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Abstract

Despite growing interest in urban vulnerability to climatic change there is no systematic understanding of why some urban centers have greater social vulnerability than others. In this article we ask whether the social vulnerability of Amazonian cities to floods and droughts is linked to differences in their spatial accessibility. To assess the accessibility of 310 urban centers we developed a travel network and derived measures of connectivity and geographical remoteness. We found that 914 thousand people live in road-less urban centers (n=68) located up to 2820 km from their state capital. We then tested whether accessibility measures explained inter-urban differences in quantitative measures of social sensitivity, adaptive capacity and an overlooked risk area, food system sensitivity. Accessibility explained marked variation in indicators of each of these dimensions and hence, for the first time, we show an underlying spatial basis for social vulnerability. For instance, floods pose a greater disease risk in less-accessible urban centers because inadequate sanitation in these places exposes inhabitants to environmental pollution and contaminated water, exacerbated by poverty and governance failures. Exploring the root causes of these spatial inequalities, we show how remote and road-less cities in Amazonia have been historically marginalized and their citizens exposed to structural violence and economic disadvantage. Paradoxically, we found places with the highest social vulnerability have the greatest natural and cultural assets (rainforest, indigenous peoples and protected areas). We conclude that increasing accessibility through road-building would be maladaptive, exposing marginalized people to further harm and exacerbating climatic change by driving deforestation.

Keywords: *EXTREME EVENTS; CITIES; REMOTENESS; SPATIAL INEQUALITIES; BRAZIL*

(3) Introduction

In this article we explore the role of two measures of spatial accessibility - geographical remoteness and road-connectivity - in determining variation in the social vulnerability of urban centers. This piece therefore advances current understanding by first elucidating the relative accessibility of hundreds of cities in the Brazilian Amazon and then exploring how this shapes social vulnerability to climatic shocks. We assess inter-urban differences in social vulnerability using quantitative measures of social sensitivity, adaptive capacity and an overlooked risk area, food system sensitivity. Finally, we engage with on-going debates about the contentious roles of roads as either 'ecologically disastrous' or pathways to development (Ibisch et al. 2016).

Social vulnerability to climatic shocks

Worldwide, cities are facing climatic shocks of increasing frequency and severity, with myriad consequences for human welfare (Field 2012). This contributes to growing interest in urban vulnerability to global environmental change (Pelling 2012, Gasper, Blohm and Ruth 2011, Revi et al. 2014, Tate 2013, Sherly et al. 2015). Consequently, understanding and reducing vulnerability to climatic shocks has advanced from academic debate to become a 'political necessity' (Hinkel 2011). Understanding why some cities are more socially-vulnerable than others is crucial for designing appropriate policy interventions. This is vital in the Global South where many cities are highly vulnerable to shocks due to development and governance failures (Parnell, Simon and Vogel 2007), compounded by over-crowding arising from rapid urbanization (Hardoy and Pandiella 2009).

Two decades of research has demonstrated that vulnerability to shocks – defined as the propensity or predisposition of people or places to be adversely affected – is multi-dimensional

(Blaikie et al. 1994) and impacts vary according to levels of development and pre-existing vulnerabilities (Birkmann 2013). Thus, hazards are not just physical events but are socially constructed situations (Cutter, Mitchell and Scott 2000). Hence, vulnerability is generally taken as the outcome of hazard exposure and the two conventional dimensions of social vulnerability (sensitivity and adaptive capacity) (Adger 2006). Extreme climatic events therefore act as threat multipliers when hazard exposure combines with social vulnerability (i.e. economic, social and political weaknesses and stresses) (Wilbanks and Kates 2010). Hazard exposure is the extent to which place or community experiences undesirable change due to system perturbations (Turner et al. 2003).

Where societies are sensitive to shocks and lack sufficient adaptive capacity, exposure to extreme climatic events causes harm through loss of assets, reduced access to services or employment (Gasper et al. 2011) and physical and mental health impacts (Wickrama and Kaspar 2007). Sensitivity is the susceptibility to harm following exposure to a shock and adaptive capacity reflects the ability of individuals or a system to anticipate, respond to and recover from stresses (Adger and Vincent 2005). It reflects development stage, such as demographic transitions in fertility, population structure and levels of education (Stephenson, Newman and Mayhew 2010). Sensitivity is affected by the impacts of previous shocks, manifested through health, nutrition and housing conditions. Adaptive capacity is likewise strongly related to development and can be analyzed at the institutional- or individual-level (or aggregates thereof). This capacity represents governance, rights and literacy (Brooks, Adger and Kelly 2005) and is often low in developing world contexts. Deficiencies can related to either specific- (e.g. related to climate-risks and agriculture) or generic-capacities (e.g. limited income or political power) (Lemos et al. 2016).

Vulnerability analysis tends to ignore food security (e.g. Cutter and Finch 2008, Mansur et al. 2016) even though climatic shocks can strongly affect food systems (Sherman et al. 2015). Climatic shocks can compromise food security by disrupting food access or impacting the natural resource base for local livelihoods (Maru et al. 2014). Moreover, floods and droughts can exacerbate chronic food insecurity and malnutrition in developing world contexts, especially among marginalized groups such as the urban poor (Ericksen 2008). The climate-food security literature is largely focused on food production (Ericksen 2008) yet a shock might instead disrupt the poor's access (Devereux and Berge 2000) to safe, affordable and nutritious food by affecting income (O'Brien 2006) or transportation networks, food storage or market dynamics (Maru et al. 2014). We therefore attempt to advance social vulnerability analysis by adding an extra dimension to Adger's (2006) framework; food system sensitivity.

Disregard of spatial inequalities

Studies have identified place-based differences in the level of social vulnerability to disasters with high intra-region variability (Cutter and Finch 2008, Cutter, Boruff and Shirley 2003), including in Latin America (Hummell, Cutter and Emrich 2016). Mapping and rankings are also widely used to describe spatial differences in vulnerability (e.g. Antwi-Agyei et al. 2012). However, to our knowledge no study has adopted a quantitative approach to test for an underlying spatial explanation for inter-urban differences in social vulnerability. Overall, vulnerability science offers only limited insights into *how* urban vulnerability may vary spatially (see Cutter, Ash and Emrich (2016)) and even fewer as to *why*. This is an important shortcoming because, for example, marginalized remote rural communities are highly vulnerable to climate change (Maru et al. 2014) and this may also be true for remote urban centers. The unclear spatial basis of urban vulnerability to climatic shocks is also important because understanding difference is vital for enabling local-level climate change adaptation (Satterthwaite, Dodman and Bicknell 2009) and humanitarian intervention during disasters. This knowledge gap is surprising given long-term recognition of spatially uneven development (i.e. inter and intra-regional disparities) (Smith 1984, World Bank 2009). Indeed, there is widespread evidence of spatial inequalities in many of the factors which constitute sensitivity to shocks and adaptive capacity. However, urban vulnerability research is dominated by case studies – biased towards metropolitan areas – using conflicting theoretical lenses and methodologies (Romero Lankao and Qin 2011).

Differences in accessibility to other cities may shape inter-urban variation in social vulnerability. Accessibility is defined as the ease with which goods and services in one location can be accessed by people living in another location (Castree, Rogers and Kitchin 2013). Within our study context of the Brazilian Amazon, we conceptualize urban accessibility as the outcome of geographical remoteness (transport distances to other cities) and road connectivity (or not). The latter is important in contexts such as Amazonia, where urban accessibility can depend largely on fluvial transport (Salonen et al. 2012). The relationship between roads and development is contentious (Rigg 2002) and it is unclear if road-less urban centers in Amazonia and elsewhere are more or less vulnerable to shocks than road-connected urban centers, when controlling for remoteness. Roads are also polemic because they have widespread negative impacts on ecosystems yet are mentioned in the Sustainable Development Goals for contributing to economic growth, despite the social and environmental costs (Ibisch et al. 2016).

Irrespective of whether less-accessible cities are more vulnerable, spatial analysis of vulnerability should also recognize the ways in which space and spatial relations are *produced* (Lefebvre 1991). Ribot (2011) argued that vulnerability research must address the social and political-economic processes that have caused marginalization and vulnerability because this is a pre-requisite for climate risk-reduction. Accordingly, we highlight two theoretical framings of spatial inequalities which can provide insights into potential spatial variation in social vulnerability. The first engages with the work of early 20th century geographers and later, geographical economists. Both groups emphasize how distance to markets determines transport costs, and suggest that economic growth is lower in less-accessible locations due to competitive disadvantage (Krugman 2011). The World Bank's (2009) view of spatial inequality is, not surprisingly, derived from geographical economics; less-accessible cities are 'lagging' in development because high transport costs and small size incur less economic growth and investment and impaired flows of finance, goods and services. They contend these constraints contribute to poverty and poor access to basic services such as electricity and sanitation. Yet, these arguments generally ignore the political and historical factors which strongly influence 'uneven development' (Smith 1984).

The second framing draws on political economy, going beyond spatial patterns to examine how differences emerge and are perpetuated. Political economic geographers have analyzed the spatial nature of inequalities in well-being (e.g. Goodchild et al. 2000, Smith 1984, Harvey and Braun 1996) using the lenses of place-specific histories and cultures, institutions and politics, power relations and justice (e.g. Massey 1979). Hence, this scholarship has examined spatial inequalities in development albeit not using a vulnerability framework nor pursuing generalizable spatial explanations.

Study aim and research questions

Here we ask whether the spatial accessibility of cities is an underlying driver of social vulnerability to extreme climatic events in the Brazilian Amazon. The vulnerability of urban Amazonians to climate change has received very little research attention (Mansur et al. 2016) and there is an urgent need for more research on the human dimensions of climatic change in this region (Brondízio et al. 2016). We address our main objective by asking four specific research questions. First, to what extent do remoteness and connectivity determine the social dimensions (social sensitivity, adaptive capacity and food system sensitivity) of urban vulnerability to climatic shocks? Second, how are these spatial inequalities produced and perpetuated? Third, what are the relative merits of potential adaptation pathways for redressing spatial inequalities and reducing social vulnerability in less-accessible urban centers? Fourth, related to question three, what might be the environmental and societal costs of increasing urban accessibility? We answer these questions using empirical data analysis (Q1 and Q2, see Results) and through the interpretation of our findings in relation to the literature and public policy (Q3 and Q4, see Discussion). Although explanations differ, geographical economics and political economy perspectives would agree that less-accessible urban centers may suffer disadvantages that limit the capacity of individuals and institutions to thrive. Hence, we predict greater social vulnerability in less-accessible urban centers due to high levels of sensitivity and low levels of adaptive capacity.

Materials and Methods

Study region

The Brazilian Amazon is well-suited to answering our research questions because many of this vast region's urban centers are located in places where accessibility is precarious (Guedes, Costa and Brondízio 2009), dependent on a transport infrastructure highly susceptible to floods (inhibiting road transport) and droughts (inhibiting river transport)(Szlafsztein 2015). These issues create challenges for municipal, state and federal governments, tasked with reducing vulnerability and protecting citizens from harm. Moreover, Amazonian urban centers face multiple vulnerability threats: rapid urbanization (Browder and Godfrey 1997); increasing exposure to extreme floods and drought events (Marengo et al. 2013), and under-development, including income poverty and low levels of education (IBGE 2010) and food insecurity (IBGE 2009).

Experimental design

Our study is based mainly on analysis of secondary socio-economic data (for dependent variables employed as indicators of social sensitivity and adaptive capacity) and spatial analysis (for independent variables) from 310 cities in the six states entirely within the Legal Amazon (Figure 1). These data-sets are supplemented by primary data on food prices collected from a subset of urban centers. Our study region had 14.48 million inhabitants, 10.58 million (or 73 percent) of which are urban, distributed in 2.70 million households (IBGE 2010). All data-sources and their spatiotemporal reference are described in Table S2.

Vulnerability Indicators

Accessibility measures

We assessed urban accessibility using measures of inter-urban connectivity and geographical remoteness within an urban hierarchy. Our focus was place-based accessibility rather than travel time or considering individual mobility, see Kwan (2013). To assess connectivity we developed a travel network for the study area in a GIS, combining information on road, river networks and urban locations (Appendix). We categorized each center as either: (a) having no connection to the road network (road-less), (b) having access to the road network but with a route requiring partial use of rivers (ferry-boats or barges to cross rivers), (c) fully connected to the road network. We calculated a remoteness score (0.0>1.0) for each center, based on minimum travel distances to centers of different levels in the Brazilian Institute for Geography and Statistics' (IBGE) urban network (Figure S1; Figure S2). Minimum travel distances between all cities were calculated by identifying routes across our network based on the likely travel potential (0/1) of an arbitrary cargo-load. Distances were standardized and weighted by level (Figure 1, Figure 2, Table S1)(IBGE 2007), with greater weighting for remoteness from higher-order cities (Table S1).

Estimating sensitivity and adaptive capacity

Vulnerability indicators are a well-established (and scrutinized) method for identifying vulnerable people, communities or regions. We used a deductive approach for selecting indicators of social vulnerability to climatic shocks, drawing on theoretical links between indicators and vulnerability dimensions (Tate 2012, Cutter et al. 2003)(Appendix). Based on consideration of theoretical linkages, our conceptualization of extreme event impacts in our study system and data availability, we considered six elements of social sensitivity (Table S2): (a) Demography (Cutter et al. 2003, Revi et al. 2014) [measure = young dependency ratio, Appendix]; (b) Sanitation (Brooks et al. 2005), [lacking tapped water, private toilet access]; (c) Ethnicity (Cutter et al. 2003) [proportion of people that are indigenous Amerindians]; (d) Health (Tol and Yohe 2007); [prevalence of low birth weight]; (e) Education (Brooks et al. 2005); [adults without completed elementary school]; (f) Rurality [rural population].

We identified four key elements indicative of adaptive capacity; (i) Healthcare provision (Gasper et al. 2011); [our measure = prevalence of low antenatal care]; (ii) Education provision (Cutter et al. 2003); [educational delays among school-age children]; (iii) Urban population growth (Stephenson et al. 2010); (iv) Poverty (Posey 2009), including income-poverty prevalence and income inequality. We normalized our indicators using minimum and maximum values and combined these into two unit-less aggregate indexes (0.0>1.0); a social sensitivity score and an adaptive capacity score.

Estimating food system sensitivity

Food access is strongly influenced by affordability so we used food prices as a proxy. We collected prices for two categories of foodstuffs: those nearly always imported to Amazonian urban centers from outside the region, via major trading centers (i.e. state capitals), and foods that are generally sourced locally, through small-scale agriculture or artisanal fishing. We assessed the price of imported foods and local staples by conducting a telephone survey of hundreds of food shops across one-hundred urban centers in Amazonas, Para and Acre. Using a structured questionnaire, we recorded the cheapest price available of five imported foods (frozen chicken, tinned meat, dried spaghetti, cracker biscuits, rice) and two locally-sourced foods; toasted manioc flour and the cheapest fish species available (see Table S2). These foodstuffs were surveyed because of their importance within Amazonian diets (Davies, Frausin and Parry 2017). *Per capita* manioc production was calculated for by dividing municipal production for 2010 by the total municipal population in 2010 (Appendix).

Statistical analysis

Our sample size allowed us to separate the effects of urban remoteness and connectivity (which are correlated; correlation = 0.46, $p<0.05$), and also account for unexplained spatial effects across our study region (e.g. in colonization history, climate, proximity to the rest of Brazil) using State as a fixed-effect control variable. All analyses were conducted in the R platform version 3.2.3. With few exceptions (Appendix), all of the modelled outcome variables were proportions and in these cases we specified generalized linear models with quasi-binomial error structures. All dependent variables were specified in their undesirable form (e.g. proportion of households without a private toilet).

Results

Accessibility measures

Around three-quarters (228/310) of the urban centers in our study region are connected through a road network (Figure 1). These centers are home to 89 percent (9.41 million people) of the region's urban population (Table I). We identified sixty-eight centers as having no road connection, inhabited by 9 percent (0.91 million people) of the urban population. Around half (n=33) of the road-less urban centers were in Amazonas state, twenty-one in Pará and four in Acre. Fourteen urban centers had partial connection to the road network. The most remote urban center was Itamariti, located in Amazonas State and 1,856 km travel distance from its own state capital (Table S1). Road-less urban centers were significantly more remote than road-connected centers (Figure S3).

High levels of social vulnerability in Amazonian urban centers

Overall, the social sensitivity and adaptive capacity deficit indicators showed that the inhabitants of urban centers in Amazonia contend with challenging development conditions that are likely to increase their risk of harm following exposure to extreme climatic events (Table S2). For instance, on average over a third (36 percent) of urban households lacked access to tapped water, nearly a quarter (23 percent) lacked a toilet and nearly two-thirds (64 percent) of adults lacked full elementary education.

Linkages between social sensitivity, adaptive capacity and accessibility

A main finding was that remote urban centers have higher levels of social vulnerability (Figure 3) because they are significantly more sensitive to shocks and have greater adaptive capacity deficits. Remoteness, connectivity and the spatial control variable explained a relatively high amount of the variation in social vulnerability to shocks, as represented by our indices of social sensitivity (R^2=0.32) and adaptive capacity deficit (R^2=0.55)(Table II). Results indicate a 10 percent increase in remoteness is associated with a 6 percent increase in social sensitivity ($p<0.01$; Figure 4A), and an 11 percent decrease in adaptive capacity, $p<0.001$)(Figure 4C). Five social sensitivity indicators were significantly higher in remote urban centers whereas rurality and low birth-weight were not significantly different (Figure S4). Considering adaptive capacity deficits, four indicators were significantly higher in remote urban centers while poverty prevalence was not significantly different (Figure S5).

Another major finding was that road-less urban centers are more sensitive to shocks (Figure 4B) and have greater adaptive capacity deficits than road-connected cities (Figure 4D). When controlling for remoteness, in road-less urban centers social sensitivity is 5 percent higher ($p<0.01$) and deficits in adaptive capacity are 51 percent higher ($p<0.001$). All social sensitivity indicators were significantly better in road-connected urban centers (Table II; Figure S6). Road-less urban centers were significantly worse for adaptive capacity measures, with the exception of urban population growth, which was not significantly different (Figure S7). For instance, in road-less urban centers income-poverty is 34 percent more likely, when controlling for other variables. State was also a significant predictor in statistical models even when controlling for accessibility measures.

The majority (61 percent) of road-connected urban centers had lower-than-average social vulnerability, including ninety-eight (relatively) non-remote (total population 7.7 million) and forty-two remote centers (0.57 million)(Table I; Figure 3). Thirty-nine percent of road-connected centers had high social vulnerability, including twenty-nine non-remote (population 0.86 million) and ten remote urban centers (0.28 million). In contrast, the majority (87 percent) of road-less urban centers had high levels of vulnerability, including twenty-five non-remote (population 0.27 million) and thirty-four remote centers (0.42 million). Hence, only 13 percent of road-less cities had low vulnerability, including seven non-remote and two remote centers. However, variation in the relationship between remoteness and social vulnerability (Figure 3) demonstrates that other contextual factors are also important determinants of vulnerability.

Linkages between urban accessibility and food system sensitivity

Our telephone survey revealed that imported food prices vary hugely among urban centers. For example, the per kilo price of frozen chicken ranged from R$2.96 to R$8. Spatial predictors together explained 30 percent of the variation in imported food prices (Table II). Food prices were significantly higher in remote urban centers, increasing by 15 percent for a 10 percent increase in relative remoteness ($p<0.01$)(Figure 4E). Controlling for remoteness, the food price index was 61 percent higher in road-less urban centers ($p<0.05$), compared to fully road-connected ones (Figure 4F). Road-connections were not significantly related to toasted manioc prices. However, toasted manioc was more expensive in remote urban centers ($p<0.10$). Fish prices and *per capita* manioc production were not associated with remoteness or connectivity, but varied by state.

