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Transmission lines are an under-acknowledged conservation threat to the Brazilian Amazon

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ABSTRACT

The environmental impacts of energy generation plants, especially those with large dams, have been widely discussed in the Amazon region, but little attention has been paid to the impacts of the associated transmission lines. These impacts are likely to be substantial given the wide geographic extent of the lines and the relatively high forest cover in the traversed areas. Publicly available information about the location and extent of the transmission line network in the Amazon is neither accurate nor current, and its environmental impacts on terrestrial ecosystems have not been assessed on a large scale. This study estimates the scale of the impact of the current and planned transmission and distribution line network using a hand-digitized dataset and the predicted impact area determined from Environmental Impact Assessments.

The Legal Amazon region contains 39,625 km of verified transmission and distribution lines, estimated to directly impact 23,467 km^2 of land. We find that the transmission line network directly impacts double the area flooded by hydroelectric reservoirs in the Legal Amazon. Of the direct impact area, 5.1% is within protected areas and 10.3% overlaps with intact forest. By 2026, the transmission line network is estimated to grow by 37% in the Legal Amazon, increasing the direct impact to forests by 70% and to protected lands by 29%. Transmission lines are impacting enough land to be considered a serious conservation threat and should be treated as such in research and environmental planning in the Amazon region.

1. Introduction

The current model for economic development in the Brazilian Amazon asserts that an expansion of energy infrastructure, including the transmission and distribution line network, is required to support continued economic growth. The energy carried by this network is intended to support a growing human population and anticipated increases in industrial activity and agribusiness within the Amazon itself, as well as in other areas of Brazil and South America. Access to energy is widely acknowledged as an important contributor to development (Johansson and Goldemberg, 2002), both globally (Martínez and Ebenhack, 2008; Pasternak, 2000) and within Brazil (Gómez and Silveira, 2010; Slough et al., 2015). To support this predicted growth in Brazil, the grid of transmission lines, known as the *Sistema Interligado Nacional* (SIN), is projected to increase in length by 46% between 2016 and 2026 (Plano Decenal de Expansao de Energia 2026, 2017). Several large projects are planned in the Legal Amazon. Electrification has many benefits, including poverty alleviation and economic development (Oguah et al., 2015). However, the expansion of the SIN is likely to add to the extensive habitat fragmentation and deforestation already present from other types of development in the Amazon region, particularly given the relatively remote location of some of the planned dams and the relatively high forest cover in the region. Unfortunately, there has been little research on these impacts and, to the best of our knowledge, the impact of the transmission line network has not been adequately evaluated from a conservation perspective.

Much of the planned expansion of the SIN in the Legal Amazon can be attributed to the need to transport energy produced by existing and planned hydroelectric dams. An estimated 79% of planned dams in the Andes-Amazon region will require new transmission line routes (Finer and Jenkins, 2012). New transmission lines are also built to further integrate the existing system by directly connecting cities to each other and to existing power plants. They also provide redundancy in case of emergencies or repairs. Finally, new lines allow energy to be moved around the grid to high demand locations to compensate for variable energy production, such as during low production from dams in the dry season (Prado et al., 2016; Madrigal and Stoft, 2012). Transmission lines are constructed to transport energy from all types of centralized power generation plants, including thermal, wind, biomass, and solar. Therefore, they will continue to be a source of environmental impacts,

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whether energy comes from renewable or non-renewable sources. As such, the existing and expected environmental consequences of their construction warrant a thorough examination, both within the context of infrastructure development, generally, and hydropower expansion, specifically, in the Amazon.

While a large body of literature exists to describe the effects of other types of infrastructure such as roads and dams on Amazonian ecosystems (e.g. Chen et al., 2015; Latrubesse et al., 2017), little research has quantified the impacts of transmission lines specifically in this region. Dias (2013) found that transmission lines stimulated deforestation around a Tucuruí dam transmission line, and McAllister et al. (2001) cautions that transmission lines may impact biodiversity. Furthermore, utility clearings and the opening of access roads have resulted in direct forest loss in some areas and may increase human access to forested areas, resulting in indirect impacts (Pereira, 2014). Environmental Impact Assessments (EIAs) also provide some insight, forecasting loss of vegetation, disturbance to wildlife and birds, erosion, and reduced water quality (Campos, 2011). However, these studies are conducted before construction, and little monitoring occurs afterwards to verify the predictions or to determine whether mitigation attempts were successful.

Despite the paucity of literature on transmission line impacts in the Amazon, we can reasonably expect certain impacts based on studies of forest fragmentation in the Amazon and on transmission line impacts elsewhere in the world. These include habitat loss, altered microclimate and vegetation, and erosion (Alamgir et al., 2017; Goosem, 2007; Laurance et al., 2017; Laurance et al., 2002; Pohlman et al., 2007, 2009). Furthermore, assessments of transmission line impacts to tropical forests in Australia have specifically described the creation of forest islands (Andrews, 1990), erosion and siltation (Andrews, 1990), altered wildlife assemblages, including increased presence of invasive small mammals (Andrews, 1990; Goosem and Marsh, 1997; Goosem, 2007), and warmer and drier microclimate inside and along corridor edges (Pohlman et al., 2007, 2009). Well-maintained corridors also keep plant and animal communities in an early successional state, may provide increased forest access for humans, and aid in the dispersal of invasive species (Andrews, 1990). At a minimum, transmission lines are contributing to the increasing rate of deforestation in the region simply due to the large land area covered by the lines, but probably have additional impacts due to large edge creation and the production of long distance corridors of repeatedly disturbed vegetation.

The direct and indirect impacts from transmission lines have not been considered in major analyses of deforestation in the region (e.g. Godar et al., 2012; Nepstad et al., 2001; Soares-Filho et al., 2006). There are likely two reasons for this. First, accurate maps of current and planned lines are difficult to obtain and verify. Second, the impacts of transmission lines on Amazonian ecosystems have not been quantified, so they are difficult to include in meta-analyses. Instead, Environmental Impact Assessments (EIAs) of transmission lines tend to include estimates of direct and indirect impacts with little information about how these impacts were estimated. Thus, the dearth of research on this topic, especially within the Amazon itself, prevents educated decision-making about energy planning and management in the region.

