:744–750
- Soares-Filho BS, Cerqueira GC, Pennachin CL (2002) Dinamica a stochastic cellular automata model designed to simulate landscape dynamics in an Amazon colonisation frontier. *Ecol Model* 154:217–235
- Soares-Filho B, Nepstead DC, Curran LM, Cerqueira GC, Garcia RA, Ramos CA, Voll E, McDonald A, Lefebvre P, Schelsinger P (2006) Modelling conservation in the Amazon basin. *Nature* 440:520–523
- Taaffe EJ, Morrill RL, Gould PR (1963) Transport expansion in underdeveloped countries; a comparative analysis. *Am Geogr Soc* 53:503–529
- Vos CC, Chardon JP (1998) Effects of habitat fragmentation and road density on the distribution pattern of the moor frog *Rana arvalis*. *J Appl Ecol* 35:44–56
- Walker R, Drzyzga SA, Li Y, Qi J, Caldas M, Arima E, Vergara JP (2004) A behavioural model of landscape change in the Amazon, basin, the colonist case. *Ecol Appl* 14:299–312
- Walsh SJ, Messina JP, Mena CF, Malanson GP, Page PH (2008) Complexity theory, spatial simulation models and land use dynamics in the Northern Ecuadorian Amazon. *Geoforum* 39:867–878
- Wassenaar T, Gerber P, Verburg PH, Rosales M, Ibrahim M, Steinfeld H (2007) Projecting land use changes in the neotropics, the geography of pasture expansion into forest. *Glob Environ Change* 17:86–104