Forest cover and reserve presence around urban centers

We found a negative relationship between urban accessibility and natural capital; there has been less deforestation around remote and/or road-less urban centers. Together, accessibility and the spatial control variable explained 58 percent of the variance in cumulative proportional forest loss at the municipal-scale. Remaining forest cover increases significantly with remoteness – to nearly 100 percent around remote urban centers (i.e. in the surrounding rural areas of the same municipality) (Table II). Remaining forest cover is significantly lower ($p<0.0001$) around road-connected than road-less urban centers (Figure 5A-B). Protected areas cover a significantly higher ($p<0.01$) proportion of remote municipalities and are more prevalent around urban centers with partial road connections than either full- or road-less urban centers (Figure 5C-D). Coverage of indigenous reserves was not significantly related to road connectivity but was strongly related to the remoteness of urban centers. Indigenous reserves coverage was very low around non-remote urban centers and very high (in many cases over 50 percent of land area) around highly remote urban centers (Figure 5E-F).

Discussion

Our findings provide clear evidence that less-accessible urban centers in Amazonia have greater social vulnerability, indicating higher potential impacts of extreme climatic events. Striking inter-urban differences in social sensitivity to shocks, adaptive capacity and food system sensitivity were partly explained by two spatial factors; remoteness from other urban centers and road-connectivity. This study therefore demonstrates an underlying spatial dimension of the vulnerability framework (Adger 2006), with significant application for refining vulnerability assessment. Our results show that marginalization affects not just subgroups of people (Young 2009) but also less-accessible *places.* We scrutinize whether urban accessibility is a 'root cause' of vulnerability (Blaikie et al. 1994) using two framings for explaining spatial inequalities (Rigg et al. 2009): geographical economics and political economy. As we attempt to illustrate, higher social vulnerability to climatic shocks is related to economic and political history (Ribot 2011). We also reflect on the context-specific relationship between accessibility and urban vulnerability, and explore adaptation pathways for reducing spatial inequalities.

This article builds on research showing high vulnerability to climate change in remote rural communities (Maru et al. 2014) and shows this also applies to remote urban centers. Our study also contributes to a small but growing literature on the human dimensions of climatic change in Amazonia (Brondízio et al. 2016, Mansur et al. 2016, Pinho, Marengo and Smith 2015, Sherman et al. 2015). It is significant that following decades of deforestation, road-building and colonization in Amazonia, four-fifths of urban centers are at least partly connected to the road network, and these urban centers are home to nine out of ten city-dwellers. In this urbanized forest 'wilderness' (Parry, Barlow and Pereira 2014) it is paradoxical (to environmentalists (Raudsepp-Hearne et al. 2010)) that we found places with the greatest natural capital to have the greatest social vulnerability We highlight the social and environmental risks posed by road-building (Ibisch et al. 2016), and consider the relevance of our findings for other systems.

Less-accessible cities are more sensitive to climatic shocks

Our study shows that inhabitants of remote and road-less urban centers are more susceptible to harm following exposure to climate shocks, reflective of an earlier stage of development and demographic transition (Stephenson et al. 2010). In other words, a given flood or drought would be more harmful to the inhabitants of less-accessible cities, even if exposure was uniform. We show how spatially unequal vulnerability to climatic shocks is partly the outcome of variable access to sanitation among urban centers. Poor sanitation reflects inadequate public infrastructure and poor housing conditions related to poverty and deprivation (Perz 2000). It also exposes people to health risks from environmental pollution and contaminated water supplies (Brooks et al. 2005). The health impacts of extreme events in Amazonia are poorly understood, but reports suggest outbreaks of diseases during floods (e.g. hepatitis and rotaviruses) and restricted access to safe drinking water, food and energy during droughts (Table S3). The ‘racial’ aspect of vulnerability relates to lack of access to resources, cultural differences and marginalization (Cutter et al. 2003). And, consistent with case studies of remote, vulnerable communities (Maru et al. 2014), indigenous people made up a greater proportion of the urban population in less accessible urban centers.

Strikingly, low-birth weight was 15 percent more likely in road-less municipalities, even when controlling for remoteness. This indicates lower levels of maternal health and nutrition (Christian 2010) and food insecurity (Rose-Jacobs et al. 2008) in these places, and supports a posited link between ‘roadless-ness’ and malnutrition (Ibisch et al. 2016). Chronic food insecurity and malnutrition in road-less urban centers in the Global South may arise from a combination of stressors including dietary intake; unemployment and housing conditions (Borders et al. 2007), the burden of insect-borne and parasitic diseases (Steketee 2003), and perhaps impacts of previous climatic shocks. We found evidence of limited education among adults in less-accessible urban centers, further supporting Ibisch’s et al’s (2016) predictions. Low education suggests the populations of less-accessible urban centers are more susceptible to harm when exposed to shocks (Brooks et al. 2005), due to increased likelihood of low salaries, informal employment access to information and limited power. Limited education in these Amazonian centers may reflect either relatively recent waves of rural-urban migration and poor rural education provision (Parry et al. 2010) or shortcomings in urban education provision. Many aspects of the potential harm experienced by the inhabitants of less-accessible urban centers are evidence of societal marginalization (c.f. Ribot (2011)).

Less-accessible urban centers have lower adaptive capacity

Adaptive capacity was lower in less-accessible centers, meaning the ability of their residents and institutions to anticipate, respond and recover from stresses is limited (Adger and Vincent 2005). Good antenatal care is vital for reducing maternal mortality and was worse in these places. This implies that local health services would be unable to effectively respond to extraordinary demands, such as disease outbreaks during extreme climatic events (Hales, Edwards and Kovats 2003). Low uptake of antenatal care in developing world contexts is linked to low availability of clinics and perceived low quality of care (Say and Raine 2007), and consistent with evidence of spatial inequalities in healthcare (Gatrell and Elliot 2014). Significant educational-stage delays among teenagers in less-accessible municipalities may reflect weak school provision with teacher absence or school closures, for example. Educational delays also illustrate the 'blurred' distinction (Hinkel 2011) between adaptive capacity and sensitivity because household deprivation also influences school attendance and attainment (Engle and Black 2008).

Population growth was faster in remote towns yet not significantly different in road-less towns, even though both forms of (relative) inaccessibility were associated with high-dependency ratios. Perhaps poor road-less towns experience relatively high rates of out-migration to larger urban centers (Garcia, Soares-Filho and Sawyer 2007) and thus the linkage between fertility and population growth is partially broken. Rapid population growth compromises adaptive capacity by over-loading public services such as water, sanitation and health and causes unemployment (Gasper et al. 2011, Stephenson et al. 2010). There is a two-way interaction between poor public service provision and under-development in Amazonia because limited local economic activity limits local investments in services and infrastructure, which reduces employment opportunities (Brondízio 2011). Moreover, embezzlement of public funds by mayors and associates is rife in remote Amazonian towns, partly due to limited state capacity for financial scrutiny in these places (Jardim 2016).

Our findings suggest that weak public administration combines with inequality and deprivation in remote and road-less urban centers to confer intergenerational disadvantages and high social vulnerability to shocks. This mirrors research in Australia showing people living in remote rural communities encounter economic and social disadvantages throughout their life course (Tanton, Gong and Harding 2012). Accessibility explained considerable variation in vulnerability, yet significant deviations from this trend highlight a tension between the utility of identifying generalizable determinants of vulnerability. It is clear that it is also important to understand contextual place-specific differences (Romero Lankao and Qin 2011) as well as develop measures of social vulnerability that are meaningful to local people (Oulahen et al. 2015).

Higher food prices in less-accessible urban centers

Urban accessibility is linked to the sensitivity of food systems because chronic high food prices in remote and road-less places make lower-income groups more vulnerable to price shocks. The prices of staple foodstuffs normally imported to Amazonia via regional centers are more than twice as expensive in the most remote centers compared to the least remote, and 61 percent more expensive in road-less urban centers. Hence, even during non-drought periods the affordability of these staple foods is lower in less-accessible places. Consequently, if price increases occurred in remote and road-less centers due to droughts the poor would face greater risks of disrupted food access (Devereux and Berge 2000, Maru et al. 2014). Indeed, if adjusting incomes by food prices

(Shorrocks and Wan 2005) income poverty would also be higher in remote and road-less urban centers. Our results tentatively support the hitherto untested assumptions that distance from markets is indicative of vulnerability to food insecurity (Haan, Farmer and Wheeler 2001). Our findings are also consistent with research in the Solomon Islands which found that overall remoteness contributed to national vulnerability because high transport costs between urban centers drove up the prices of imported foodstuffs (Schwarz et al. 2011). Linkages between accessibility and the price of locally-produced foods were less apparent. In summary, our results of food prices and birth-weight support findings that the impacts of climate shocks on food insecurity and malnutrition are unequally distributed (Grace, Brown and McNally 2014).

Urban vulnerability in Amazonia

Research into climatic change in Amazonia is dominated by environmental concerns (e.g. Davidson et al. 2012) and understanding of local health and social impacts is sorely lacking (Brondízio et al. 2016). This bias does an injustice to the ~25 million inhabitants of Amazonia, who are increasing exposed to extreme hydro-climatic events (Marengo et al. 2013, Filizola et al. 2014). Our study therefore makes an important contribution to current knowledge, especially in relation to cities. Overall, we found high levels of social vulnerability for Amazonian urban centers. This is congruent with a recent Brazil-wide vulnerability assessment (Hummell et al. 2016) albeit our analysis controls for the potential biases of using only municipal-scale aggregate data that homogenizes differences in rural and urban social vulnerability (Cutter et al. 2016). This is important because the ways in which urban Amazonians cope (or not) with flood and drought events are likely to be qualitatively different to the strategies and capacities of rural communities (Pinho et al. 2015, Sherman et al. 2015). Our central findings are also supported by a case study of Eirunepé, a town with poor public service provision, rendered 'invisible' to outsiders by its remoteness (Schor 2013). Other smaller-scale urban studies in the Brazilian Amazon have also found on-going deficiencies in infrastructure, public services and employment opportunities (Costa and Brondízio 2011). Moreover, Mansur et al. (2016) found that within urban centers the marginalized poor tend to live in the areas most prone to flooding, combined with low levels of sanitation. Spatial inequalities with richer regions in Brazil are persistent because two decades ago Browder and Godfrey (1997) observed that rapid population growth in Brazil's 'rainforest cities' had not been accompanied by sufficient economic growth or local development, resulting in 'over-urbanization' (see Appendix). Urban expansion in 1980s entailed rapid shantytown growth, pollution, poor access to social and medical services and inadequate provision of basic services such as water and sanitation (Perz 2000, Guedes et al. 2009).

Underlying drivers of spatial inequalities

Our quantitative findings provide insights into the consequences of accessibility for social vulnerability to climatic shocks but they cannot explain *why* remote and road-less urban centers are under-developed. We interpret our results using the positivist explanations posited by geographical economists versus the more critical, Marxist-influenced arguments of political economy. The importance of transport costs in economic geography (Hoover 1948) could partially explain high food prices in remote Amazonian urban centers. 'New' geographical economists argued that proximity to major centers also promotes higher economic growth due to greater flows (of information, ideas and technology (Krugman 1999)), and agglomeration economies in which larger markets grow faster (Krugman 2011). Using this lens, southern Brazil is a more attractive place to produce than the north because of concentrated purchasing power and intermediate input availability (Krugman 1999). These factors have sustained market and supplier concentration and may also partly explain relatively low social vulnerability to hazards in southern Brazil (Hummell et al. 2016). The World Bank (2009) certainly follows a core-periphery doctrine and regards spatial inequalities in economic growth between well-connected ‘leading’ areas and less-accessible ‘lagging’ areas as inevitable. Gallup et al. (1999) suggested that ‘hinterland regions’ are geographically disadvantaged and exhibit inhibited development due to high transport costs. Applied to our results, high social vulnerability in less-accessible urban centers is related to under-development, a consequence of high transport costs impeding flows of goods (ranging from imported food items to exported natural resources or agricultural produce), information and ideas. However, critical/radical geographers have long-criticized the reduction of space to an economic variable (Bunker 1989). Using absolute notions of space, they argue, ignores the role of politics, power and history in *producing* space and spatial relations (following Lefebvre (1991)). Hence, assumptions that spatial inequalities are inevitable or even desirable (Hirschman 1958) are rejected.

Understanding the underlying causes of marginalization and vulnerability is an important pre-requisite of any climate-risk reduction approach (Ribot 2011). However, vulnerability and resilience research can offer little guidance on how spatial inequalities emerge and has been criticized for ignoring, power, history and social relations (Brown 2016), but see Romero Lankao and Qin (2011)). In contrast, political economists have explored the role of history and power structures in producing unequal regional development (Smith 1984, Massey 1979, Martin 1999) and their insights provide useful heuristic tools for interpreting spatially uneven social vulnerability. Political economic explanations for spatial inequalities in development rest on Lefebvre’s (1968) contention that space is always political, reflects social facts and influences social relations. Moreover, political economists argue that, left unchecked, capitalism inevitably leads to uneven regional development. In that sense, spatial inequality in Amazonia is unsurprising because urbanization in developing countries has been characterized by inequality between rural and urban, between urban centers and within urban centers (Smith 1996). We argue that the underlying explanation for higher social vulnerability in less-accessible urban centers is that politics and history – both inextricable from capitalist penetration of Amazonia (Browder and Godfrey 1997) - have shaped the urban hierarchy and created ‘spatially uneven institutional geographies’ (Amin and Thrift 1995). For example, highways in Amazonia have been strategically placed to facilitate resource extraction, agricultural expansion and international trade. The Amazonian urban hierarchy has also been profoundly influenced by the politics of migration, colonization, state-creation and regional identities (Browder and Godfrey 1997).

To understand the causal mechanisms leading to underdevelopment in less-accessible urban centers we point to Young (2009). She reasoned that structural inequalities are unjust and result from five forms of oppression; exploitation, marginalization, powerlessness, cultural domination and violence. Young addressed inequalities among social groups and we extend this to explore how oppression may have created spatial inequalities in social vulnerability. Clearly, the economic history of Amazonia has been defined by the exploitation of natural resources and labor to meet global demand for commodities. The rubber boom led to the diffusion of poor migrants across Amazonia and was characterized by exploitation of workers and direct or indirect violence against indigenous peoples (Dean 1987, Guzmán 2013). Notably, rubber-wealth accumulated in large trading centers rather than in provincial outputs. Applying Massey’s (1979) analysis to contemporary Amazonia, the labor demands of Manaus’ industrial district could mean that under-development in provincial cities suits the demands of capital interests because it promotes a flow of cheap labor. Marginalization of remote and road-less urban centers also reflects political centrism - the concentration of power and capital in capital cities (Massey, Amin and Thrift 2003). Historical analysis shows that remote places *become* marginalized and under-developed due to distance from centers of power, which systematically exclude certain social and ethnic groups (Rigg et al. 2009, Kanbur and Venables 2005). Importantly, certain interests benefit from regional inequality and its perpetuation and these interests are over represented in the political and economic institutions reproducing these inequalities (Rigg et al. 2009). Cultural domination of indigenous people arises from unequal power relations and colonial history (Richmond and Ross 2009), which is itself linked to capitalist penetration. Our results show that indigenous people are more populous in the marginalized less-accessible urban centers. We also show how social vulnerability predisposes the citizens of relatively inaccessible urban centers to harm from extreme events, through violence that is structural (Baker 2010) and 'silent' (food insecurity and malnutrition (Watts 1983)).

Policy options for reducing social vulnerability in Amazonia

Would transport infrastructure improvements benefit vulnerable people living in less-accessible urban centers? According to the World Bank (2009), investing in transport infrastructure in the Global South can reduce distances between cities and encourages increased economic growth. Geographical economists have also argued that development in 'hinterlands' is constrained by transport costs and recommended investment in related infrastructure (Henderson 1999). Although causality is unclear, improved transport infrastructure has been associated with economic growth (Calderón and Servén 2014) and may lead to a decline in the primacy of large cities. Proponents believe these investments stimulate growth and reduces poverty by lowering transport costs and boosting productivity, wages, information flows and labor mobility (e.g. Reardon, Stamoulis and Pingali 2007). However, urban agglomerations may continue to thrive even if initial locational advantages are eroded by new transport infrastructure (Venables 1999).

Furthermore, a political economy lens suggests that making road-less urban centers road-connected would affect social groups unequally and reinforce existing vulnerabilities. In South-East Asia, connecting remote communities with roads has been motivated by quelling insurgency and market integration, the latter having mixed economic effects (Rigg 2002).

The social risks posed by building roads in Amazonia are supported by evidence that they become focal points for violent social conflict (Dalakoglou and Harvey 2012), marginalization of vulnerable social groups and disease outbreaks (Barcellos et al. 2010, Ibisch et al. 2016). Moreover, road-building in Amazonia would be mal-adaptive because the inevitable deforestation and land-use change would contribute to further climate change (Ibisch et al. 2016), outweighing the potential benefits to some inhabitants of a given city (Eriksen et al. 2011). Indeed, new roads could undermine the 'resourcefulness' of remote places (Maru et al. 2014) if deforestation reduced access to diversified livelihoods and natural-resource use and in-migration compromised existing social relations. Nevertheless, the persistence of forest poverty in order to privilege a conservationist agenda and mitigate climate change is unjust (Brown 2016). River-dependency is problematic for road-less urban centers in Amazonia during drought periods and warrants investment in adaptation (Maru et al. 2014). Alternative more climate-friendly strategies for maintaining accessibility during droughts include hovercraft transport (Kubo, Akimoto and Moriwake 2003) or improved air transport infrastructure (e.g. more hydroplanes). The impacts of transport problems could also be reduced by moving towards a more local food system (Sundkvist, Milestad and Jansson 2005).

If resilience is the antonym of vulnerability then building the former is critical to reducing the latter (UNDP 2014). Brown (2016) argues that building resilience can be radical – escaping assumptions of economic growth – through 'positive transformations' that redress structural inequalities. After all, balanced economic growth is not the only means of redressing spatial inequalities and justice. Accounting for historical wrongs is also a legitimate criterion for making spatially-targeted policy choices (Rigg et al. 2009). Yet, identifying suitable pathways is challenging because actions must address the root causes of spatial inequalities in welfare *and* facilitate adaptation to a changing climate. Resilient development requires communities, neighborhoods and urban centers to enhance their adaptive capacity for absorbing change, diversity, adaptive governance, learning and self-organization (Nelson, Adger and Brown 2007, Hardoy and Pandiella 2009). Adaptations must achieve transparent government (Leichenko 2011) and give voice and representation to vulnerable populations (Fransen et al. 2013). Those from marginalized places and social groups must be involved in the decision-making processes that set policy agendas. This would enable interventions to account for local priorities for livelihoods (Bunce, Brown and Rosendo 2010), and thus engage with the place-based nature of vulnerability (Cutter et al. 2003). The Brazilian government has invested in policies likely to assist the poor and vulnerable with adaptation including health promotion and cash transfers (Lemos et al. 2016). However, key services such as education, sanitation and healthcare are worse in less-accessible places, evidence of distributive injustice. Further challenges in the Brazilian Amazon include deficiencies in tax collection (Costa and Brondízio 2011), a lack of public early warning systems, (Pinho et al. 2015) and a poorly-funded natural disasters agency that overlooks long-term adaptation (Szlafsztein 2015).