In this article, we provide the first complete, geographically referenced dataset of transmission and distribution lines in the Legal Amazon and an initial assessment of their impacts. We present an independent, image-based assessment of the current extent of this network and compare it to two government-provided transmission line maps. We characterize the amount of forest and protected areas impacted, and compare the land area impacted by the network to the land area impacted by roads and hydroelectric reservoirs in the region. Finally, we conclude this article with future research directions and pathways to reduce the environmental impact of future transmission line projects.

BOX 1

The current state and future plans for the transmission line system in the Legal Amazon

The power supply in Brazil is predominantly dependent on hydropower, which is vulnerable to drought and changes in seasonal rainfall. Therefore, a highly interconnected transmission system in the country is critical to allow the movement of energy around the country to compensate for changes in production (Prado et al., 2016; Pereira, 2014). The *Empresa de Pesquisa Energética* (EPE), a public energy research company in Brazil, estimates that the SIN will grow by 46% in length across the entire country from 2016 to 2026 (Plano Decenal de Expansao de Energia 2026, 2017). Several projects, in various stages of licensing, are planned to be operational within the Legal Amazon by 2026. These projects include transmission lines that provide energy to more remote communities in the northern states of Pará and Acre, connect Manaus in Amazonas state to Boa Vista in Roraima state, connect the Belo Monte dam directly to southern parts of Brazil, further integrate the Amazon region with the northeast region of Brazil, and to connect the SIN in Brazil with the grids in Bolivia, Guyana, Suriname, and French Guiana (Plano Decenal de Expansao de Energia 2026, 2017). In total, 9231 km of new lines will be built in the northern region and 5082 km will be built in the central-west region (which partly overlaps with the Legal Amazon), all expected to be operational by 2026 (Plano Decenal de Expansao de Energia 2026, 2017). However, these figures do not consider all of the transmission lines that will be built to support new electrical plants (small or large hydropower, geothermal, biomass, etc.) in the Legal Amazon.

A major driver of new transmission lines comes from the construction of hydroelectric dams in the Amazon region. Hydropower currently accounts for 65% of the national installed capacity of the SIN, and 6 new large dams (> 30 MW) and 17 small dams are planned for the Legal Amazon (EPE, 2016; Plano Decenal de Expansao de Energia 2026, 2017). Additionally, one natural gas thermoelectric plant, four solar plants, and one biomass plant are planned in the Legal Amazon (Plano Decenal de Expansao de Energia 2026, 2017). Each new plant typically requires new transmission lines and substations in order to connect it to the grid. Dam sites in Brazil are often far from the location where most of the energy is consumed (e.g., approximately 50% the energy load of the SIN is consumed in the southern region of Brazil (Plano Decenal de Expansao de Energia 2026, 2017)). Due to the vast land area of the Amazon, transporting power from generation sites to centers-of-use often requires hundreds of kilometers of transmission lines. For example, the Madeira transmission system, built to connect the Santo Antonio and Jirau dams to the SIN near São Paulo, is 2375 km, the longest high voltage line in the world (Cardoso et al., 2014). Many of these lines, especially those connecting the remote locations in the Amazon, will cut directly through forested areas. Because the currently available data from government agencies do not include complete and precise location information for all the proposed or completed transmission lines, it has been difficult for independent research to evaluate expected impacts to the region.

2. Methods

2.1. Mapping the transmission line network

To obtain a highly accurate dataset from which to estimate transmission line impacts, the SIN was hand-digitized in ArcGIS by tracing the path of transmission lines detected using 2017 ESRI World Imagery (pixel size varying from 10 to 30 m resolution, depending on the location) (ESRI, 2017). We visually inspected images covering the entire Legal Amazon, starting from publicly available datasets of transmission lines and power generation plants. Once a line was located, it was traced to its origin at a substation or power source. From there, we located and traced other lines that originated at the same source. Since all lines originate at a substation or generation plant, this was an effective way to ensure the entire region was searched. All visible transmission and distribution lines were recorded, regardless of size or voltage, including instances where the lines themselves were visible or only the posts or towers that support the transmission lines were detected. Distribution lines within cities were not typically included, as they were extremely difficult to detect.

2.2. Estimating impact area

Because there are few studies in published or grey literature on the impacts of transmission lines in the Amazon, we relied on estimates of impact areas from 16 EIAs for individual transmission lines (Appendix A). EIAs were found on http://licenciamento.ibama.gov.br/. Brazilian law requires that infrastructure projects of a certain size produce an EIA during the licensing process, which includes an estimate of land area impacted, but does not specify methodology by which to quantify impacts (Resoluçao CONAMA N 001, 1989). The Terms of Reference for construction projects from the licensing agency (*Instituto Brasileiro do Meio Ambiente*, IBAMA) define the impacted area as locations where the environmental resources will be modified by the project in terms of their quality or potential for conservation or exploitation. The direct impact area generally corresponds with the easement range (regulated by the Brazilian Association of Technical Standards via Regulation 5422/85, which includes the mandated minimum distances between obstacles and the transmission line) plus some buffer area that may be disturbed (Campos, 2011). We were unable to find information on how indirect distances were designated, except that the distance of estimated impact is adjusted in some way to account for differences in anthropomorphized vs. natural areas (Belo Monte Transmissora de Energia, 2015). Transmission line EIAs discuss the use of field surveys and thematic maps to assess expected impacts within the direct and indirect impact areas, but do not discuss how the range was designated prior to these studies (Ecology Brasil, 2014; JGP, 2014). To determine the direct and indirect impact area for use in this study, we reviewed the EIAs to determine the buffer area designated as “directly” or “indirectly” impacted for all available projects (Appendix A). Because there was a range of distances presented, we relied on the median distance of 400 m to both sides of the line for the directly impacted area. For the indirect impact area, there was a near-consensus of a 5 km distance to both sides of the line. These distances were applied to the current network dataset and the planned lines dataset (EPE, 2015b) to estimate the land area directly and indirectly impacted by current and planned network (the direct impact was subtracted from the indirect impact area, as the two are cumulative). Where two transmission lines were within the direct or indirect impact buffer of another line, the overlapping impact area was only counted once.

We overlaid with the current and planned transmission line impact areas with maps of forested area (PRODES, 2016) and protected areas and indigenous reserves (FUNAI, 2004; Departamento de Áreas Protegidas, 2016) to determine how much impacted land area fell into these categories.

2.3. Comparisons to other types of infrastructure

In cases where transmission lines strictly follow the road network, their impact may overlap with the impact of the road. Depending on the frequency with which this occurs, ignoring this overlap would arguably lead to an over-estimation of the impact of transmission lines. Thus, the locations where the impact areas of transmission lines do not overlap with those from roads can be considered to have “additional” impact. To find the additional impact, we first determined the direct impact area of the road network by reviewing the twelve available EIAs for road projects in the Legal Amazon (Appendix A). The median distance estimated for the direct impact zone was 1.25 km to both sides of a road. We applied this distance to a government paved road network database (IBGE, 2015) to determine the direct impact area of the road network. The impact area based on the median road buffer was spatially removed from the impact area of the transmission lines to determine the impact area due solely to the transmission lines.

Finally, the flooded reservoir area in the Legal Amazon (from Tucker-Lima et al., 2016) was compared to the direct impact area of transmission line network in order to provide context as to the scale of the impact of the powerline compared to other types of energy infrastructure. When considering the direct impacts to forested areas from a dam, the most straightforward metric to use was the size of the reservoir, since other sources of forest loss from dam construction are more difficult to quantify (Barreto et al., 2011; Lees et al., 2016; McAllister et al., 2001).

2.4. Evaluation of available datasets

We compared three transmission line data sets for the Legal Amazon: our verified dataset (which includes lower-voltage distribution lines, where they were detectable), a dataset available from the EPE website (EPE, 2015a) and a dataset from the Agência Nacional de Energia Elétrica (ANEEL) website (ANEEL, 2016). We were unable to find a public distribution line dataset. The shapefiles were first projected into the same geographic coordinate system, and the total lengths of the datasets were compared. We then created 400 m buffers around each dataset and compared the corresponding direct impact area estimates. We also compared the overlap of these impact zones between datasets, adopting our dataset as the gold standard, given that the geographic locations and presence of the lines were verified through satellite imagery. These two metrics provided a more thorough picture of the completeness and geographic accuracy of each dataset than length alone. For example, these metrics would identify situations where a dataset captured the correct length of lines, but the lines were geographically misplaced or all ran parallel to each other. When comparing the government datasets to our dataset, a government dataset was considered to be accurate and complete if its impact area was of equal size and in the same location as our verified dataset.

3. Results

3.1. The geographic extent of the transmission line network

Based on the verified dataset, which to our knowledge is the most current, geographically accurate dataset, we estimate the overall length of the electrical line network within the Legal Amazon to be 39,625 km (Fig. 1). Current and planned transmission lines are not evenly distributed geographically across the Amazon (Fig. 1, Appendix D). The highest concentration of both current and planned transmission lines occurs in the southern and eastern part of the Legal Amazon, where there is the greatest population density and the greatest number of current dams. A lower density of transmission lines occurs in the northern part of the Amazon, and a large swath of the western Amazon has no current or planned transmission lines. For the whole Legal Amazon, an additional 14,537 km of lines are planned (Fig. 1).