Study limitations

Establishing linkages between indicators of social vulnerability and urban accessibility is an important first-step in elucidating spatial inequalities in the potential impacts of climatic change, but important questions remain. Our indicators-based approach cannot account for how agency and subjective perceptions of shocks influence the capacity of individuals and groups to cope with environmental change (Romero Lankao and Qin 2011). Hence, we may over-estimate vulnerability in less-accessible urban centers by failing to account for structural adaptations to climate shocks - in transport, early warning systems or livelihoods – which enhance coping capacity (Hardoy and Pandiella 2009). People living in remote places may have rich local ecological knowledge, cultures of reciprocity and sharing, a strong sense of place and belonging and informal institutions which help them deal with uncertainty (Smith and Huigen 2009, Maru et al. 2014, Sherman et al. 2015). In addition, we assess only place-accessibility (assuming shorter travel distances mean greater accessibility) and ignore space-time constraints mediated through, for example, mobilities related to the effects of social difference (Kwan 2013). Finally, it is important to establish whether a relationship between accessibility and social vulnerability exists in other systems. Relatively inaccessible cities are found in the Congo Basin, Mekong Delta, Sahara, Himalayas, Arctic, all of which are increasingly exposed to climatic change (Field 2012).

Conclusions

The unique contribution of this article is using novel empirical evidence to show an underlying spatial basis for the social vulnerability of cities to climatic shocks. This was achieved by evaluating the geographic remoteness and road-connectivity of hundreds of urban centers in the Brazilian Amazon and testing the role of these accessibility measures as determinants of social sensitivity, adaptive capacity and a novel component; food system sensitivity. Understanding vulnerability to extreme climatic events is essential for developing policies that protect vulnerable places and people from harm (Field 2012). Despite clear evidence of widespread spatial inequalities in development and growing interest in the vulnerability of urban populations to environmental change, until now we have lacked a systematic framework for understanding how and why some urban centers have greater social vulnerability than others. Our results show that higher sensitivity to floods and droughts in remote and road-less Amazonian urban centers is related to under-development, including poor sanitation which increases disease risk. Furthermore, limited adaptive capacity in less-accessible urban centers reflects deficient public administration and deprivation, constraining the ability to respond to and recover from shocks. Hence, we demonstrate an underlying spatial basis for vulnerability, which advances Adger's (2006) framework and Cutter's (2003) placed-based analysis. Vulnerability assessments of multiple places at community-scale (Cinner et al. 2013) or county-scale (Cutter and Finch 2008) have not attempted to systematically *explain* spatial patterns of vulnerability.

We have explored how the underlying causes of high social vulnerability in less-accessible urban centers are rooted in political and economic history (Smith 1984, Ribot 2011), which has led to structural economic disadvantage through high transport costs (Krugman 1999) and under-development. Adaptation pathways for reducing vulnerability in less-accessible urban centers should build adaptive capacity through transparent and inclusive governance that accounts for historical injustices and context-specificity. In contrast, even if building new roads brought certain advantages such as improved educational access, these may well be outweighed by the social costs borne by already marginalized people (Ibisch et al. 2016). New roads could also reinforce existing vulnerabilities by fueling conflict and disease and eroding social relations in less-accessible urban centers. Moreover, the poorest of Amazonia's urban poor often depend on rural livelihoods (Parry et al. 2014), which could be undermined by the inevitable deforestation from new roads, which can be 'ecologically disastrous' (Ibisch et al. 2016).

Deforestation would also increase overall hazard exposure to climatic shocks by contributing to global climate change.

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Figure captions

Figure 1: Map illustrating the Brazilian Amazon, road connectivity and remoteness scores of the 310 urban centers included in this study. Also shown is the road network (official and unofficial) and river network. Coloured circles indicate the level of remoteness for each urban center.

Figure 2: Travel distances from Amazonian urban centers to the nearest centers of different levels in a hierarchical urban network. Urban centers are ranked in decreasing order of overall remoteness score (A)(gray), based on a weighted composite of distances to (B) Own regional center (blue); (C) Any regional center (dark red); (D) Sub-regional center (light brown); (E) Zonal center (orange); (F) Local center (green). Journeys could be made by river or road and mean distances are displayed by colored dashed lines for each journey type.

Figure 3: Relationship between remoteness and social vulnerability of urban centers in Amazonia. Social vulnerability is defined here as the sum of two dimensions of social vulnerability to shocks (social sensitivity and adaptive capacity deficit) and is illustrated in relation to two accessibility measures; connectivity (by shape) and remoteness from other cities in a hierarchical urban network (by color).

Figure 4: Relationship between urban accessibility and social vulnerability indicators. (A) Social sensitivity scores are related to remoteness from other cities ($P < 0.01$) and connectivity to roads ($P < 0.001$) **(B)**. Adaptive capacity deficits are higher in more remote cities ($P < 0.001$) **(C)** and in road-less cities ($P < 0.001$) **(D)**. A price index of five key imported foodstuffs (frozen chicken, tinned meat, spaghetti, rice and biscuits) was significantly higher in more remote cities

(P < 0.01) **(E)** and in cities unconnected to the road network, i.e. dependent on rivers (P < 0.05) **(F)**.

Fig 5: High natural capital and reserve coverage around less-accessible cities. The proportion of original forest remaining (i.e. inverse of deforestation extent) is higher around cities that are (A) remote (P < 0.001) and (B) unconnected to the Amazonian road network (P < 0.001). Remoteness is associated with higher proportional coverage of (C) protected areas (P < 0.01) and (D) indigenous reserves (P < 0.001). The coverage of protected areas (E) and indigenous reserves (F) is not significantly different around road-less and road-connected urban centers.

Table I: The number of urban centers and their inhabitants related to accessibility and social vulnerability. Low and high are defined as above or below the overall mean score for social vulnerability (SocVu) and remoteness (Rem). Also shown is the total number of urban inhabitants (Pop, in thousands) in each category.

SocVu	**Rem**	**Road-connected**			**Partial**			**Road-less**			**Grand total**		
		N	%	Pop 1000s	N	%	Pop 1000s	N	%	Pop 1000s	N	%	Pop 1000s
Low	Low	98	*43*	7,693	4	*29*	161	7	*10*	151	109	35	8,005
Low	High	42	*18*	575	1	*7*	11	2	*3*	70	45	15	656
High	Low	65	*29*	857	7	*50*	66	25	*37*	274	97	31	1,198
High	High	23	*10*	283	2	*14*	19	34	*50*	419	59	19	721
Total		**228**	***100***	**9,408**	**14**	***100***	**256**	**68**	***100***	**915**	**310**	**100**	**10,579**

Table II: Results of statistical models assessing the relationships between urban accessibility and indicators of social sensitivity, adaptive capacity deficit, food system sensitivity and environmental measures. Road-less coefficients are compared to being road-connected. Significant ($p<0.05$) state effects in relation to Acre (control group) are shown. Letters relate to Rondonia (RO); Roraima (RR); Pará (PA); Amapá (AP); Amazonas (AM).

	Remoteness					Connectivity (Road-less)				Compared to Acre	
Model	**R2**	**coeff**	**SE**	**t**	**p**	**coeff**	**SE**	**t**	**p**	**Better***	**Worse***
Sensitivity models											
sensitivity score	0.32	0.58	0.21	2.83	**0.0050**	0.55	0.09	6.26	**0.0000**	RO	RR
dependency ratio	0.58	0.18	0.05	3.30	**0.0011**	0.17	0.02	7.12	**0.0000**	PA; RO	AP
no tap water	0.21	2.35	0.56	4.19	**0.0000**	-0.69	0.24	-2.86	**0.0045**	RR	PA; RO
no toilet	0.46	1.46	0.28	5.12	**0.0000**	0.31	0.12	2.57	**0.0107**	ALL	
indigenous people	0.56	4.88	0.65	7.50	**0.0000**	0.98	0.50	1.98	**0.0487**		RR
low birth weight	0.08	0.09	0.15	0.60	0.5504	0.15	0.06	2.41	**0.0164**	RO	(RR)
low education	0.24	0.87	0.17	5.25	**0.0000**	0.25	0.07	3.52	**0.0005**		AM; AP
rurality	0.07	0.21	0.34	0.62	0.5365	0.37	0.14	2.54	**0.0116**	AP; (AM)	
Adaptive capacity deficit models											
adap cap deficit	0.55	1.05	0.23	4.61	**0.0000**	0.51	0.09	5.36	**0.0000**	RO; AM	
low antenatal	0.42	0.73	0.26	2.78	**0.0058**	0.47	0.11	4.15	**0.0000**	AM; PA; RO	
education delay	0.42	0.70	0.26	2.76	**0.0062**	0.39	0.11	3.57	**0.0004**	RO	PA
urban growth	0.1	0.90	0.38	2.36	**0.0191**	0.11	0.17	0.64	0.5209	AM; PA; RO; (RR)	
poverty	0.62	0.08	0.13	0.60	0.5464	0.34	0.05	6.36	**0.0000**	RO	PA
inequality	0.39	0.47	0.09	5.18	**0.0000**	0.08	0.04	2.10	**0.0362**	PA; RO	RR
Food system models											
Imported food prices	0.3	1.47	0.53	2.78	**0.0068**	0.61	0.26	2.35	**0.0209**	AM; PA	
Farinha price	0.24	1.32	0.74	1.80	0.0758	-0.17	0.35	-0.49	0.6235		(PA)
Fish price	0.35	2.76	1.76	1.57	0.1214	-1.12	0.83	-1.36	0.1803	(AM)	(PA)
Manioc production	0.21	-0.22	0.62	-0.35	0.7249	-0.29	0.25	-1.16	0.2461		ALL
Natural capital models											
Forest remaining	0.58	3.15	0.72	4.37	**0.0000**	2.06	0.26	8.00	**0.0000**	AP; RR	PA; RO
Protected areas	0.26	2.70	0.89	3.02	**0.0027**	-0.50	0.53	-0.95	0.3454		AM; PA; (RR)

Indigenous reserves	0.37	5.04	0.69	7.28	**0.0000**	-0.17	0.36	-0.46	0.6440	RR

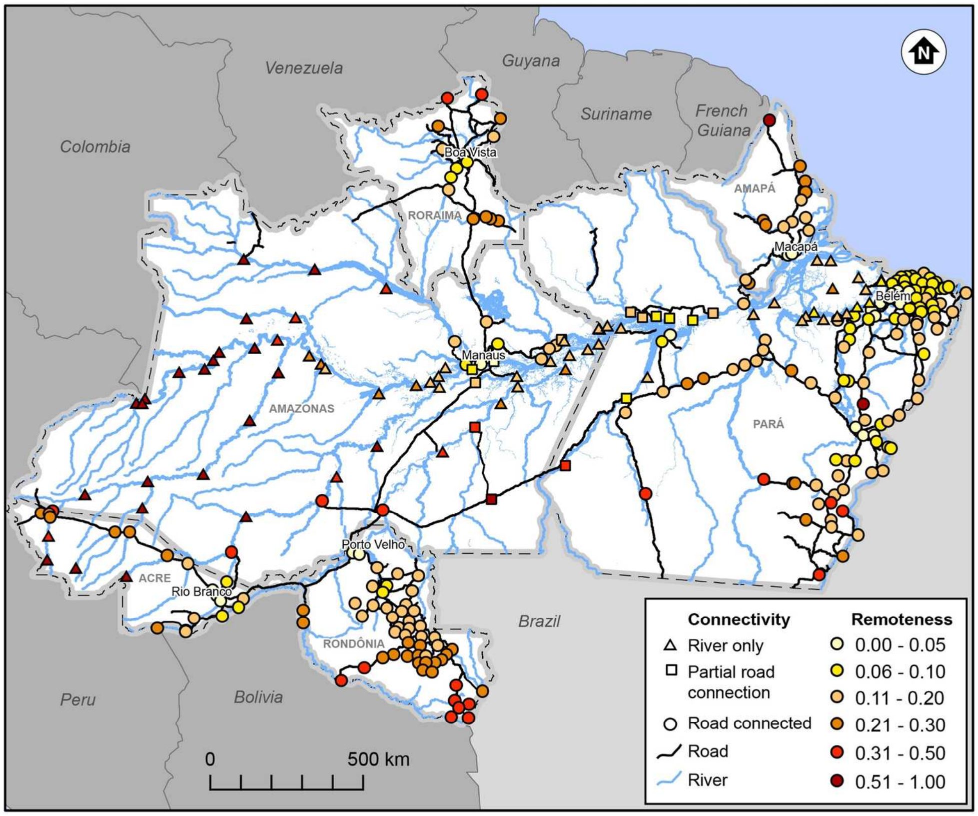

Figure 1: Map illustrating the Brazilian Amazon, road connectivity and remoteness scores of the 310 urban centers included in this study. Also shown is the road network (official and unofficial) and river network. Colored circles indicate the level of remoteness for each urban center.

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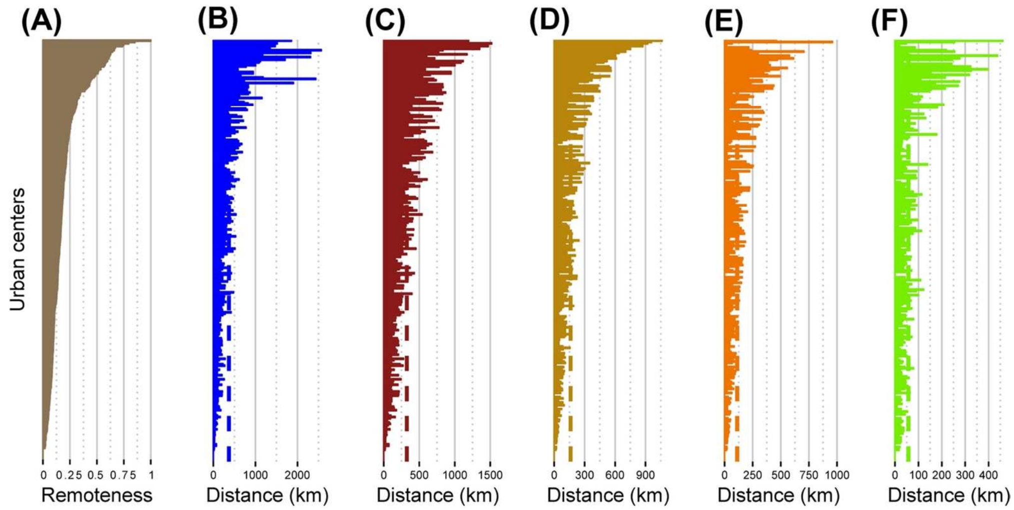

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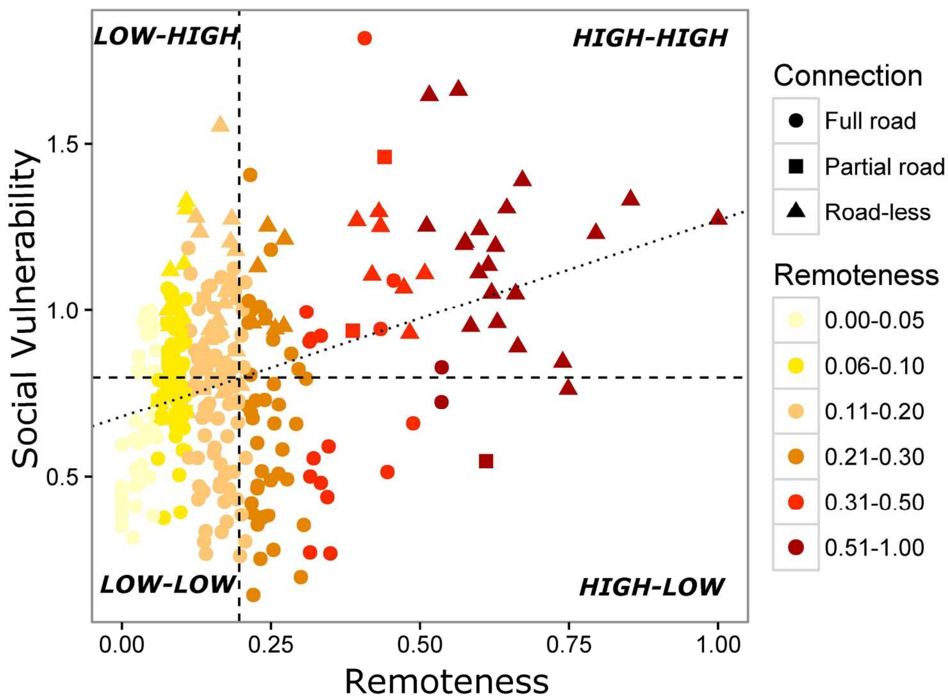

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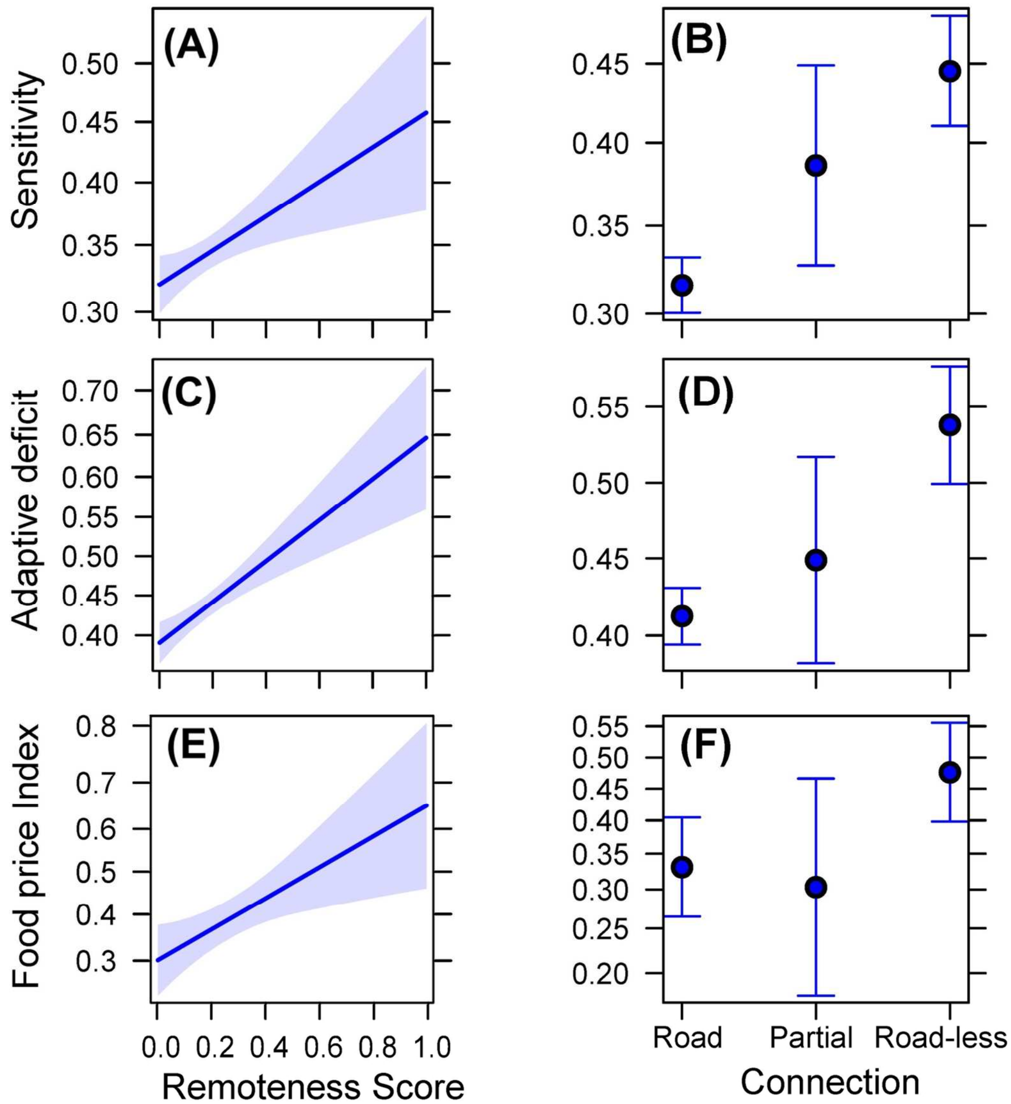