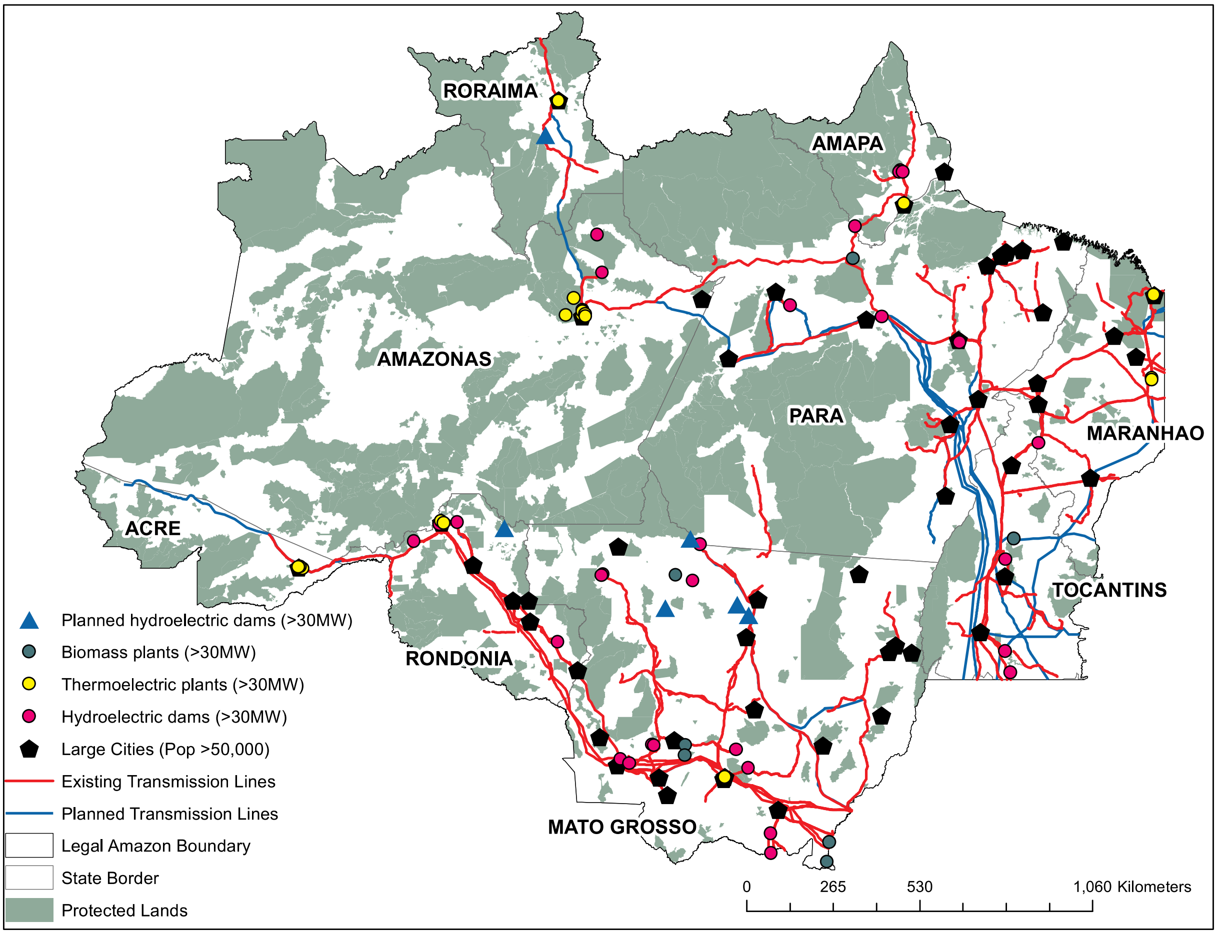

Fig. 1. The current (from the verified dataset developed for this project) and planned transmission and distribution lines (EPE, 2015b). Also shown are existing large (> 30 MW) energy generation plants, hydroelectric plants to be built by 2026, state capitals, and protected lands (Indigenous reserves and all types of protected areas) in the Legal Amazon of Brazil.

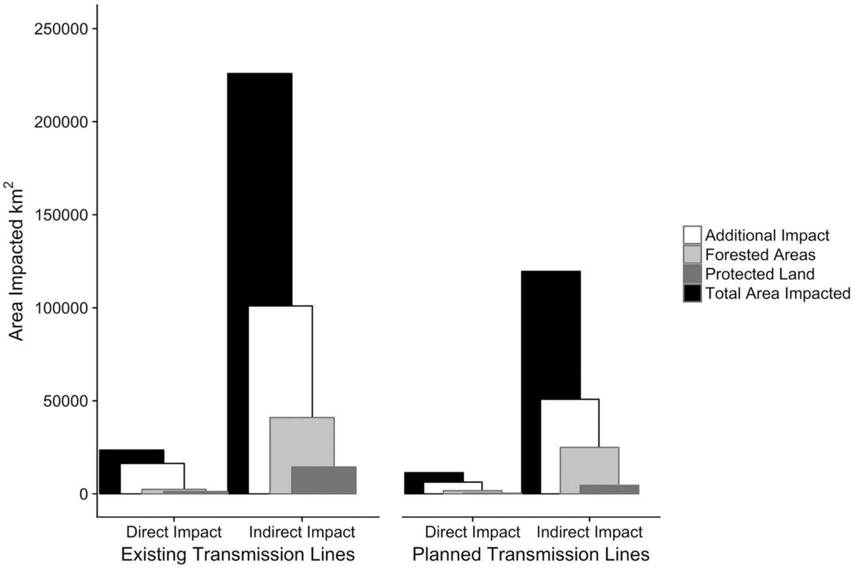

Fig. 2. The land area directly (within 400 m of a line) and indirectly (within 5 km of a line) impacted by current and planned electrical lines in the Legal Amazon, and amount of forest and protected land (including Indigenous reserves) directly and indirectly impacted. Additional impact refers to areas where the transmission line impact (at 400 m) does not overlap with the direct impact of a road (at 1.25 km).

3.2. Estimates of area impacted

Based on the median direct impact distance of 400 m, as determined from the available transmission line EIAs from the Legal Amazon, 23,467 km^2 of land are currently directly impacted by the transmission system in the Legal Amazon. An additional 224,588 km^2 are indirectly impacted (assuming a 5 km indirect impact buffer on both sides of all lines), adding up to a total of 248,034 km^2 impacted overall. An additional 11,334 km^2 of direct impact and 118,885 km^2 of indirect impact (a total impact of 130,219 km^2) are expected by 2026, if all of the planned lines are constructed (Appendix B, Fig. 2).

Transmission lines currently impact protected areas and forested areas, and the planned lines will increase this impact (Figs. 2, 4A). Of the total area of directly and indirectly impacted land, 5.1% and 6.4%, respectively, is within a protected area or indigenous reserve. This impact is fairly diffuse across the Amazon, with impacts occurring to protected areas or indigenous reserves in every state (Appendix B & D). As of 2016, forested areas were impacted in all states, with 2413 km^2 of forest currently directly impacted (10.3% of the total direct impact area) and another 40,977 km^2 indirectly impacted (18.2% of the total indirect impact area). Planned projects will also impact intact forest, with 1700 km^2 of direct impact and another 24,956 km^2 of indirect impact expected to forested areas. However, these results for planned transmission lines are an underestimate given that the planned lines dataset does not include transmission lines to every planned dam (Fig. 1), some of which are in more remote areas and thus may pass through forest.

3.3. Comparisons with other infrastructure projects

To put the potential scale of the impact of transmission lines in the region in perspective, we compared the network's impact area to that from roads and hydroelectric reservoirs. The government database of the paved federal road network in Brazil documents 365,980 km of roads in the Legal Amazon (IBGE, 2015). The length of the electrical line network is currently 10.8% of the length of the road network (up to 14.8% of the road network if all the planned lines are constructed and the road network remained the same). Some transmission lines (31% of the network) currently follow the paved road network (Fig. 2). In these cases, it is unclear whether the transmission lines further increase the impact of the roads. However, a majority of the transmission line network does not closely follow the road network. Sixty nine percent of the current direct impact area and 55% of the planned direct impact area for transmission lines does not overlap with the direct impact area of the paved road network (indicating that the line is at least 1.65 km away from an official road). Thus, these lines may be considered to cause additional impact (Figs. 2 and 4B), although they cannot be considered completely independent of roads due to the necessity of access roads, which may be unpaved, for powerline maintenance.