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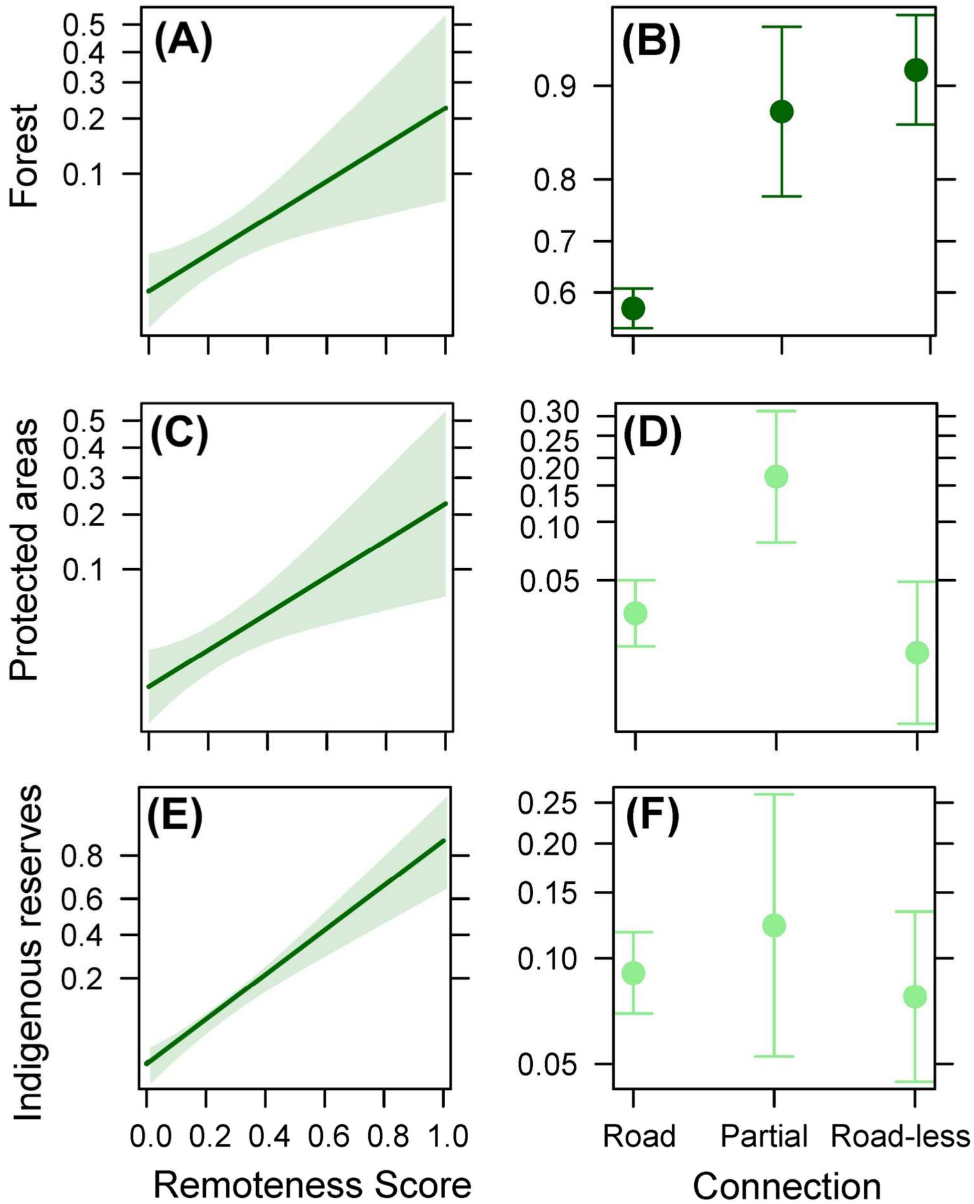

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Supplementary Material for Parry et al,

"Social vulnerability to climatic shocks is shaped by urban accessibility".

1 Context

1.1 Urbanization of the Brazilian Amazon

Although the focus of this paper is not urbanization dynamics *per se*, the historical economic and political forces that shaped urbanization in Amazonia are important for understanding the contemporary urban network(s) as well as intra-regional differences in transport infrastructure, economic activity and culture. These urbanization dynamics have been well-described through decades of scholarship in Latin American geography and Area Studies (Browder and Godfrey 1997, Garcia, Soares-Filho and Sawyer 2007, Guedes, Costa and Brondízio 2009, Costa and Brondízio 2011). By 1980 most people in the Brazilian Amazon lived in urban areas, prompting Becker's (1985) description of an 'urban forest'. As of 2010, three quarters of the region's inhabitants lived in urban areas, ranging from the metropolitan areas of Manaus and Belem (each with around 2.2 million people) to small towns populated by a few thousand people (IBGE 2010). The urbanization of Amazonia was intimately connected with the region's colonization history, which has focused on resource extraction. The underlying driving forces of Amazonian urbanization can be interpreted in various ways. A Marxist explanation is that urbanization plays a key role in the absorption of capital surpluses (Harvey 2008) whereas demographers or economists tend to focus on phases of development, in relation to fertility and migration-decisions, stimulated by economic and social opportunity (Perz 2000). Less contentious is that distinct differences in regional geography in Amazonia resulted from centuries of resource extraction (see Bunker (1989)), which did and still frequently involve the displacement and subordination of indigenous peoples (Guzmán 2013).

Many of the older Amazonian cities began as forts, ports, trading posts for forest products and religious missions during the Portuguese colonial period, or as trading centers for some agricultural commodities in the late 18th Century (Browder and Godfrey 1997). During the rubber boom - from around 1850 to 1920 - new and existing trading centers grew and were linked to rural rubber-tapping settlements as well as urban networks consisting of local, regional and world cities (Dean 1987). The next major phase of Amazonian settlement and urbanization was promoted as national integration and gathered pace in the 1960s. Although Brazil's military government (1964-1985) enthusiastically advanced the 'opening up' of Amazonia, grandiose plans for developing Amazonia began during democratic rule with the ideas of Getulio Vargas in the 1940s and were further developed under Kubitschek's government in the 1950s (Browder and Godfrey 1997). Highway creation was central to development plans yet there were (and are) two quite distinct motivations for improving accessibility to the region. On the one hand, the national government bulldozed new settlement roads and promoted agricultural colonization and migration to the Amazon through tax breaks, assisted agricultural loans and land titles. Populating Amazonia with farmers – and service centers - was perceived to be securing the region from external threats and was also an attempt to alleviate social unrest and landlessness caused by agricultural mechanization in the south of the country, i.e. relieving demographic pressure. The main focus of agricultural expansion was cattle-ranching, and marked the beginning of large-scale deforestation in the Brazilian Amazon. Browder and Godfrey (1997) considered the resulting areas of agricultural colonization to be populist frontiers. On the other hand, there were so-called corporatist frontiers in which large mines served as growth poles for the extraction of iron ore, kaolin, bauxite and gold. The benefits of these export-oriented mining projects such as Carajás were framed around generating migration and new employment – in many cases in brand new cities - and paying off external debt. Mining projects were often accompanied by energy generation projects such as hydro-electric plants, to satisfy the energy demands of refining processes.

Following the opening of new highways in the 1960s and 70s (e.g. the Belém-Brasilia and the Trans Amazonian Highway) many old fluvial cities were linked to the expanding network of road-based settlement (Becker 1985). Linkages led to mixing of cultures and ethnicities and the next itineration of new Amazonian identities, including cattle culture (Hoelle 2014). Prior to this period the Amazonian population consisted largely of the mixed descendants of indigenous people, African slaves and early European colonists and in rural contexts, are known as *caboclos* (Nugent 1993). Over the proceeding decades thousands of kilometers of planned and unplanned roads were built, leading to the advance of the agriculture-forest frontier. New-found accessibility opened up forests to logging, wildcat and large-scale mining and widespread uncontrolled deforestation, the former mainly for cattle pasture. Over half a century agricultural expansion has caused the loss of hundreds of thousands of square kilometers of forest (Wood and Porro 2002, Malhi et al. 2008). Agricultural practices and land-uses have also changed radically, such as in Mato Grosso state, which is now largely deforested, dominated by intensive cattle-ranching and mechanized farming of soy and only 18% of the population live in rural areas (IBGE 2010). The urban network and its socioeconomic and demographic characteristics both reflect and drive the deforestation processes in Amazonia (Wood and Porro 2002).

In Amazonia there are still many cities inaccessible by road, located either in the delta/estuary (see (Mansur et al. 2016)) or inland along the main channel or major tributaries (Costa and Brondízio 2011). There are vast road-less areas in the northern, central and western Brazilian Amazon, where the population is distributed between urban areas, and rural areas including remote sparsely settled sub-tributaries and more densely populated areas along main river channels, particularly in the *várzea* floodplain. The pre-frontier – defined by Parry et al. (2014) as municipalities with at least 90% of their original forest cover – is perhaps the least accessible area in Amazonia yet had also urbanized by the 2000 census. The end of rubber subsidies led to a rural exodus in these areas in the 1970s and 80s. However, the 'emptying' of more remote rural areas through rural-urban migration is on-going (Parry et al. 2010b), partly due to a desire to access education and other urban opportunities (Parry et al. 2010a). The main economic activities in pre-frontier municipalities are fishing, small-scale agriculture and harvesting of non-timber forest products, alongside public employment and welfare contributions. Nevertheless, rural economies in the pre-frontier are also now supported by sustainable development reserves and related institutions. However, non-tribal *caboclos* – many of whom now live in urban centers - have long been marginalized members of Amazonian society (Nugent 1993).

Urbanization of Amazonia has therefore been ‘disarticulated’ – variable in space and time due to differential economic and settlement pressures and histories (Browder and Godfrey 1997). Overall, the Brazilian Amazon had become urbanized by 1980 (IBGE 1980), the culmination of significant urban expansion from the 1950s onwards. Towns and cities grew through rural-urban migration, urban-urban migration and internal population growth (due to more births than deaths, plus population momentum). It is arguable that dividing Amazonian people into binary rural or urban categories is inadequate because it hides the multi-sited nature of many Amazonian household, which adopt complex rural-urban livelihood strategies (Padoch et al. 2008, Parry et al. 2014, Winklerprins 2002). Nevertheless, it is irrefutable that rapid urbanization in the Brazilian Amazon is inextricably linked to a larger urban population and high rates of urban poverty and deprivation. Nearly two decades ago, Browder and Godfrey (1997) contended that urban population growth in ‘rainforest cities’ was not accompanied by sufficient economic growth or local development, resulting in ‘over-urbanization’. They, along with Perz (2000) and Guedes et al (2009), demonstrated how rapid urbanization been accompanied by inadequate provision of basic services such as water and sanitation, rapid shantytown growth and pollution and poor access to social and medical services.

1.2 Extreme climatic events in Amazonia

Seasonal flood pulses follow spatiotemporal patterns of rainfall across the Amazon Basin and are an inherent part of this social-ecological system. The livelihoods and life-ways of rural Amazonians are well adapted to the challenges and opportunities posed by the dry, low-water season and wet, high-water seasons (Harris 2000). Traditionally, rural Amazonians have engaged in floodplain agriculture during low-water-periods because the river beaches provide fertile land following the annual deposition of alluvial sediment, which originates in the Andes. The low-water season was previously also utilized for rubber-tapping to supply global markets although contemporary dry-season extraction is now focused on commercial fishing to supply urban markets in Amazonia and beyond. When river levels are high, traditionally livelihoods focus on upland *terra firme* agriculture – mainly farming bitter manioc - and the harvest of Brazil nuts (*Bertholettia excelsa*). In spite of ingenious adaptations to the seasonally changing environment the rise and fall in river levels also carries inherent risks for those that live along the Amazon and its tributaries (Chibnik 1994). Extreme flooding can make houses uninhabitable, and lead to losses of livestock and annual and perennial crops if located in areas subject to occasional flooding. The rich but risky nature of floodplain resources is thought to have largely restricted pre-Colombian river-settlements to riverine bluffs – the spaces where rivers intersect upland (Denevan 1996). In the Amazon's delta/estuary water level pulses are on much shorter cycles related to tides, and thus the influence of rainfall is much reduced.

Droughts and floods represent a major – and growing – hazard to Amazonian people for several reasons. First, much urban expansion has occurred in areas prone to flooding, and urban environments offer fewer adaptation options than rural settlement, where houses can be dissembled and rebuilt in response to changing hydrology. Second, within urban centers the marginalized poor tend to live in the areas most prone to flooding, combined with low levels of sanitation (Mansur et al. 2016). The health impacts of floods are increased in unsanitary environments (e.g. where households lack clean water or sewerage). Health risks from extreme events include water-borne (e.g. rotaviruses) and insect-borne diseases (e.g. malaria (Anderson et al. 2011) and are greatest for infants and older people. Third, due to urbanization and dietary changes, food security in the Amazonian population is now linked to access to foodstuffs imported from other regions, including frozen chicken, rice and beans (Nardoto et al. 2011). Access to these foodstuffs therefore depends on access to other cities across long-distance and precarious transport networks which are susceptible to both droughts in the case of rivers and floods for road-transport (Szlafsztein 2015, Marengo et al. 2013). Among road-less cities it is perhaps those cities further up the major tributaries which are most exposed to droughts because the river levels upstream are relatively low- and navigation problematic - even in normal dry seasons (L. Parry & N. Filizola, personal observations). The final reason is that extreme hydro-climatic events have become more frequent and severe in the Amazon Basin in recent decades (Marengo et al. 2013).

The occurrence of extreme hydro-climatic events in Amazonia is linked to global climate change and caused by both El Nino events (e.g. 1998 and 2015) and temperature anomalies in the tropical North Atlantic (Marengo et al. 2008). These large-scale climatic processes led to major floods in 2009, 2012 and 2014 and droughts in 2005 and 2010 (Marengo et al. 2013, Marengo et al. 2011). Flood and droughts have major social and environmental impacts across Amazonia. For example, the 2009 flood is estimated to have affected 238,000 people across 38 municipalities (Filizola et al. 2014). Droughts cause widespread forest fires, affecting human health, the environment and economies (Smith et al. 2014, Barlow et al. 2012). Low water levels cut off fishers' access to oxbow lakes and other natural resources and cause mass fish mortality through hypoxia (Marengo et al. 2013). Low water levels can also severely interrupt boat transport such as during the 2005 drought when river levels in some places were 7-8 m below normal (Marengo et al. 2008).

Urban populations across the Amazon region have been subjected to droughts and floods, the latter causing widespread inundation of housing, as well as severe disruption to public services and commerce (Costa and Brondízio 2011, Guedes et al. 2012). Drought exposure is also harmful to the city-dwellers due to exposure to smoke from forest fires and, in the case of road-less cities, severely restricted access to goods and services due to low river levels causing disruption of river transport (Lewis et al. 2011). In Brazil, the Civil Defense (*Defesa Civil*) is responsible for adapting to and coping with natural disasters, in conjunction with municipal governments. This institution has made hundreds of declarations of states of emergency across Amazonia over the past 20 years, prompting the delivery of food, medical care and refuge assistance (Marengo et al. 2013). However, there is an urgent need for improved governance, communication of weather and river forecasts and an early warning system to reduce risk during disasters (Pinho, Marengo and Smith 2015). Consistent with global predictions, extreme climatic events are predicted to become more frequent and severe in Amazonia over coming decades (Field 2012).

2 Additional information on methods

2.1 Conceptualizing urban remoteness

We conceptualize urban remoteness as the outcome of travel distances between an urban center and other cities within a hierarchical urban network. We adopt a hierarchical approach following Christaller's (1966) articulated theory of central places. This theory described a nodal hierarchy consisting of a larger number of smaller population centers surrounding fewer larger centers. Hence, settlement order is positively related to area of influence and negatively related to number of settlements. Christaller posited that urban services are concentrated in the largest centers, which have the greatest potential for attracting economic and social activities and spreading them to surrounding centers. This classical locational model makes several additional assumptions including: consumers favor the nearest market; transport costs are equal in all directions and are proportional to distance; that there is a hierarchy of services according to frequency of use. The area of influence around a given urban center in the network can be seen as a territory which is constituted by interactions among places through flows of resources, people and information (Harvey 1989). Resource flows include capital, services and commodities, and movements of people include migrations and commuting.

2.2 Measuring remoteness within an urban hierarchy

The Amazonian urban network is conceived as a set of functionally articulated, interconnected urban centers with flows along them by roads, rivers or other means of communication (Guedes et al. 2009). Unlike either Christaller's classic geographical study or more recent regional analysis (Guedes et al. 2009), we are not attempting to explain or predict city locations. Instead, we analyze urban location – inter-urban distances - within an existing model of urban networks in Amazonia in order to allow us to estimate inter-urban variance in remoteness. To account for hierarchy, we draw on the urban network developed by Brazilian Institute for Geography and Statistics (IBGE) (2007). They used secondary data and empirical research to quantify dozens of categories of service provision and commerce in urban centers, in addition to transport linkages and flows of people, resources and information between centers. IBGE's data-driven urban hierarchy closely resembles Christaller's theoretical model, consisting of few metropoles (akin to metropolitan areas), and larger numbers of non-metropole (smaller) state capitals; sub-regional centers; zonal centers and lastly, local centers. We consider that using IBGE's hierarchy is preferable to assuming a fixed relationship between urban importance and population size, which is insufficient to explain infrastructure and service provision (Guedes et al. 2009). Although higher-order cities tend to have larger populations (Table S1) the relationship is variable due to the complex influences of history, politics and regional geographies. We draw only on those parts of IBGE's network that overlap with our study area. In this study we follow the official Brazilian definition of urban and rural, following the classification of the IBGE. In Brazil, an urban center is normally always the administrative center for a particular municipality (of the same name) which includes the urban area and a surrounding area of influence.

The IBGE urban network is broadly compatible with other attempts to categorize urban hierarchies in the Brazilian Amazon. Browder and Godfrey (1997) argued that urbanization in Amazonia had followed a disarticulated pattern, yet they recognized the negative relationship between hierarchy-order and number of settlements. Furthermore, the intra-regional distinctions they made in terms of diverse frontiers and urban linkages are congruent with the IBGE model for Amazonia, which is actually a number of different networks connecting either to metropoles in Amazonia (Manaus and Belém) or outside (Brasilia). Guedes et al (2009) attempted to incorporate rural settlements into their hierarchy and it cannot therefore be directly compared to the IBGE model, although their finding of local hierarchies around sub-regional centers holds true. Finally, the IBGE model is consistent with Garcia et al's (2007) urban hierarchy model for the Brazilian Amazon. They used a gravity model – which attempts to explain and predict the extent of spatial interaction according to population size, distance and other variables - and found a nested spatial pattern of municipalities, unconstrained by state boundaries. We excluded from our study three states that are in the Legal Amazon because they are partially out of the Amazon biome

(Maranhão, Mato Grosso and Tocantins). We chose the IBGE network due to its consistency with other models and because it is inherently governmental. Our results on vulnerability assessment consequently have greater relevance and potential to influence government policy.