The current land area flooded by reservoirs in the region is 12,171 km^2 (Tucker-Lima et al., 2016). The direct impact area of the transmission line network is roughly twice that amount of land (Appendix B). The transmission line impact is inherently more spatially spread out and thus less obvious to detect, but the direct impact area from transmission lines covers far more land than the reservoirs overall.

3.4. Comparing the verified dataset with publicly available official datasets

Our verified dataset measured a similar length of lines (39,625 km) as the EPE dataset (36,469 km), but twice as much as the ANEEL dataset (18,643 km) (Fig. 5A). However, the estimate of directly impacted area from our verified dataset was far larger (23,446 km^2) than that of the other two datasets (15,233 km^2 by EPE, 14,488 km^2 by ANEEL) due to its wider geographic spread. To determine the geographic accuracy of the government datasets, we overlaid the direct impact area of the EPE dataset with the direct impact area of our verified dataset. The EPE dataset only overlapped with 57.5% of the impact area of the verified dataset (13,496 km^2 overlapped) (Fig. 5B). The direct impact area calculated around the ANEEL dataset was 63.4% of the size of the impact area around the verified dataset, and only 1.4% of the impact area (320 km^2) overlapped geographically with the impact area around the verified dataset (Fig. 5B). These results reveal the inaccuracies associated with the existing official datasets and highlight the importance of independently mapping these transmission lines before any attempt to assess and quantify the environmental impact of these lines.

4. Discussion

Transmission and distribution lines currently directly impact 23,446 km^2 of the Legal Amazon. Based on very limited information on larger impacts, we estimate that the network currently directly or indirectly influences a total of nearly 250,000 km^2, which is roughly the size of the state of Rondônia and 4.6% of the Legal Amazon land area. In the southern and eastern states, impacts from the network exist within a landscape already heavily impacted by other major infrastructure projects. However, the western Amazon has not been widely developed, but the impacts from transmission projects in western states will double (or in the case of Acre, triple) in the coming decade. Thus, the lack of research and understanding of transmission line impacts to the surrounding ecosystems is particularly concerning. Our goal here is to highlight the often-overlooked impacts of the transmission lines, especially the widely distributed nature of this impact. We make initial estimates of the spatial extent of impact, but emphasize that additional research is necessary to understand even basic information about how transmission lines impact landscapes in the Amazon. Furthermore, we advocate that transmission lines in the Amazon be more thoroughly considered when assessing and quantifying the environmental impacts of current and future infrastructure development.

4.1. Environmental impacts

We estimate that 2412 km^2 of forest (10% of the direct impact area) are currently directly impacted by the transmission and distribution network, and an additional 40,977 km^2 of forests (18% of the indirect impact area) are indirectly impacted. These estimates of impacted forested area are likely to be an understatement of the overall impact of the network to forests since it only considers currently existing forest. A historical analysis of forest loss around these lines is required to fully understand their long-term impacts. More specifically, historical data would help distinguish areas that were already cleared prior to powerline construction from areas that were cleared because of these lines, either due to the utility corridors or due to associated development or human activity around the lines. Compared to currently forested areas, impacts may be less severe in areas that were developed prior to line construction and in areas that have since been completely cleared. A thorough quantification of forest loss through time in currently deforested areas is critical to better attribute forest loss to transmission line construction in order to understand future impacts. Additionally, a more nuanced assessment of the overall health of the remaining forest is necessary to understand how transmission lines drive edge-related changes to forest.

A suite of deforestation and edge related impacts have been described in the Amazon. Despite the lack of research specifically on transmission lines, it is likely that many commonly described edge effects are occurring in the forests around these projects. Most prominently, we expect habitat loss and altered communities inside the utility corridors (Fahrig, 2003; Haddad, 2015; Pereira, 2014). This type of fragmentation likely will result in altered vegetation community structure and composition along the edges of the utility corridors (Goosem, 2007; Laurance et al., 2017; Laurance et al., 2002), and altered microclimate along the edges (Alamgir et al., 2017; Laurance et al., 2017; Pohlman et al., 2007; Pohlman et al., 2009). This may increase vulnerability of forests around transmission lines to fire, severe weather, and soil erosion (Alamgir et al., 2017; Goosem, 2007;

Laurance et al., 1998; Laurance et al., 2000), while increasing greenhouse gas emissions and reducing capacity for carbon sequestration (Chaplin-Kramer et al., 2015; Laurance et al., 2000). These changes may cause subsequent alteration to the behavior and composition of faunal communities and isolate individual populations (Benítez-López et al., 2010; Gascon et al., 1999; Goosem and Marsh, 1997; Goosem, 2007; Laurance et al., 2004; Murcia, 1995; Rich et al., 1994). Finally, it is likely that the cleared corridors in the forest may increase access for mining, settlement, illegal logging, and hunting or poaching (Andrews, 1990; Barber et al., 2014; Laurance, 1998; Laurance et al., 2015; Laurance and Burgués Arrea, 2017). However, further research is required to understand the extent and severity of these effects around the network specifically in the Amazon.

For linear clearings in general, the degree of impact on the surrounding forest depends largely on whether the canopy was maintained over the clearing (Develey and Stouffer, 2001; Goosem, 2000), the width of the clearing (Laurance et al., 2004; Pohlman, Turton, & Goosem, 2007), the community composition of the matrix and vegetation regrowth or “sealing” of the edges (Didham and Lawton, 1999; Goosem, 2007; Laurance et al., 2017; Pohlman et al., 2009), the original habitat type (Murcia, 1995; Yahner, 1988), and the orientation and age of the clearing (Goosem, 2007; Murcia, 1995). The maintenance of a utility corridor generally involves a regular cutting or mowing schedule, sometimes accompanied by the use of herbicides (Madrigal and Stoft, 2012; McAllister et al., 2001). This activity may maintain an early successional community in the corridors that may encourage the growth of invasive grasses (Clarke and White, 2008). While the expansion plan for the SIN discusses building lines above the tree level to reduce the need for clearing (Plano Decenal de Expansao de Energia 2026, 2017), most of the current high-voltage lines in the Legal Amazon already have wide, open canopy corridors and will continue to require this type of maintenance. Thus, we can expect a cascade of edge related changes to most of the forest within the impact areas.