2.3 Our transport network and connectivity assessment

The travel network we developed was based around moving hypothetical cargo and economical passenger travel between different locations and therefore assumed truck transport along roads and ferry-boat-size transport along rivers. The road transport element was based on a road network developed from satellite imagery from 2010 by the Amazon Institute of Man and Environment. This layer included both unofficial roads (nearly always unpaved dirt roads) and official public roads (sometimes paved). For river navigation we constructed a river-transport network by combining different hydrological layers from IBGE. We used Google Earth imagery to identify whether river crossings involved bridges or boats.

2.3.1 Calculating travel distances between cities

All distances were calculating used the Network Analyst extension in ArcGIS 10.1. Our method for calculating travel distances between cities allowed for a mixed transport option in which cargo could be moved from a truck to a boat (or vice versa) although we included a 50 km distance 'penalty' in these cases due to the costs time and loading costs of switching. We have not attempted to estimate travel time between cities due to the highly variable speeds, which are dependent on either boat-type (L.P. unpublished data) or road-paving and seasonal rainfall, which affects road-conditions and river-levels, currents and navigability.

2.3.2 Calculating remoteness scores

For each urban center we estimated a standardized remoteness score (0.0 to 1.0) and applied weightings of 0.5 for proximity to major centers, 0.25 relating to proximity to a sub-regional center, 0.15 to the nearest zone center and 0.10 to the nearest local center (Table S1). Lower-order centers were more numerous than higher-order centers (Table S1). We gave higher weighting for remoteness from higher order cities, following the theoretical and empirical evidence described above and the following assumptions: (i) interactions with higher-order cities are relatively more important than smaller centers due to the clustering of services and commerce; (ii) interactions are stronger when cities are closer (i.e. less remote from one another); (iii) when considering the remoteness of a given urban center, its own hierarchy-order is also relevant because a well-serviced urban center will depend less on service provision from other urban areas. (iv) Potential linkages to any state capital are relevant but distance to your own state capital is uniquely important due to the centralized nature of many government services. (v) Sub-regional centers are analogous to the medium-sized nodes described in (Guedes et al. 2009) and are considered to be important within our network. Because there are only two 'metropoles' in the Brazilian Amazon we created 'regional centers' as a single large city category from metropoles and state capitals. Cities in the southern part of our study area interact with Brasilia so it would be misleading to 'penalize' cities in Acre and elsewhere for the distance to Manaus or Belem. If the distance to a higher-order urban center was less than to a lower-order urban center we used the former.

2.4 Additional information on estimating sensitivity and adaptive capacity

Indicators are generally used as proxies in vulnerability assessment because its dimensions cannot be directly measured (Hinkel 2011) and/or because data for more precise measures of sensitivity and adaptive capacity are often unavailable (de Sherbinin 2014). As a prelude for our quantitative vulnerability assessment we first defined (Füssel 2007), (i) our system of analysis (the Brazilian Amazon); (ii) attributes of concern (urban populations); (iii) the external hazard (floods and droughts, albeit their threat is used only implicitly in our selection of vulnerability indicators), (iv) a temporal reference (the recent past, considering 2010 as a period with optimal data availability). We focus on current rather than future vulnerability due to the huge challenge of accurately predicting extreme events (de Sherbinin 2014) and the difficulty of devising realistic future measures of sensitivity and adaptive capacity (Preston, Yuen and Westaway 2011). In addition to conceptual framing and decisions regarding temporal and spatial scales, an important aspect of vulnerability assessment is the selection of indicators, including how they represent system characteristics and how they are weighed and aggregated (Eakin and Luers 2006). Our chosen six indicators of social sensitivity, with justification were:

(a) Demography (Cutter, Boruff and Shirley 2003, Revi et al. 2014); our chosen measure was the young dependency ratio because a high burden of childcare reduces women's income-earning opportunities and may also be related to a high risk of food insecurity.

(b) Sanitation ((Brooks, Adger and Kelly 2005); lacking tapped water, private toilet access). Poor sanitation causes pollution and untreated sewage is a major problem in Amazonian cities (Perz 2000). Tapped water is important for avoiding contamination and thus closely linked to health (Perz 2000).

(c) Ethnicity (Cutter et al. 2003); we used indigenous people because within Amazonia they have been historically oppressed and marginalized (Guzmán 2013).

(d) Health (Tol and Yohe 2007); although their study was exclusively on adaptive capacity we interpret health status as a sensitivity measure; low birth weight [<2500g]. Low birth weight is a proxy and crude measure of newborn health and indicative of maternal health and nutrition (Kramer 1987, Christian 2010).

(e) Education (Brooks et al. 2005); adults without completed elementary school.

(f) Rurality (rural population). We considered this important because cities provide goods and services to their rural hinterland, and urban services and households may come under additional stress if there is a relatively large rural population exposed to the same climate shock (e.g. distress migration) (Brooks et al. 2005, Stephenson, Newman and Mayhew 2010).

We identified four key elements indicative of adaptive capacity;

(i) Healthcare provision (Gasper, Blohm and Ruth 2011); we measured this using the prevalence of low antenatal care.

(ii) Education provision (Cutter et al. 2003); educational delays among school-age children.

(iii) Urban population growth (Stephenson et al. 2010, Gasper et al. 2011): rapid population growth erodes adaptive capacity and increases population sensitivity to climate change by endangering development, provision of basic services, and stalling poverty eradication.

(iv) Poverty (de Sherbinin 2014, Posey 2009, Gasper et al. 2011), including income-poverty prevalence (proportion of households living in absolute poverty, as defined by the Brazilian government) and income inequality. Income poverty is related to household capacity to access safe, nutritious food, healthcare, and shelter when exposed to hazards (Perz 2000). Income inequality is associated with multiple forms of harm ((Wilkinson and Pickett 2010): including negative physical and mental health, based on worldwide evidence, including from Brazil (Lynch et al. 2000).

We did not apply weighting to different elements due to a lack of strong justification for weighting (Hinkel 2011) and because of uncertainty about the relationships between indicators (Tate 2012). For example, it would be uninformative to give different weightings to the young dependency ratio and sanitation because these variables are linked. There is evidence that children face greater health risks when flood causes the contamination of water supplies (Revi et al. 2014). People with low incomes tend to live in poorer housing with worse infrastructure (Guenni, Cardoso and Ebi 2005, Revi et al. 2014) and thus income poverty also has complex linkages to other indicators. We checked correlations among our chosen predictors and found no correlation greater than 0.61 for sensitivity indicators and 0.66 for adaptive capacity indicators (see Tables S4 and S5), which falls within acceptable levels (see (Cinner et al. 2013)). Further details of units, spatial scale, data ranges and sources are shown in Table S2.

2.5 Additional information on estimating food system sensitivity

The distinction between imported and local foods is important because it is likely that access to these foods is related in different ways to urban accessibility and the susceptibility of food transport networks and food production to extreme events. We consider that imported foodstuffs will be (a) more expensive at all times (i.e. a chronic problem) in remote and road-less cities, due to higher transport costs and lower-scale economies, and (b) relatively more expensive when climate extremes increase travel times and journey costs (i.e. an acute problem), whether through low-water levels affecting fluvial transport, or flood conditions affecting road transport. The chronic problem we posit is supported by evidence that food prices (and therefore, purchasing parity) can vary a lot within countries (Kanbur and Venables 2005). The acute problem proposed is supported by anecdotal evidence that during Amazonia droughts low water levels can severely disrupt navigation (Lewis et al. 2011), leading to longer journey times and higher transport costs or local food shortages. Given that we used a one-time only cross-sectional survey of food prices across Amazonia, we are not able to determine the influence of seasonality (i.e. acute influences) on imported food access and are limited to discussing chronic effects of accessibility. Regarding 'local' foods, we recognize that these foods are in fact traded widely across Amazonia and hypothesize that prices are generally lower in less-accessible cities because they are further from regional centers, where the demand from larger, wealthier populations is likely to push up prices.

Telephone numbers for mini-markets, and supermarkets were extracted from online telephone catalogues and through our network of contacts. Data were collected in July and August 2014. The food items whose prices we analyze in this paper are also sold in quantifiable and consistent units unlike, for example, bread or most fruits and vegetables . We also surveyed the price of beans but excluded these from analyses because the availability of locally-produced and imported varieties varied by municipality. In most cases we surveyed two shops per urban center and did our analysis using the average price for each item. We chose not to combine imported and local food prices into a single 'food sensitivity index' because we hypothesize different relationships with respect to remoteness and connectivity. Data on *per capita* manioc production was calculated for by dividing the municipal production for 2010 (based on the Municipal Agricultural Production database) by the total municipal population in 2010 (IBGE 2010).

2.6 Further information on statistical analysis

In exploratory analysis we included control variables for coastal/estuarine location (0/1) and international frontier (0/1). As neither were significant nor were related to our hypotheses, these were not included in our main models. Moreover, the road-less category of cities included coastal cities and cities in the Amazon Delta Estuary, for which a riverine or coastal distinction becomes blurred.

We chose not to use urban population size as an underlying predictor of vulnerability. Urban population size is correlated with remoteness score (correlation = 0.17, $p<0.05$) but not with connectivity. Importantly, we consider that urban population size may have a complex relationship with vulnerability, because on the one hand, rapid population growth can drive vulnerability yet on the other hand, growth may eventually cause a larger population (with more internal service provision) to be relatively more accessible to other centers in the urban network.

In six cases (urban population growth rate; low antenatal care and educational delay; social sensitivity score, adaptive capacity score and imported food price index) we first normalized the dependent variable and then used a quasi-binomial error structure. Per capita manioc production was heavily-left skewed (i.e. low in many places and high in relatively few places) so a quasi-poisson error structure was fitted. We used untransformed data and a Gaussian error structure for the price models of toasted manioc and the cheapest available fish.

Most of the outcome variables we modelled were specific to the urban populations of each municipality. This was possible because we were able to scrutinize the 2010 socioeconomic census data (from IBGE) at the level of census sector and thus summarize indicators for all the urban sectors in municipality. However, for several measures of sensitivity (low birth-weight and low adult education) and adaptive capacity (antenatal consultations, educational delay) we had only municipal-scale data. Because these variables may vary significantly between rural and urban Amazonian populations, we first checked for a potential urbanization bias by running linear models of each measure against urbanization rate (proportion of municipal population residing in the urban center). For all measures other than low-birth weight, urbanization was a significant predictor of the outcome. Therefore, we used the residuals from the urbanization model as our vulnerability indicator. In other words, we question if these vulnerability indicators in a given municipality are relatively high or level, given the level of urbanization.

To avoid creating separate models (and therefore increasing the risk of Type I error) for each of the imported foods we modelled only the imported price index by first normalizing prices of each of the five foods to create an aggregate score (0.0 to 5.0). We normalized this score and then modelled using a quasi-binomial error structure. For the imported foodstuffs we normalized the price of each for the 88 cities where we had full price data and combined into an un-weighted price index. We had fewer prices for fish (n=69 cities) than manioc flour (n=97 cities) so we analyzed data separately.

Note that for our three models of environmental measures (coverage of original forest; fully protected areas and indigenous reserves) we do not assume causal relationships with remoteness and connectivity and thus interpret outputs in terms of correlative associations.

3 Elaboration of results

Accessibility results: The median population size of all three categories of inter-urban connectivity was ten thousand inhabitants, although the most populous road-connected city (1.79 million people; Manaus) was much larger than those of partially-connected (71 and 70 thousand people, respectively). The most remote city referred to the in main text, Itamariti, has 4,472 inhabitants and is located on the River Juruá. In addition to being 1,856 km travel distance from its own state capital, Itamariti is 1,195 km from any regional center, 1,063 km from its nearest sub-regional center and 461 km travel from either the nearest zonal center or local center. Urban centers tended to be much closer to the nearest small-center (e.g. mean travel distance to a local center = 57 km) than the nearest regional center (mean = 323 km) (Figure S2). The most remote decile (n=31) of urban centers was mainly road-less (n = 24) but included two urban centers with partial road connections and five fully road-connected urban centers.

Additional descriptive results related to mean values across the study area: The 59,295 indigenous people living in urban centers equate to just 0.6% of the region's urban population (mean = 1 %). On average, nearly half (48 %) of children (6-14 years old) were in a school grade below that expected for their age. Urban centers had also grown rapidly, by an average of 47 % in the decade to 2010. However, nearly a half (n = 144 or 46 %) of municipalities have not yet urbanized (i.e. majority of people still living in rural area). Urban income poverty is high: on average, 48 % of city-dwellers were living in 'absolute' (as opposed to extreme) per capita poverty (≤ R$255 per month in 2010, or US$3.65/day/person), and income inequality was also high (mean GINI score of 0.58).

Social sensitivity and adaptive capacity models: Urban centers in Rondonia were – compared to Acre - less sensitive whereas urban centers in Roraima were more sensitive. Urban centers in Rondonia and Amazonas had greater adaptive capacity (i.e. smaller deficits) than those in Acre. Four of the five cities with the greatest deficits in adaptive capacity were road-less (Santa Rosa do Purus and Jordão in Acre; São Paulo de Olivença in Amazonas, Chaves in Pará) and one road-connected, Uiramutã. The five cities with the highest social sensitivity to shocks are two road-connected cities in Roraima (Uiramutã and Amajari), two road-less cities (Jordão in Acre and Santa Isabel do Rio Negro) in Amazonas and Jacareacanga, and a partially road-connected city in Pará State. Examples of low social sensitivity in road-less urban centers are Salvaterra and Soure, both tourist centers on Marajó Island, Pará. Among the most remote urban centers there are examples of low social sensitivity, including two international-border cities (Tabatinga and Oiapoque) and two urban centers in southern Pará (Jacundá and Novo Progresso).

Food prices: The price of imported foods was significantly higher in Acre than in Amazonas or Pará. The region's staple carbohydrate, toasted manioc flour was more expensive in remote urban centers and cheaper in Pará than in Acre (the control), at $p<0.10$.

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Supplementary Figures

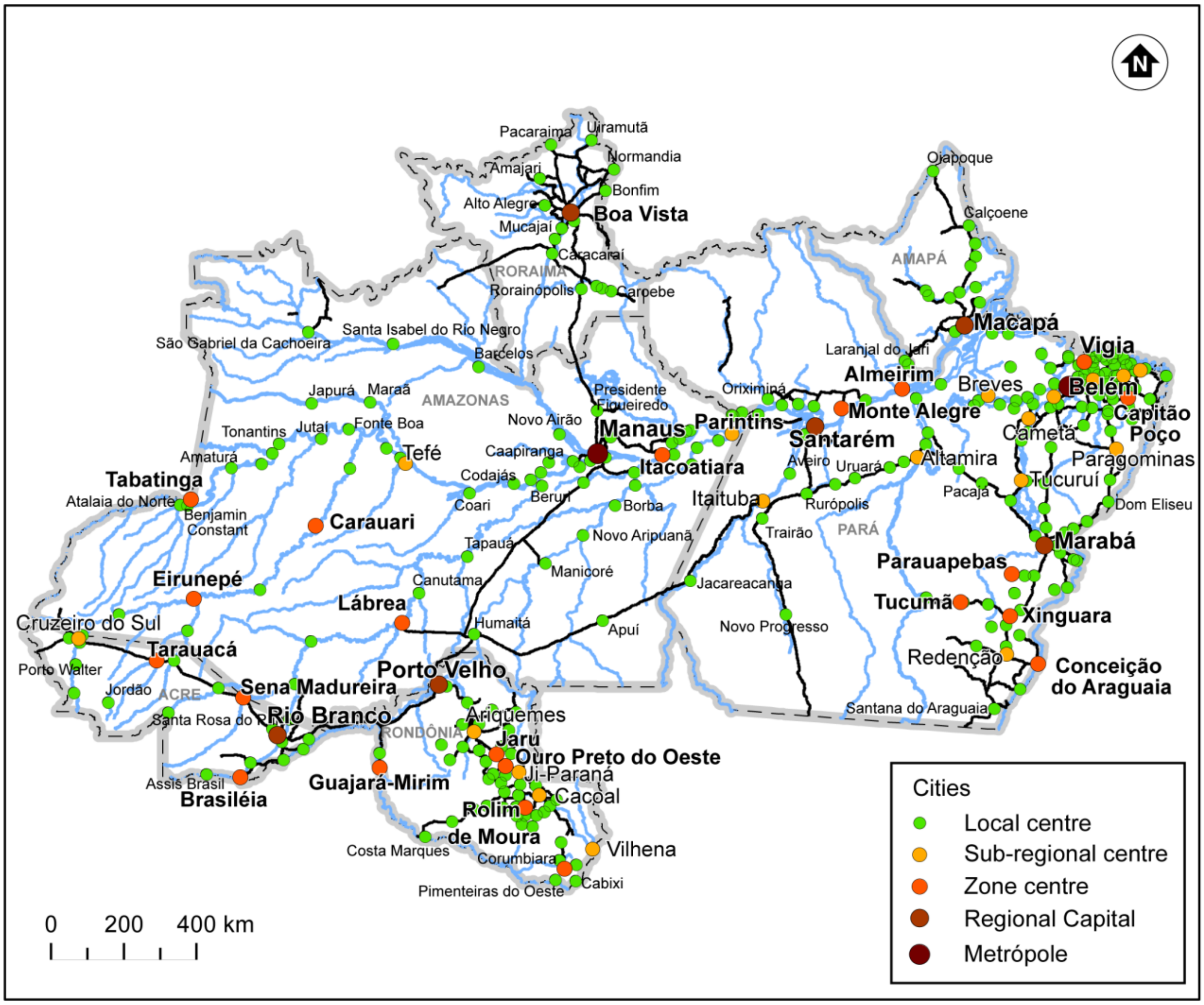

Figure S1: Map of the urban hierarchy in the Brazilian Amazon. Based on the classifications of the Brazilian Institute of Geography and Statistics (IBGE 2007) and illustrated alongside the road network (major roads show in black) and river transport network (major rivers shown in blue).

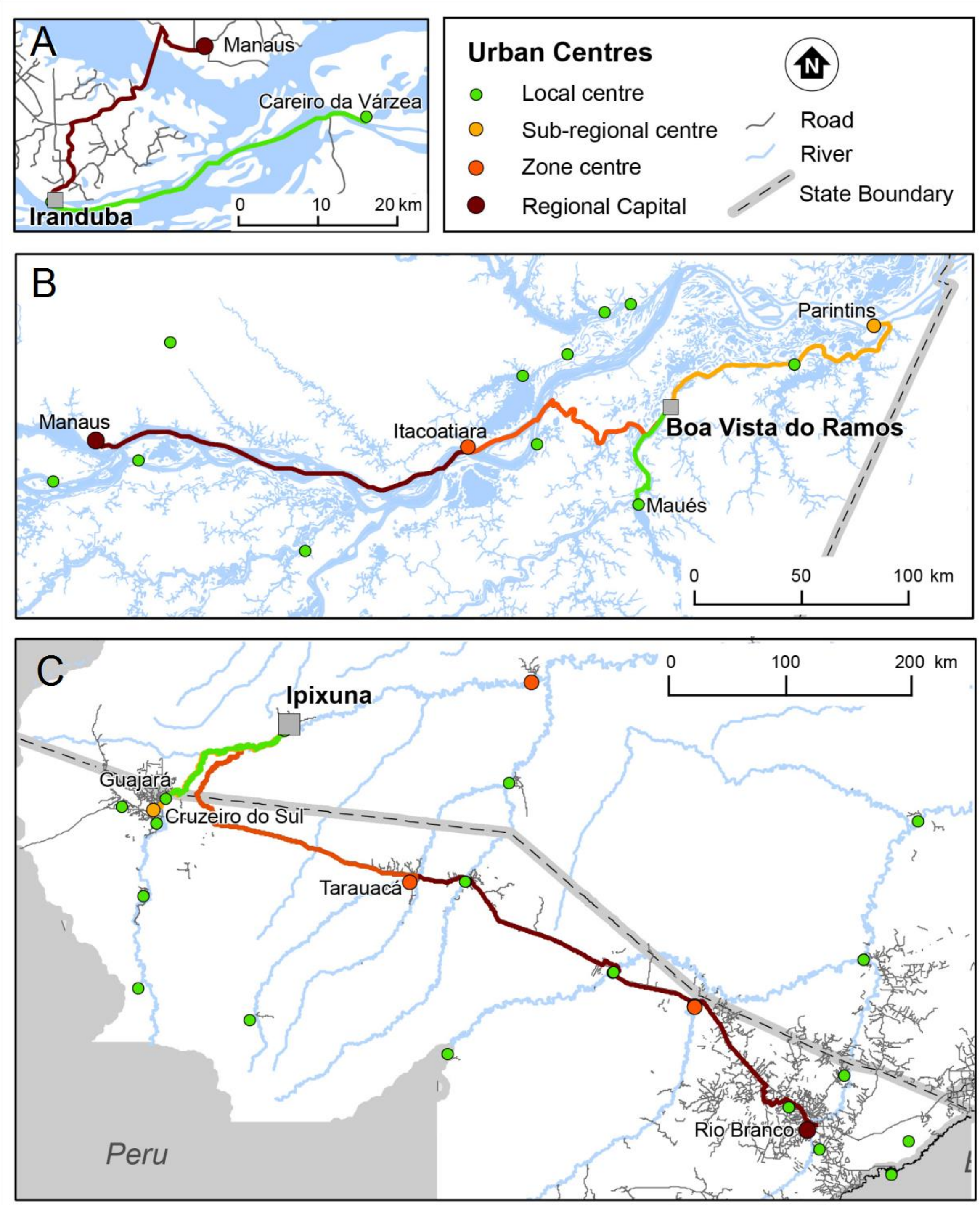

Figure S2: Exemplar travel routes connecting urban centers to other centers in the hierarchical urban network. Routes shown are from (A) Iranduba; (B) Boa Vista dos Ramos, and (C) Ipixuna.

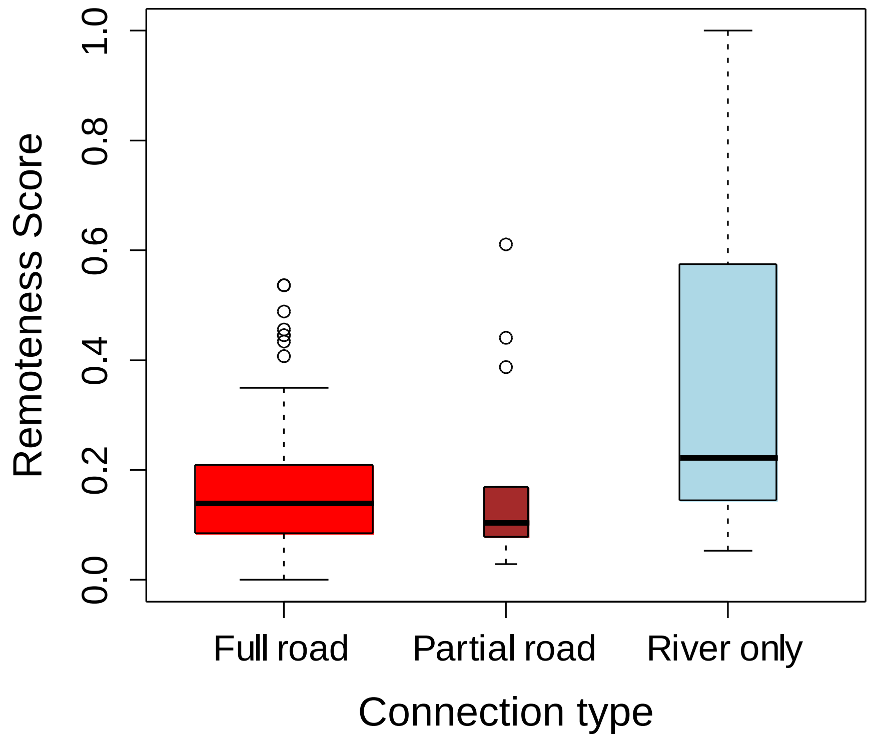

Figure S3: Boxplots of connectivity against remoteness for 310 urban centers. Remoteness is the sum of travel distances to different categories of urban center, weighted for their position in the urban hierarchy. Box widths represent the number of cities in each category. Road-less cities are significantly more remote than road-less cities ($DF = 307$, $R^2 = 0.21$, $F = 42.3$, $p < 0.001$).

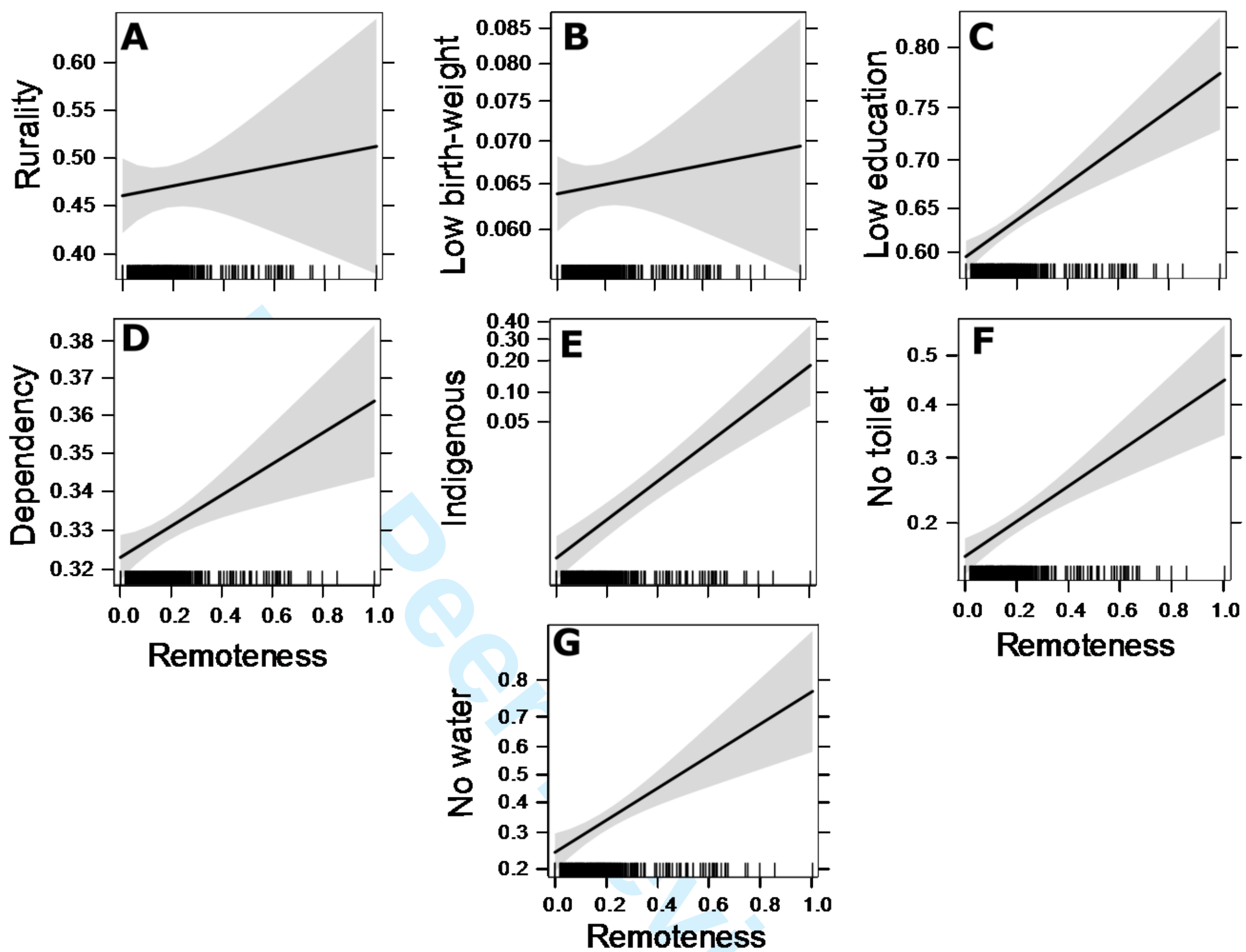

Figure S4: Independent effects of remoteness from other urban centers on measures of social sensitivity to shocks. Remoteness scores are weighted composites of travel distances to other centers in a hierarchical urban network. Graphs are based on statistical models, controlling for co-variates (see Table 2). All indicators are expressed as proportions and include: (A) Rurality in that municipality; (B) Live births < 2500g; (C) Adults with completed elementary education; (D) Youth dependency ratio (< 15 / > 15 years old); (E) Indigenous people in urban population; (F) Households lacking an internal toilet; (G) Households lacking tap water.

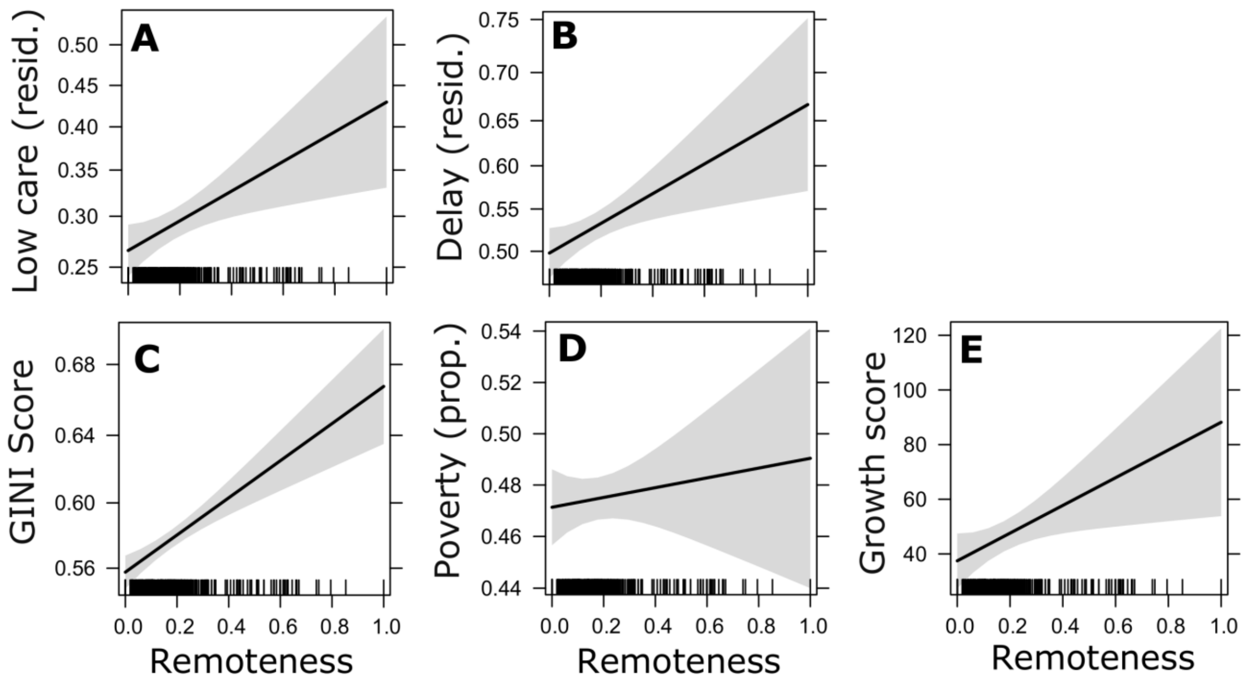

Figure S5: Independent effects of urban remoteness on indicators of adaptive capacity deficits. Remoteness scores are weighted composites of travel distances to other centers in a hierarchical urban network. Graphs are based on statistical models, controlling for co-variates (see Table 2). (A) Prevalence of low antenatal care (residual); (B) Prevalence of educational delays among 15-year olds (residual); (C) GINI score of income inequality in urban households; (D) Prevalence of income poverty (< ½ minimum salary *per capita* per month) in urban households; (E) Urban growth rate 2000-10.

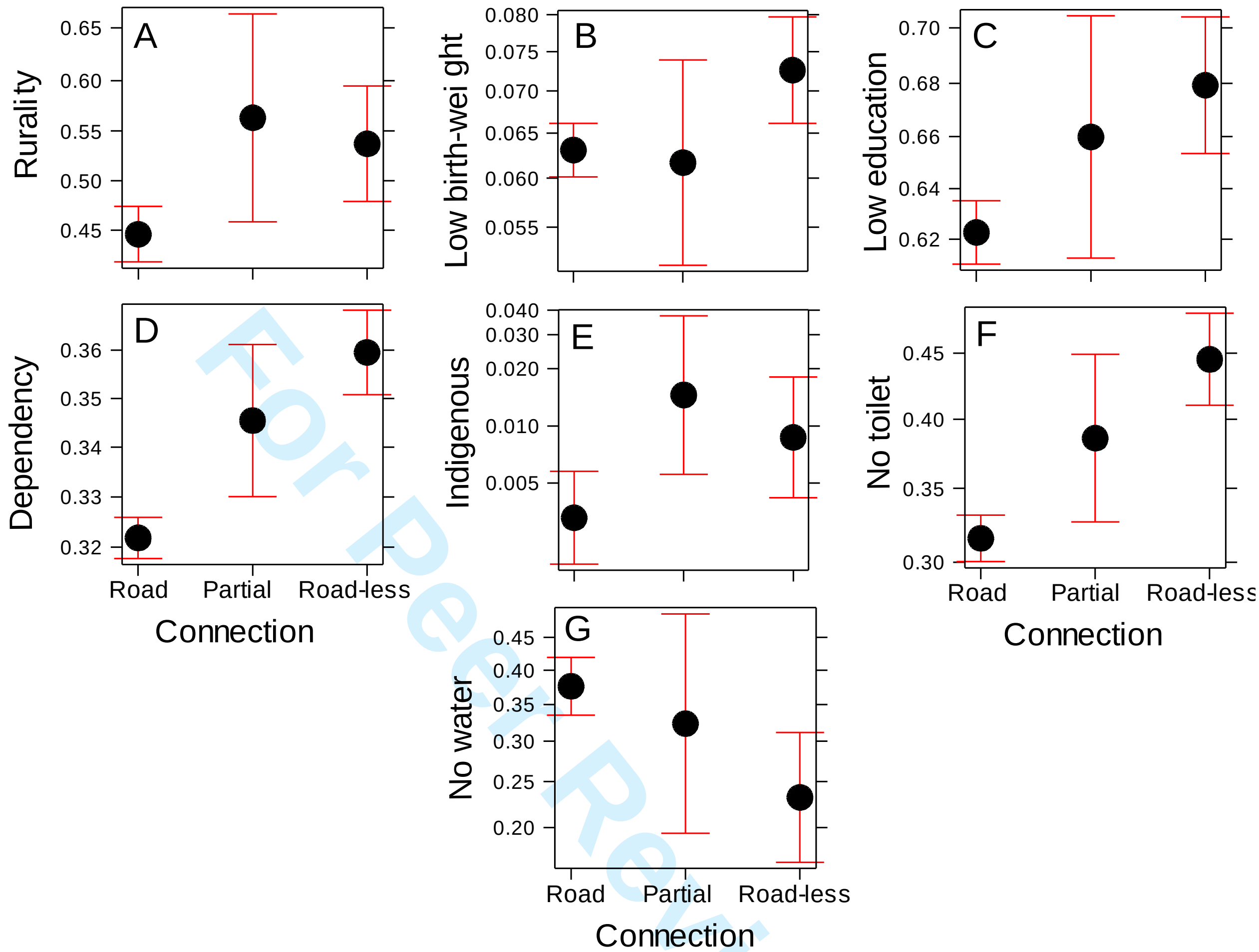

Figure S6: Independent effect effects of urban connectivity (road connected or not) on indicators of social sensitivity to shocks. Graphs are based on statistical models, controlling for co-variates (see Table 2). All indicators are expressed as proportions and: (A) Rurality in that municipality; (B) Live births < 2500g; (C) Adults with completed elementary education; (D) Youth dependency ratio (< 15 / > 15 years old); (E) Indigenous people in urban population; (F) Households lacking an internal toilet; (G) Households lacking tap water.

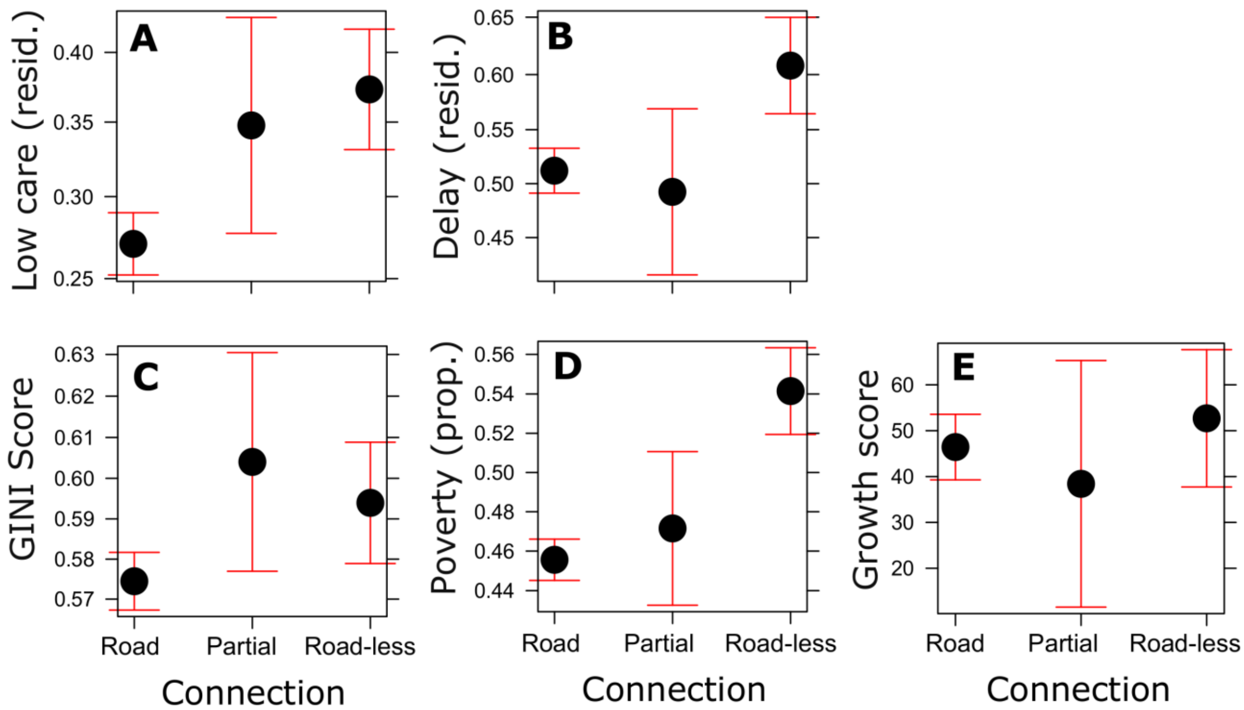

Figure S7: Independent effects of urban connectivity (road connected or not) on indicators of adaptive capacity deficits. (A) Prevalence of low antenatal care (residual); (B) Prevalence of educational delays among 15-year olds (residual); (C) GINI score of income inequality in urban households; (D) Prevalence of income poverty (< ½ minimum salary *per capita* per month) in urban households; (E) Urban growth rate 2000-10.