Like roads, transmission lines create linear clearings when they pass through forested areas, producing new edges while reducing the amount of available core habitat. However, most utility corridors are characterized by a grass or shrub community within the clearing, so they may have different impacts compared to a sealed road. Microclimatic changes may be reduced along a utility corridor compared to a road clearing because utility corridors typically have a grassy or vegetated surface, which allows for more efficient evaporative cooling (Pohlman et al., 2007). Therefore, desiccation of vegetation on the edges of utility corridors may be reduced. Since most of the area impacted by transmission lines does not overlap with the area impacted by roads, transmission lines are likely an additional driver of fragmentation and land change, but the degree of impact is unclear. Currently, both roads and transmission lines more heavily impact the eastern and southern Amazon, along the arc of deforestation. However, the western and northern states of Acre, Amapá, Amazonas, and Roraima contain only 8% of the electrical lines and 15.5% of the roads combined, but the impact areas of transmission lines in these states will double or triple in after all of the construction is completed. Considering that these states have experienced much less land conversion and have fewer roads, new electrical lines may have higher environmental impacts compared to new lines built in already converted areas.

4.2. Caveats to our methodology

Our results provide a rough estimate of the area impacted by transmission lines in the Legal Amazon, but the estimated area is not specific to particular projects or ecosystems due to the lack of good information on impacts in the literature. The available EIAs of transmission line projects presented a wide range of possible impact areas (35 m–1 km for direct impact, see Appendix A). It is likely that the lower end of this range is more appropriate for smaller projects such as the distribution lines, while the higher end of the range is more accurate for high voltage lines. High-voltage transmission lines typically require larger rights-of-way than distribution lines, since they are larger structures (International Finance Corporation-World Bank Group, 2007). Our verified dataset does not distinguish between the transmission lines, sub-transmission lines, and distribution lines as it was not possible to accurately differentiate between types of lines based only on satellite imagery. Therefore, the median impact distance from the EIAs was the best possible estimate currently available to extrapolate across the entire system, but accounting for transmission line type and design, when possible, may lead to substantially improved estimates of impact area.

The criteria used to define the impact area around transmission lines are not clearly stated in the EIAs, and thus we are unable to judge whether they are ecologically sound. Globally, EIAs are notorious for underestimating the spatial and temporal impacts of projects (Alamgir et al., 2018; Fonseca et al., 2017). Thus, further research is required to determine whether EIAs are using appropriate impact areas based in ecological data. In the ecological literature, studies in tropical forests have produced a range of estimates for impact distances into a forest from an edge, concluding that forests anywhere from 300 m-3 km of an edge are at high risk for fragmentation-related impacts (Andrews, 1990; Ewers et al., 2017; Laurance et al., 2000; Laurance et al., 2002).The direct impact estimates from the EIAs ranged from 35 m–1 km, and thus those projects with estimates on the lower end may underestimate impact to forested areas.

Finally, we find that government-provided datasets are inaccurate for current transmission lines. Given this, it is possible the planned lines dataset may also be inaccurate, especially considering that the dataset does not include transmission lines linking some of the planned dams to the grid (Fig. 1). Similarly, the roads dataset only contains paved roads and may also be incomplete. Despite the potential inaccuracies in both these datasets, they are still useful to put into context the scale of impacts from current and future transmission lines and to highlight the need for more accurate and verified infrastructure data.

4.3. Transmission lines and other energy infrastructure

We compare the land area directly impacted by transmission lines to the land area currently flooded by reservoirs in the Legal Amazon. Despite the entirely different set of impacts from these two infrastructure types, we compare their impact areas to provide perspective as to the scale of the impact of transmission lines in the overall scheme of energy and infrastructure development in the Amazon. Furthermore, like the area flooded for reservoirs, much of the direct impact area for transmission lines is not available for reforestation, since utility corridors must be maintained for access and proper function. We find that the total area impacted by transmission lines may be greater than the area flooded by reservoirs and thus may have more widespread impacts on terrestrial ecosystems. Arguably, the terrestrial impacts of dams may go beyond the reservoir (Chen et al., 2015; McAllister et al., 2001), but, due to the complexity involved in understanding indirect impacts, we are unable to compare indirect impacts from either infrastructure type without more detailed information. Furthermore, transmission lines may be considered as part of a dam project in some contexts. The consequences of the construction of dams themselves have been discussed frequently in the context of the Amazon, quantifying change to forest structure (Ferreira et al., 2013), the amount of forest lost due to reservoir flooding (Cochrane et al., 2017) or due to other indirect causes such as displacement of people or the construction of new infrastructure to support the dam (Chen et al., 2015). However, previous investigations into the terrestrial impacts of dams do not quantify the impacts associated with the transmission system specifically, instead typically lumping it in with other "indirect impacts" (Barreto et al., 2011.; Laurance et al., 2015; Lees et al., 2016). Thus, the large scale of the impact from transmission lines compared to the sum of all the flooded area in the Amazon is further evidence that transmission lines are a conservation threat in the region and must be considered specifically in the planning and environmental impact assessment phase of these projects.

Transmission and generation (e.g. large dams) projects undergo separate auctions, environmental review, and licensing processes and are typically constructed and operated by different companies. Transmission and generation were separated legally during electrical sector reform in the 1990s in order to facilitate the privatization of the energy sector (Cardoso et al., 2014; De Araújo et al., 2008). Because they are different sectors and project types, environmental licensing is also done separately. However, we argue that transmission lines should be considered as a part of the larger power generation project (hydroelectric, thermal, wind, solar small hydroelectric, etc.) during the planning and licensing phase, rather than separate from it, or undergo simultaneous and outcome-dependent environmental review.