Table S1: Levels in the urban hierarchy used for calculating remoteness scores. Scores (0.0 to 1.0) are based on inter-urban travel distances weighted by the position of different cities in a hierarchical urban network.

Order	Center type	N	Weight	Mean pop (1000s)	Mean dist. (km)	Max dist. (km)	Max. distance for an urban center[a] to a destination[b]
1	Regional (own)[1]	-	0.25	2,300 / 265.9	371	2566	Ipixuna[a] to Manaus[b]
2	Regional (any)[1]	13	0.25	2,300 / 265.9	324	1520	Atalaia do Norte[a] to Manaus[b]
3	Sub-regional	18	0.25	74.66	162	1063	Itamariti[a] to Cruzeiro do Sul[b]
4	Zone	21	0.15	33.41	112	959	São Gabriel da Cachoeira[a] to Manaus[3,b]
5	Local	258	0.10	11.07	57	461	Itamariti[a] to Eirunepe[b]

[1] *This category also includes state capitals that are metropoles and larger cities that are not state capitals. Metropoles included towns within the metropolitan area of Belem and Manaus, population each around 2.3 million. The mean population of regional capitals was = 265,900.*

[3] *Manaus is a state capital but happened to be closer than any Zone Center.*

Table S2: Details of vulnerability indicators used in analysis of urban vulnerability. Measures for each element of social sensitivity, adaptive capacity and food system sensitivity are shown, along with their weightings (W). For young dependency ratio, the mean value is equivalent to 3.0 children (< 15 years old) for each 'adult' (≥ 15). We consider indicators of health status (e.g. prevalence of live births < 2500g) and educational attainment (e.g. completed elementary education among adult population) to represent sensitivity whereas the provision of good health-care (e.g. reasonable levels of antenatal care) and good education (e.g. low delays and high pass-rates) reflect adaptive capacity. Residual refers to the residual from an urbanization proportion~predictor model (see Appendix).

Element	W	Measure	Unit	Scale	N	Source	Min	Mean	Max
Dimension: sensitivity									
Demography	1	Young dependency ratio	Proportion	Urban	310	IBGE 2010	0.23	0.33	0.46
Sanitation	0.5	Households lacking tapped water	Proportion	Urban	310	IBGE 2010	0.00	0.36	1.00
Sanitation	0.5	Households lacking toilet	Proportion	Urban	310	IBGE 2010	0.01	0.23	0.73
Ethnicity	1	Indigenous people	Proportion	Urban	310	IBGE 2010	0.00	0.01	0.58
Health	1	Low-birth weight	Proportion	Munic.	310	DATASUS 2010	0.00	0.07	0.20
Education	1	Adults without completed elementary	Residual	Munic.	310	IBGE 2010	0.31	0.64	0.88
Rurality	1	Rural population	Proportion	Munic.	310	IBGE 2010	0.00	0.47	0.96
Dimension: adaptive capacity									
Healthcare prov.	1	Low antenatal care (0 to 3 consultations)	Residual	Munic.	310	DATASUS 2010	0.01	0.21	0.90
Education prov.	1	Educational delay (6-14 year olds)	Residual	Munic.	310	IBGE 2010	0.24	0.48	0.72
Pop. growth	1	Urban growth 2000 to 2010**	Proportion	Urban	310	IBGE 2010	-14.89	47.44	428.20
Poverty	0.5	Absolute poverty prevalance	Proportion	Urban	310	IBGE 2010	0.19	0.48	0.74
Poverty	0.5	Income inequality	GINI score	Munic.	310	IBGE 2010	0.42	0.58	0.80
Dimension: food system sensivity									

Prices	1	Price of 5 key imported foods	Normalized	Urban	88	Parry 2014	1.01	2.10	3.71
Prices	[0.2]	Price of chicken	R$/KG	Urban	88	Parry 2014	2.96	5.56	8.00
Prices	[0.2]	Price of tinned meat	R$/320g	Urban	88	Parry 2014	1.35	3.39	5.69
Prices	[0.2]	Price of spaghetti	R$/500g	Urban	88	Parry 2014	1.50	2.17	3.25
Prices	[0.2]	Price of biscuits	R$/packet	Urban	88	Parry 2014	2.15	2.96	4.99
Prices	[0.2]	Price of rice	R$/KG	Urban	88	Parry 2014	0.99	2.44	4.25
Prices	1	Toasted manioc flour	R$/Litre	Urban	97	Parry 2014	1.63	4.21	8.00
Prices	1	Price of cheapest fish	R$/KG	Urban	69	Parry 2014	2.00	7.36	13.40
Production	1	Per capita manioc production	T/capita/yr	Munic.	310	PAM 2010	0.00	0.81	8.13
Dimension: natural capital									
Forest cover	1	Original forest remaining	Proportion	Munic.	310	PRODES 2010	0.00	0.60	0.99
Protected areas	1	Strictly protected area coverage	Proportion	Munic.	310	MMA 2014	0.00	0.05	0.72
Indigenous reserves	1	Spatial coverage	Proportion	Munic.	310	MMA 2014	0.00	0.12	0.99

*** Based on normalized proportional change.*

Table S3: Exemplar media reports of health impacts from floods and droughts in Amazonas Sate, Brazil, between 2006 and 2015

Event	Date	Place(s)	Health impact(s)	Web link
Flood	14/07/15	Multiple places	Diarrhea (rotaviruses); Hepatitis; Leptospirosis	http://radioagencianacional.ebc.com.br/geral/audio/2015-07/cheias-dos-rios-provocam-aumento-de-doencas-no-amazonas
Flood	02/04/15	Multiple places	Diarrhea (rotaviruses)	http://g1.globo.com/am/amazonas/noticia/2014/04/surto-de-colera-em-municipios-do-amazonas-e-descartado-pela-fvs.html
Flood	06/07/15	Multiple places	Diarrhea (rotaviruses); Hepatitis-A; Leptospirosis	http://portalamazonia.com/noticias-detalhe/saude/diarreia-lidera-ranking-de-doencas-comuns-durante-enchente-no-amazonas/?cHash=656bd4f0b9cb37b4fcdff124bfbc781e
Drought	11/02/16	Rio Negro	Lack of drinking water and supplies	http://g1.globo.com/am/amazonas/noticia/2016/02/estiagem-deixa-3-cidades-do-am-em-alerta-e-ameaca-isolar-comunidades.html
Drought	17/09/10	Multiple places	Lack of drinking water and supplies	http://www1.folha.uol.com.br/cotidiano/800709-com-estiagem-doencas-ameacam-populacao-ribeirinha-no-amazonas.shtml
Drought	11/10/05	Multiple places	Lack of drinking water and supplies	http://www1.folha.uol.com.br/fsp/cotidian/ff1110200513.htm

Table S4: Correlations among normalized measures of social sensitivity indicators. Residuals were used for low birth-weight (< 2500g) and low education because only municipal-scale data were available for these variables.

	No toilet	**No tapped water**	**Young dependency ratio**	**Indigenous people**	**Low birth-weight**	**Adults without elementary education**	**Rurality**
No toilet	100 *	-8.91	-60.84 *	-7.13	-18.63 *	-45.47 *	-10.59
No tapped water	-8.91	100 *	21.89 *	8.02	15.19 *	-20.69 *	7.74
Young dependency ratio	-60.84 *	21.89 *	100 *	28.1 *	16.27 *	32.44 *	21.12 *
Indigenous people	-7.13	8.02	28.1 *	100 *	8.66	-1.75	13.97 *
Low birth-weight	-18.63 *	15.19 *	16.27 *	8.66	100 *	-0.27	0.37
Adults without elementary education	-45.47 *	-20.69 *	32.44 *	-1.75	-0.27	100 *	0.03
Rurality	-10.59	7.74	21.12 *	13.97 *	0.37	0.03	100 *

Table S5: Correlations among normalized measures of indicators of adaptive capacity deficits.

Residuals were used for antenatal care, educational delay and GINI score because only municipal-scale rather than urban-only data were available for these variables.

	Population growth	Low antenatal care	Educational delay	Absolute poverty	GINI score
Population growth	100 *	18.59 *	14.54 *	-0.29	12.46 *
Low antenatal care	18.59 *	100 *	46.64 *	35.44 *	57.21 *
Educational delay	14.54 *	46.64 *	100 *	65.85 *	28.87 *
Absolute poverty	-0.29	35.44 *	65.85 *	100 *	27.94 *
GINI score	12.46 *	57.21 *	28.87 *	27.94 *	100 *

Table S6: Summary data on accessibility measures and social vulnerability score for the 310 urban centers. Includes ranking of geographical remoteness (RRank) and an overall social vulnerability score (SV) (plus ranking [SVRank]) for social sensitivity and adaptive capacity deficit, combined. Travel distances (km) are to; own regional center (D1); any regional center (D2); sub-regional center (D3); zonal center (D4); local center (D5).

Sort	Municipality	UF	Connect	Rem	RRank	D1	D2	D3	D4	D5	SV	SVrank
1	Itamarati	AM	Riv only	1.00	1	1856	1195	1063	461	461	1.27	15
2	São Gabriel da Cachoeira	AM	Riv only	0.85	2	959	959	959	959	255	1.33	8
3	Atalaia do Norte	AM	Riv only	0.80	3	1520	1520	921	67	48	1.23	22
4	Benjamin Constant	AM	Riv only	0.75	4	1472	1472	873	20	20	0.76	174
5	Tabatinga	AM	Riv only	0.74	5	1472	1472	873	0	0	0.84	129
6	São Paulo de Olivença	AM	Riv only	0.67	6	1258	1258	660	215	86	1.39	7
7	Carauari	AM	Riv only	0.66	7	1351	1351	752	0	0	0.89	113
8	Ipixuna	AM	Riv only	0.66	8	2566	834	238	238	219	1.05	54
9	Santa Isabel do Rio Negro	AM	Riv only	0.65	9	705	705	705	705	255	1.31	10
10	Eirunepé	AM	Riv only	0.63	10	2317	772	640	0	0	0.96	78
11	Amaturá	AM	Riv only	0.63	11	1173	1173	574	300	55	1.19	27
12	Tapauá	AM	Riv only	0.62	12	706	605	605	577	438	1.05	53
13	Envira	AM	Riv only	0.61	13	2309	578	445	195	166	1.14	32
14	Apuí	AM	Partial	0.61	14	718	718	613	613	277	0.55	249
15	Pauini	AM	Riv only	0.60	15	1704	469	469	469	245	1.24	20
16	Santo Antônio do Içá	AM	Riv only	0.60	16	1119	1119	521	354	34	1.11	36
17	Tonantins	AM	Riv only	0.59	17	1088	1088	489	387	34	0.95	85
18	Juruá	AM	Riv only	0.58	18	989	989	391	362	243	1.20	25
19	Japurá	AM	Riv only	0.57	19	1003	1003	406	406	171	1.20	26
20	Jordão	AC	Riv only	0.56	20	778	778	540	323	323	1.66	2
21	Oiapoque	AP	Full road	0.54	21	557	557	557	557	298	0.83	137
22	Jacundá	PA	Full road	0.54	22	585	585	483	483	397	0.73	188
23	Santa Rosa do Purus	AC	Riv only	0.52	23	561	561	561	400	325	1.65	3
24	Jutaí	AM	Riv only	0.51	24	947	947	348	348	112	1.25	18
25	Marechal Thaumaturgo	AC	Riv only	0.51	25	949	949	317	317	154	1.11	37
26	Novo Progresso	PA	Full road	0.49	26	656	656	382	382	318	0.66	221
27	Manicoré	AM	Riv only	0.48	27	596	547	547	494	146	0.93	98
28	Canutama	AM	Riv only	0.47	28	1183	457	457	215	215	1.07	47
29	Guajará	AM	Full road	0.46	29	2435	704	19	19	19	1.09	42
30	Costa Marques	RO	Full road	0.45	30	736	736	372	331	111	0.51	255
31	Jacareacanga	PA	Partial	0.44	31	614	614	336	336	276	1.46	5
32	Boca do Acre	AM	Full road	0.43	32	1903	223	223	223	173	0.94	90
33	Maraã	AM	Riv only	0.43	33	831	831	235	235	171	1.25	19
34	Barcelos	AM	Riv only	0.43	34	438	438	438	438	270	1.30	12
35	Fonte Boa	AM	Riv only	0.42	35	835	835	236	236	112	1.11	39
36	Uiramutã	RR	Full road	0.41	36	427	427	427	427	215	1.82	1
37	Porto Walter	AC	Riv only	0.39	37	810	810	178	178	154	1.27	16
38	Novo Aripuanã	AM	Partial	0.39	38	450	450	450	347	146	0.94	92
39	Cabixi	RO	Full road	0.35	39	872	872	130	65	48	0.27	305
40	Pimenteiras do Oeste	RO	Full road	0.35	40	830	830	172	52	52	0.59	238

41	São Francisco do Guaporé	RO	Full road	0.34	41	625	625	261	220	73	0.44	278
42	Rio Maria	PA	Full road	0.33	42	425	425	383	256	116	0.48	265
43	Lábrea	AM	Full road	0.33	43	1155	386	386	0	0	0.92	102
44	Santana do Araguaia	PA	Full road	0.32	44	586	586	205	205	108	0.55	247
45	São Félix do Xingu	PA	Full road	0.32	45	478	478	385	102	102	0.91	104
46	Chupinguaia	RO	Full road	0.32	46	728	728	133	90	75	0.50	261
47	Colorado do Oeste	RO	Full road	0.32	47	827	827	83	43	43	0.27	304
48	Humaitá	AM	Full road	0.31	48	935	208	208	208	208	0.91	108
49	Floresta do Araguaia	PA	Full road	0.31	49	396	396	354	227	116	0.99	70
50	Pacaraima	RR	Full road	0.31	50	318	318	318	318	181	0.80	159
51	Corumbiara	RO	Full road	0.31	51	770	770	121	37	37	0.35	296
52	Cerejeiras	RO	Full road	0.30	52	807	807	121	0	0	0.20	309
53	Calçoene	AP	Full road	0.30	53	340	340	340	340	66	0.82	143
54	Caroebe	RR	Full road	0.29	54	349	349	349	349	25	0.66	223
55	Assis Brasil	AC	Full road	0.28	55	365	365	365	122	122	0.87	119
56	Seringueiras	RO	Full road	0.28	56	554	554	189	148	41	0.49	263
57	Uarini	AM	Riv only	0.27	57	676	676	77	77	50	1.21	23
58	Coari	AM	Riv only	0.27	58	404	404	211	211	131	0.95	86
59	São João da Baliza	RR	Full road	0.27	59	324	324	324	324	17	0.58	240
60	Mâncio Lima	AC	Full road	0.26	60	712	712	42	42	36	0.72	194
61	Parecis	RO	Full road	0.26	61	607	607	134	72	38	0.51	258
62	Borba	AM	Riv only	0.26	62	311	311	311	208	86	0.94	89
63	São Luiz	RR	Full road	0.26	63	307	307	307	307	17	0.66	222
64	Rorainópolis	RR	Full road	0.26	64	293	293	293	293	56	0.78	166
65	Vilhena	RO	Full road	0.25	65	776	776	0	0	0	0.28	303
66	Anapu	PA	Full road	0.25	66	366	366	230	230	78	0.91	106
67	Santa Maria das Barreiras	PA	Full road	0.25	67	509	509	131	96	96	1.18	29
68	Alto Alegre dos Parecis	RO	Full road	0.25	68	583	583	131	55	35	0.49	264
69	São Miguel do Guaporé	RO	Full road	0.25	69	515	515	150	109	41	0.38	289
70	Anajás	PA	Riv only	0.24	70	324	240	219	219	178	1.25	17
71	Feijó	AC	Full road	0.24	71	411	411	279	52	52	0.98	73
72	Codajás	AM	Riv only	0.24	72	274	274	274	274	62	0.97	75
73	Amapá	AP	Full road	0.24	73	275	275	275	275	55	0.73	182
74	Alta Floresta D'Oeste	RO	Full road	0.24	74	563	563	122	46	26	0.38	292
75	Primavera de Rondônia	RO	Full road	0.23	75	599	599	62	62	31	0.52	253
76	São Felipe D'Oeste	RO	Full road	0.23	76	586	586	76	50	31	0.25	308
77	Rodrigues Alves	AC	Full road	0.23	77	675	675	14	14	14	1.01	62
78	Alvarães	AM	Riv only	0.23	78	628	628	29	29	29	1.13	33
79	Serra do Navio	AP	Full road	0.23	79	273	273	273	273	18	0.47	268
80	Espigão D'Oeste	RO	Full road	0.23	80	591	591	54	54	28	0.35	295
81	Nova Brasilândia D'Oeste	RO	Full road	0.23	81	508	508	131	60	37	0.47	273
82	Placas	PA	Full road	0.23	82	265	265	252	252	63	0.60	235
83	Cruzeiro do Sul	AC	Full road	0.22	83	686	686	0	0	0	0.73	184
84	Santa Luzia D'Oeste	RO	Full road	0.22	84	557	557	97	21	21	0.15	310
85	Ourilândia do Norte	PA	Full road	0.22	85	383	383	290	18	18	0.67	214
86	Maués	AM	Riv only	0.22	86	343	343	203	154	62	0.96	80
87	Pimenta Bueno	RO	Full road	0.22	87	580	580	43	43	28	0.39	287
88	Novo Horizonte do Oeste	RO	Full road	0.22	88	538	538	99	26	26	0.42	283
89	Tarauacá	AC	Full road	0.22	89	455	455	232	0	0	1.00	68
90	Uruará	PA	Full road	0.22	90	326	326	189	189	63	0.69	203
91	Guajará-Mirim	RO	Full road	0.22	91	347	347	347	0	0	0.81	152

92	Amajari	RR	Full road	0.22	92	217	217	217	217	139	1.41	6
93	Pedra Branca do Amapari	AP	Full road	0.21	93	254	254	254	254	18	1.03	60
94	Pracuúba	AP	Full road	0.21	94	246	246	246	246	43	0.96	79
95	Nova Mamoré	RO	Full road	0.21	95	303	303	303	49	49	0.71	196
96	Tucumã	PA	Full road	0.21	96	378	378	285	0	0	0.56	245
97	Normandia	RR	Full road	0.21	97	222	222	222	222	94	1.08	43
98	Castanheiras	RO	Full road	0.21	98	503	503	76	54	35	0.30	301
99	Vitória do Jari	AP	Full road	0.20	99	281	281	281	119	23	0.83	135
100	Cumaru do Norte	PA	Full road	0.20	100	408	408	92	92	88	1.00	66
101	Alvorada D'Oeste	RO	Full road	0.20	101	467	467	80	80	30	0.38	288
102	Manoel Urbano	AC	Full road	0.20	102	253	253	253	92	92	0.92	101
103	Tefé	AM	Riv only	0.20	103	610	610	0	0	0	0.78	167
104	Rolim de Moura	RO	Full road	0.20	104	536	536	76	0	0	0.26	307
105	Laranjal do Jari	AP	Full road	0.20	105	267	267	267	118	23	0.73	185
106	Machadinho D'Oeste	RO	Full road	0.19	106	317	317	154	143	63	0.66	220
107	Medicilândia	PA	Full road	0.19	107	431	431	84	84	44	0.72	190
108	Ministro Andreazza	RO	Full road	0.19	108	506	506	36	36	36	0.43	279
109	Anori	AM	Riv only	0.19	109	222	222	222	222	40	0.88	118
110	Boa Vista do Ramos	AM	Riv only	0.19	110	327	327	142	136	62	1.03	58
111	Beruri	AM	Riv only	0.19	111	220	220	220	220	41	1.18	30
112	Pacajá	PA	Full road	0.19	112	288	288	151	151	78	1.06	51
113	Água Azul do Norte	PA	Full road	0.19	113	292	292	200	74	74	0.77	169
114	Goianésia do Pará	PA	Full road	0.19	114	279	279	136	136	114	0.88	114
115	Viseu	PA	Full road	0.19	115	342	342	104	104	92	1.13	34
116	Urupá	RO	Full road	0.19	116	443	443	78	60	29	0.51	254
117	Brasil Novo	PA	Full road	0.19	117	475	475	41	41	41	0.83	138
118	Bannach	PA	Full road	0.18	118	331	331	122	86	86	0.83	136
119	Gurupá	PA	Riv only	0.18	119	384	186	186	112	84	1.27	14
120	Senador José Porfírio	PA	Full road	0.18	120	429	371	91	91	39	1.07	45
121	Porto de Moz	PA	Riv only	0.18	121	340	267	185	68	68	1.21	24
122	Bonfim	RR	Full road	0.18	122	191	191	191	191	94	1.09	41
123	Campo Novo de Rondônia	RO	Full road	0.18	123	327	327	116	116	59	0.72	192
124	Mirante da Serra	RO	Full road	0.18	124	402	402	103	63	19	0.46	274
125	Bonito	PA	Full road	0.18	125	264	264	142	142	85	0.80	156
126	Presidente Médici	RO	Full road	0.18	126	464	464	34	34	34	0.51	257
127	Tartarugalzinho	AP	Full road	0.18	127	203	203	203	203	43	1.06	49
128	Silves	AM	Full road	0.18	128	283	283	204	92	23	0.62	231
129	Cacoal	RO	Full road	0.18	129	537	537	0	0	0	0.36	294
130	Dom Eliseu	PA	Full road	0.18	130	250	250	157	157	61	0.76	177
131	Nova Olinda do Norte	AM	Riv only	0.18	131	226	226	226	123	40	1.06	50
132	Nova União	RO	Full road	0.17	132	411	411	84	44	19	0.51	259
133	Tailândia	PA	Full road	0.17	133	210	210	159	159	97	0.84	130
134	Vitória do Xingu	PA	Full road	0.17	134	458	400	48	48	39	0.83	139
135	Barreirinha	AM	Riv only	0.17	135	396	340	72	72	69	1.02	61
136	Buritis	RO	Full road	0.17	136	301	301	117	117	59	0.42	282
137	Urucará	AM	Riv only	0.17	137	315	315	129	125	15	0.75	178
138	São Sebastião do Uatumã	AM	Partial	0.17	138	305	305	144	115	15	0.81	151
139	Rurópolis	PA	Full road	0.17	139	221	221	147	147	88	0.80	157
140	Teixeirópolis	RO	Full road	0.17	140	421	421	49	33	31	0.33	299
141	Alto Alegre	RR	Full road	0.17	141	167	167	167	167	113	1.10	40
142	Ulianópolis	PA	Full road	0.17	142	310	310	99	99	61	0.93	100

143	Santa Cruz do Arari	PA	Riv only	0.17	143	177	177	177	177	77	0.93	94
144	Conceição do Araguaia	PA	Full road	0.17	144	413	413	102	0	0	0.54	250
145	Chaves	PA	Riv only	0.17	145	528	125	125	125	50	1.55	4
146	Governador Jorge Teixeira	RO	Full road	0.16	146	335	335	121	42	42	0.48	267
147	Vale do Paraíso	RO	Full road	0.16	147	381	381	73	38	38	0.47	271
148	Almeirim	PA	Full road	0.16	148	277	276	243	0	0	0.79	165
149	Anamã	AM	Riv only	0.16	149	185	185	185	185	40	0.97	76
150	Vale do Anari	RO	Full road	0.16	150	301	301	108	80	56	0.67	215
151	Trairão	PA	Full road	0.16	151	338	338	64	64	64	0.79	162
152	Cutias	AP	Full road	0.16	152	174	174	174	174	60	0.93	97
153	Itapiranga	AM	Full road	0.16	153	262	262	172	71	23	0.86	120
154	Altamira	PA	Full road	0.16	154	515	452	0	0	0	0.59	239
155	Canaã dos Carajás	PA	Full road	0.16	155	201	201	201	67	63	0.85	126
156	Nhamundá	AM	Riv only	0.15	156	461	268	87	87	5	0.85	127
157	Nova Esperança do Piriá	PA	Full road	0.15	157	267	267	125	91	45	1.01	63
158	Theobroma	RO	Full road	0.15	158	322	322	117	31	31	0.57	243
159	Urucurituba	AM	Riv only	0.15	159	228	228	208	38	38	0.92	103
160	Cujubim	RO	Full road	0.15	160	236	236	111	111	69	0.80	158
161	Itaubal	AP	Full road	0.15	161	161	161	161	161	63	1.07	44
162	Caapiranga	AM	Riv only	0.15	162	159	159	159	159	65	0.94	91
163	Autazes	AM	Riv only	0.15	163	187	187	187	101	40	0.91	105
164	Piçarra	PA	Full road	0.15	164	168	168	168	152	45	0.72	189
165	Cachoeira do Piriá	PA	Full road	0.14	165	254	254	98	98	49	1.07	46
166	Rondon do Pará	PA	Full road	0.14	166	161	161	161	161	42	0.71	199
167	Terra Santa	PA	Riv only	0.14	167	239	239	111	111	37	0.68	209
168	Pau D'Arco	PA	Full road	0.14	168	368	368	28	28	28	0.69	206
169	Sapucaia	PA	Full road	0.14	169	217	217	180	38	38	0.85	124
170	Xapuri	AC	Full road	0.14	170	174	174	174	72	71	0.82	142
171	São Geraldo do Araguaia	PA	Full road	0.14	171	158	158	158	158	45	0.85	125
172	Ji-Paraná	RO	Full road	0.14	172	430	430	0	0	0	0.27	306
173	Ouro Preto do Oeste	RO	Full road	0.14	173	389	389	45	0	0	0.33	298
174	Brasiléia	AC	Full road	0.14	174	224	224	224	0	0	0.71	198
175	Porto Grande	AP	Full road	0.14	175	156	156	156	156	43	0.70	200
176	Epitaciolândia	AC	Full road	0.14	176	222	222	222	2	2	0.62	228
177	Aveiro	PA	Riv only	0.14	177	170	170	109	109	109	0.83	140
178	Jaru	RO	Full road	0.14	178	337	337	94	0	0	0.30	302
179	Oriximiná	PA	Partial	0.14	179	160	160	149	149	45	0.77	172
180	Prainha	PA	Partial	0.14	180	168	168	168	71	71	1.03	56
181	Cacaulândia	RO	Full road	0.14	181	277	277	64	61	57	0.46	275
182	Tomé-Açu	PA	Full road	0.14	182	166	166	134	134	56	0.77	171
183	Faro	PA	Riv only	0.14	183	272	272	91	91	5	0.89	112
184	Presidente Figueiredo	AM	Full road	0.13	184	125	125	125	125	122	0.68	212
185	Caracaraí	RR	Full road	0.13	185	134	134	134	134	91	0.82	141
186	Afuá	PA	Riv only	0.13	186	479	85	85	85	50	1.24	21
187	Redenção	PA	Full road	0.13	187	396	396	0	0	0	0.47	270
188	Novo Airão	AM	Full road	0.13	188	124	124	124	124	100	1.00	64
189	Monte Negro	RO	Full road	0.13	189	265	265	54	54	54	0.43	280
190	Garrafão do Norte	PA	Full road	0.13	190	222	222	115	46	45	0.85	123
191	Xinguara	PA	Full road	0.13	191	254	254	151	0	0	0.56	246
192	Nova Ipixuna	PA	Full road	0.13	192	131	131	131	131	68	0.81	149
193	Portel	PA	Riv only	0.12	193	299	255	60	60	22	1.28	13

194	Juruti	PA	Riv only	0.12	194	189	189	91	91	60	0.79	164
195	Baião	PA	Full road	0.12	195	243	243	70	70	32	0.88	116
196	Itacoatiara	AM	Full road	0.12	196	191	191	191	0	0	0.76	175
197	Oeiras do Pará	PA	Full road	0.12	197	196	196	91	91	24	1.11	38
198	Novo Repartimento	PA	Full road	0.11	198	181	181	72	72	72	0.94	93
199	Salinópolis	PA	Full road	0.11	199	212	212	68	68	37	0.56	244
200	Ipixuna do Pará	PA	Full road	0.11	200	218	218	54	54	50	1.19	28
201	Parintins	AM	Riv only	0.11	201	422	281	0	0	0	0.69	204
202	Melgaço	PA	Riv only	0.11	202	279	237	40	40	22	1.33	9
203	Bagre	PA	Riv only	0.11	203	224	224	45	45	45	1.30	11
204	Óbidos	PA	Partial	0.11	204	116	116	116	116	45	0.70	202
205	Aurora do Pará	PA	Full road	0.11	205	170	170	102	92	11	1.03	57
206	Itapuã do Oeste	RO	Full road	0.11	206	125	125	90	90	79	0.58	242
207	Maracanã	PA	Full road	0.11	207	162	162	90	90	34	0.90	109
208	Abel Figueiredo	PA	Full road	0.11	208	121	121	121	121	28	0.74	180
209	Concórdia do Pará	PA	Full road	0.11	209	119	119	119	119	29	0.77	173
210	Curralinho	PA	Riv only	0.10	210	176	176	83	83	24	1.14	31
211	Careiro	AM	Partial	0.10	211	110	110	110	110	52	0.94	87
212	Sena Madureira	AC	Full road	0.10	212	167	167	167	0	0	0.77	170
213	Mãe do Rio	PA	Full road	0.10	213	160	160	110	81	11	0.65	225
214	Santa Luzia do Pará	PA	Full road	0.10	214	205	205	49	49	44	0.70	201
215	Ferreira Gomes	AP	Full road	0.10	215	111	111	111	111	43	0.84	131
216	São Sebastião da Boa Vista	PA	Riv only	0.10	216	145	145	82	82	55	0.76	176
217	Curionópolis	PA	Full road	0.10	217	139	139	139	38	30	0.58	241
218	Acrelândia	AC	Full road	0.10	218	113	113	113	113	34	0.83	134
219	Cachoeira do Arari	PA	Riv only	0.10	219	100	100	100	100	72	0.98	74
220	Alto Paraíso	RO	Full road	0.10	220	190	190	51	51	51	0.68	211
221	São João de Pirabas	PA	Full road	0.10	221	197	197	53	53	34	0.93	95
222	Quatipuru	PA	Full road	0.10	222	207	207	47	47	32	0.91	107
223	Rio Crespo	RO	Full road	0.10	223	204	204	42	42	42	0.39	286
224	Primavera	PA	Full road	0.10	224	202	202	47	47	32	0.83	133
225	Mocajuba	PA	Full road	0.10	225	210	210	40	40	32	0.89	111
226	Magalhães Barata	PA	Full road	0.10	226	155	155	85	85	16	0.66	219
227	Parauapebas	PA	Full road	0.10	227	155	155	155	0	0	0.50	260
228	Irituia	PA	Full road	0.10	228	167	167	89	45	23	0.83	132
229	Ourém	PA	Full road	0.10	229	187	187	46	46	44	0.71	197
230	Santarém Novo	PA	Full road	0.10	230	179	179	57	57	34	0.80	155
231	Curuá	PA	Partial	0.09	231	101	101	101	101	46	0.95	84
232	Capitão Poço	PA	Full road	0.09	232	207	207	86	0	0	0.82	144
233	Cantá	RR	Full road	0.09	233	95	95	95	95	52	1.00	65
234	Palestina do Pará	PA	Full road	0.09	234	108	108	108	108	13	0.73	183
235	Itaituba	PA	Partial	0.09	235	278	278	0	0	0	0.68	207
236	Marapanim	PA	Full road	0.09	236	143	143	79	78	21	0.65	224
237	Plácido de Castro	AC	Full road	0.09	237	99	99	99	99	34	0.62	230
238	Eldorado dos Carajás	PA	Full road	0.09	238	110	110	110	67	30	0.82	147
239	Augusto Corrêa	PA	Full road	0.09	239	229	229	18	18	18	0.94	88
240	Paragominas	PA	Full road	0.09	240	270	270	0	0	0	0.74	181
241	Iracema	RR	Full road	0.09	241	93	93	93	93	42	1.03	59
242	Rio Preto da Eva	AM	Full road	0.09	242	79	79	79	79	79	0.86	122
243	São Miguel do Guamá	PA	Full road	0.09	243	145	145	67	67	23	0.81	154
244	Brejo Grande do Araguaia	PA	Full road	0.09	244	100	100	100	100	13	0.77	168

245	Bom Jesus do Tocantins	PA	Full road	0.08	245	94	94	94	94	28	0.79	161
246	Acará	PA	Full road	0.08	246	93	93	93	93	29	1.06	52
247	Breu Branco	PA	Full road	0.08	247	205	205	22	22	22	0.90	110
248	Manacapuru	AM	Full road	0.08	248	84	84	84	84	51	0.81	150
249	Capixaba	AC	Full road	0.08	249	81	81	81	81	60	1.04	55
250	Breves	PA	Riv only	0.08	250	257	243	0	0	0	1.12	35
251	Limoeiro do Ajuru	PA	Full road	0.08	251	138	138	46	46	46	0.96	81
252	Curuçá	PA	Full road	0.08	252	129	129	65	61	23	0.82	145
253	Alenquer	PA	Partial	0.08	253	81	81	81	81	46	0.84	128
254	Tracuateua	PA	Full road	0.08	254	199	199	16	16	16	0.88	117
255	Muaná	PA	Riv only	0.08	255	107	107	55	55	55	1.00	67
256	São Domingos do Capim	PA	Full road	0.08	256	102	102	63	63	47	1.07	48
257	Manaquiri	AM	Partial	0.08	257	80	80	80	80	42	0.96	83
258	São Caetano de Odivelas	PA	Full road	0.07	258	112	112	81	23	23	0.67	213
259	Ariquemes	RO	Full road	0.07	259	215	215	0	0	0	0.37	293
260	Porto Acre	AC	Full road	0.07	260	64	64	64	64	64	0.79	163
261	Bragança	PA	Full road	0.07	261	211	211	0	0	0	0.75	179
262	Tucuruí	PA	Full road	0.07	262	204	204	0	0	0	0.68	208
263	São João da Ponta	PA	Full road	0.07	263	112	112	58	31	23	0.68	210
264	Soure	PA	Riv only	0.07	264	87	87	87	55	3	0.72	193
265	Santa Maria do Pará	PA	Full road	0.07	265	113	113	42	42	28	0.72	195
266	Igarapé-Açu	PA	Full road	0.06	266	113	113	43	43	23	0.67	216
267	Salvaterra	PA	Riv only	0.06	267	85	85	85	52	3	0.73	186
268	Igarapé-Miri	PA	Full road	0.06	268	99	99	44	44	30	0.79	160
269	Monte Alegre	PA	Partial	0.06	269	98	98	98	0	0	0.73	187
270	Nova Timboteua	PA	Full road	0.06	270	138	138	26	26	9	0.55	248
271	Peixe-Boi	PA	Full road	0.06	271	146	146	17	17	9	0.62	232
272	Colares	PA	Full road	0.06	272	74	74	74	26	26	0.72	191
273	Cametá	PA	Full road	0.06	273	176	176	0	0	0	0.88	115
274	Belterra	PA	Full road	0.06	274	53	53	53	53	53	0.67	217
275	Mucajaí	RR	Full road	0.05	275	51	51	51	51	42	0.82	146
276	Ponta de Pedras	PA	Riv only	0.05	276	62	62	43	43	43	0.96	82
277	Vigia	PA	Full road	0.05	277	99	99	69	0	0	0.64	227
278	Capanema	PA	Full road	0.05	278	160	160	0	0	0	0.38	291
279	Terra Alta	PA	Full road	0.05	279	93	93	30	30	25	0.69	205
280	São Domingos do Araguaia	PA	Full road	0.05	280	53	53	53	53	25	0.93	96
281	Bujaru	PA	Full road	0.05	281	53	53	48	48	33	0.81	153
282	Moju	PA	Full road	0.05	282	78	78	28	28	28	1.00	69
283	São Francisco do Pará	PA	Full road	0.05	283	92	92	21	21	21	0.50	262
284	Santo Antônio do Tauá	PA	Full road	0.04	284	62	62	37	37	18	0.62	229
285	São João do Araguaia	PA	Full road	0.04	285	43	43	43	43	25	0.93	99
286	Iranduba	AM	Full road	0.04	286	38	38	38	38	38	0.99	71
287	Inhangapi	PA	Full road	0.04	287	86	86	17	17	17	0.64	226
288	Itupiranga	PA	Full road	0.04	288	38	38	38	38	38	0.99	72
289	Santa Bárbara do Pará	PA	Full road	0.04	289	41	41	41	41	23	0.61	233
290	Mazagão	AP	Full road	0.04	290	34	34	34	34	34	0.97	77
291	Santa Isabel do Pará	PA	Full road	0.03	291	44	44	29	29	18	0.53	251
292	Benevides	PA	Full road	0.03	292	31	31	31	31	14	0.48	266
293	Careiro da Várzea	AM	Partial	0.03	293	26	26	26	26	26	0.82	148
294	Bujari	AC	Full road	0.03	294	26	26	26	26	26	0.86	121
295	Senador Guiomard	AC	Full road	0.03	295	26	26	26	26	26	0.60	236

296	Barcarena	PA	Full road	0.03	296	26	26	26	26	26	0.51	256
297	Candeias do Jamari	RO	Full road	0.02	297	22	22	22	22	22	0.67	218
298	Abaetetuba	PA	Full road	0.02	298	71	71	0	0	0	0.52	252
299	Castanhal	PA	Full road	0.02	299	71	71	0	0	0	0.41	284
300	Marituba	PA	Full road	0.02	300	21	21	21	21	21	0.47	269
301	Santana	AP	Full road	0.02	301	22	22	22	22	12	0.61	234
302	Ananindeua	PA	Full road	0.02	302	17	17	17	17	17	0.32	300
303	Porto Velho	RO	Full road	0.00	306.5	0	0	0	0	0	0.38	290
304	Rio Branco	AC	Full road	0.00	306.5	0	0	0	0	0	0.41	285
305	Manaus	AM	Full road	0.00	306.5	0	0	0	0	0	0.45	276
306	Boa Vista	RR	Full road	0.00	306.5	0	0	0	0	0	0.45	277
307	Belém	PA	Full road	0.00	306.5	0	0	0	0	0	0.35	297
308	Marabá	PA	Full road	0.00	306.5	0	0	0	0	0	0.60	237
309	Santarém	PA	Full road	0.00	306.5	0	0	0	0	0	0.43	281
310	Macapá	AP	Full road	0.00	306.5	0	0	0	0	0	0.47	272