Problematically, most of the transmission lines associated with new dams are not considered in the EIA for the dam; often, only the lines that connect to the first substation are accounted for in these analyses (Electrobrás, 2009; RAS Rio Branco LT, 2011). In many cases, other associated new lines would not be necessary if a new plant was not being constructed. Furthermore, the environmental licensing of transmission projects occurs after a concession has been granted to a transmission company. Therefore, transmission projects, unlike generation projects, are planned and auctioned off before socio-environmental costs are considered (Campos, 2011; Cardoso, 2014). To illustrate these problems, the construction of the Santo Antônio and Jirau hydropower complex began in 2008, but the environmental impact study (or *Relatório Ambiental Simplificado*, RAS) for the Porto Velho-Rio Branco line, which distributes power from these dams in Rondônia to the capital city of the state of Acre, was not completed until 2011. Although these dams can technically operate without this line, the report openly states that failing to build the transmission line was out of the question because the dam had already been constructed (Rio Branco Transmissora de Energia LTDA, 2011). A similar situation occurred with the 2362 km transmission line connecting the Madeira dams to São Paulo: only the first 5 miles of the line were accounted for in the Clean Development Mechanism report, which judges the sustainability of the dam (Fearnside, 2015).

In regard to regional planning, Strategic Environmental Assessment is not required in Brazil (Fonseca et al., 2017), but *Avaliação Ambiental Integrada* (AAI, Integrated Environmental Assessment) have been done for most basins in the Amazon. However, the AAI for the Teles Pires basin, which assess the cumulative impacts of six large dams and seven small dams in the basin, did not mention transmission projects specifically (EPE, 2009; Gallardo et al., 2017). EPE performs electrical planning and inventory studies that involve larger-scale measures of sustainability (Cardoso, 2014), but environmental licensing is done on a project basis, without regard for cumulative impacts. Because of these issues, it is clear that transmission projects are not given sufficient consideration in the planning and licensing phases. This piecemeal approach to quantifying impacts and approving hydropower projects is inherently problematic: although the impacts from the transmission system are not thoroughly considered during the evaluation of the dam project or even in regional impact studies, there is little chance of rejecting their license after the dam is already built. Furthermore, the delay in the licensing of transmission projects after the power plant is operating may result in the inability to transport power in a timely fashion to consumers (Cardoso, 2014). Generation and transmission projects should be considered together during environmental review, since their function and impacts are inextricably tied.

4.4. *The importance of validated data*

We highlight that the development of accurate maps of transmission line networks are important for fully quantifying impacts. Publicly available Brazilian government sources contained 92% (EPE) and 47% (ANEEL) of the powerline network length mapped by our verified dataset, but they only captured 65% (EPE) and 63% (ANEEL) of the size of the impact area of the verified dataset. These discrepancies are likely the result of three factors: 1) dataset age (EPE was published in 2015 and ANEEL in 2016); 2) the omission of some transmission lines (especially in the ANEEL dataset); and 3) the lack of inclusion of lower voltage lines (< 250 kV) in the government sources. However, the lower voltage lines may also be impactful from an ecological perspective, so the lack of information about lower voltage lines prevents a thorough analysis of the impacts of the energy grid using just public sources. The differences in the datasets indicate that the transmission line network in the Legal Amazon is quickly increasing and that not all publicly available datasets are highly accurate. As we have shown, selecting the wrong dataset could result in only capturing 1.4% of the area actually impacted by transmission and distribution lines, which certainty would lead to misleading insights. For a more detailed discussion of the discrepancies in these datasets, see Appendix C.

4.5. *Suggestions for future development and research*

The construction of transmission lines is a near universal global issue, relevant to developed and developing countries alike. Transmission lines are required to connect any type of centralized energy generation (thermal, hydropower solar, wind, etc.) with centers of use, whether or not the world embraces more renewable energy sources. Because transmission line construction and maintenance are wide-reaching issues, more research is necessary to understand their impacts. In the Amazon region specifically, important gaps include their influence on land use, land cover, and native vegetation over time, proper quantification of impact areas to be used in future EIAs (or verification of their accuracy), and the severity of edge effects and changes to ecological processes around utility corridors. Additionally, the socio-economic impacts of the lines, both positive and negative, have yet to be thoroughly assessed in the region.

In regard to the management and construction of transmission lines in the Amazon, we compiled a general list of suggestions from the literature and our own observations to reduce and mitigate the environmental impacts of current and future projects.

- *Improve transparency about the process and data used in transmission line site selection and subsequent environmental impact assessments and ensure that government sources provide the best datasets possible.* This will allow third party monitoring of how these projects are planned and operated, which may improve environmental outcomes.
- *Ensure all associated infrastructure for a given project is part of the Environmental Impact Assessment process.* This will reduce the incidence of environmentally damaging projects being forced through the approval process because they are necessary for the functioning of other infrastructure (Laurance et al., 2015).
- *Prioritize the construction of new lines in areas that have already been*

converted away from natural vegetation, or follow the road networks as closely as possible. This will reduce the additional impact of transmission lines (International Finance Corportation-World Bank Group, 2007; Laurance et al., 2014).

- *Construct new lines above forest canopy (tower elevation).* If it is necessary to run a transmission line across a forested area, constructing lines that do not interrupt the forest canopy reduces forest loss and fragmentation effects (Campos, 2011; International Finance Corporation-World Bank Group, 2007; Public Service Commission of Wisconsin, 2009). An above-canopy line is already operating near Manaus, Amazonas, and the PDE 2026 discussed this as part of its infrastructure expansion plan (Plano Decenal de Expansao de Energia 2026, 2017). However, this option may cost more to build and maintain and forest must still be disturbed to build the towers themselves, so it is preferable to avoid forested areas if possible.
- *For long distance lines, consider high-voltage, direct current (HVDC) rather than high-voltage, alternating current (HVAC) transmission, if above-canopy lines are not possible.* DC transmission, over long distances, reduces energy loss as well as construction costs compared to the more common AC transmission, while requiring less space horizontally for the towers, thus reducing corridor width (Meah and Ula, 2007). AC is currently used for most of the SIN and most energy distribution systems. Some long distance lines in Brazil are already using HVDC technology, including the longest existing transmission line that links the Madeira River complex to the southern part of Brazil.
- *Maintain corridors with regard for natural vegetation.* In cases where forest must be cleared for a corridor, vegetation should be managed to promote habitat as close to natural as possible, while still maintaining functionality of the utility corridor and considering the cost and probable lack of financial resources allocated for maintenance. In newer lines, parts of the easement are typically left intact (Cardoso et al., 2014), and ideally, this should be part of the requirements to receive an Operating License. Examples of this include only removing problematically large vegetation (Campos, 2011), prioritizing the removal of invasive plant species, prioritizing mechanical removal over the use of herbicides, and allowing regrowth along the margins to produce a more gradual edge (International Finance Corporation-World Bank Group, 2007; Public Service Commission of Wisconsin, 2009). Some of these procedures are included in mitigation proposals in the EIAs, including selective vegetation removal and regrowth (Campos, 2011).

5. Conclusions

Transmission and distribution lines are a significant source of environmental impact in the Legal Amazon and must be accounted for when characterizing the impact of infrastructure in the region. Their full impacts, including the amount of forest lost due to construction in the region have yet to be expressly determined, despite their prevalence and continued expansion. An approach to decision-making that incorporates cumulative environmental impacts into both the infrastructure planning and licensing processes and the current powerline maintenance strategies has great potential to limit the impacts associated with existing and new transmission lines in the Legal Amazon of Brazil.

Associated data

https://doi.org/10.6084/m9.figshare.7308869.v1

Conflicts of interest

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Appendix A. The Environmental Impact Assessments from the Amazon Basin that were reviewed to determine buffer distances for the direct and indirect areas of impact. All posted projects in the Amazon region were reviewed from http://licenciamento.ibama.gov.br/

Project	Project type	Year	Area of influence direct	Area of influence indirect	Document reviewed
Oriximinã	Transmission Line	2017	NA	NA	All Available
Cuiaba - Ribeiraozinho - Rio Verde Norte	Transmission Line	2017	35 m	5 km	RIMA
Sistema de Transmissão Xingu Rio	Transmission Line	2017	100-500 m	5 km	EIA
Xingu - Estreito	Transmission Line	2016	500 m	5 km	RAS
Jurupari - Laranjal do Jari	Transmission Line	2016	NA	NA	All Available
Jurupari - Oriximina e Jurupari-Laranjal do Jari - Macapa	Transmission Line	2016	NA	NA	IFL-CP
Manaus - Boa Vista	Transmission Line	2015	1 km	5 km	EIA
Oriximina - Juruti - Parintins	Transmission Line	2015	150 m	2.5 km	RIMA
Xingu – Parauapebas - Miracema	Transmission Line	2015	500 m	5 km	RIMA
Jauru - Porto Velho	Transmission Line	2015	40 m	5 km	RIMA
Tucuruã – Xingu - Jurupari	Transmission Line	2014	1 km	5 km	EIA
Tucurui – Itacaiãnas - Colinas	Transmission Line	2014	35 m	5 km	RAS
Porto Velho - Rio Branco	Transmission Line	2012	NA	NA	All Available
Oriximina - Silves-Eng. Lechuga - Manaus	Transmission Line	2012	NA	NA	All Available
Oriximina - Silves-Eng. Lechuga - Manaus - Lote C	Transmission Line	2012	NA	NA	All Available
Coletora Porto Velho - Araraguara	Transmission Line	2015	500 m	5 km	EIA
BR 174 Trecho Manaus - Pacaraima	Road	2017	NA	1 km	RCA
BR 153 Paranã - Santa Catarina	Road	2017	300 m	NA	RIMA
BR 158 Pavimentão	Road	2017	2500 m	15 km	EA Contorno
BR 319	Road	2017	5 km	Counties	RIMA

BR 307 São Gabriel da Cachoeira - Front Brasil - Venezuala	Road	2017	NA	NA	All Available
BR 230 Rurãpolis BR 422 Novo Rep. Tucuruã	Road	2017	NA	NA	All Available
BR 230 Rurãpolis - Maraba	Road	2016	NA	50 km	RIMA
BR 153 to go	Road	2015	500 m	5 km	EPL
BR 163 Duplicacão	Road	2015	500 m	1 km	RIMA
BR 163 Trecho Guaranta-Ruropolis	Road	2014	2 km	50 km	EA
Contorno Norte de Curitiba	Road	2013	500 m	Municipalities	RIMA
BR 317 Boca do Acre	Road	2012	5 km	25 km	RIMA

Appendix B. The total area, forest area, and protected areas impacted in each state by the a) current transmission and distribution system; b) planned transmission system, and c) other types of infrastructure projects

A

		Current							
		Lines (km)	All			Protected areas		Forest	
State	State area (km^2)		Direct (km^2)	Total (km^2)	% of state	Direct (km^2)	Total (km^2)	Direct (km^2)	Total (km^2)
Acre	186,113.2	428.3	270.9	3041.3	1.6	5.9	92.9	14.0	725.4
Amapá	144,852.2	797.1	560.7	6663.9	4.6	60.1	960.1	107.6	1798.1
Amazonas	1,781,863.9	692.8	548.8	6752.0	0.4	70.8	1007.9	203.4	3355.1
Maranhão	262,313.1	6482.4	3238.6	33,009.9	12.6	423.9	4411.0	141.2	2209.6
Mato Grosso	936,913.8	12,872.1	8145.9	83,562.6	8.9	167.1	2161.6	739.3	11,696.3
Para	1,275,339.2	8277.5	4804.0	52,866.1	4.1	359.4	5147.0	784.0	14,457.6
Rondônia	261,343.7	4683.6	2654.2	27,734.8	10.6	3.6	158.7	376.1	6287.7
Roraima	243,605.1	721.6	576.6	7173.5	2.9	57.5	910.7	25.6	2560.8
Tocantins	272,351.8	4669.8	2646.9	27,230.8	10.0	56.9	782.0	21.4	299.7
Total	5,364,695.9	39,625.2	23,446.6	248,034.9	4.6	1205.3	15,631.9	2412.7	43,390.2

B

		Planned							
		Lines (km)	All			Protected areas		Forest	
State	State area (km^2)		Direct (km^2)	Total (km^2)	% of state	Direct (km^2)	Total (km^2)	Direct (km^2)	Total (km^2)
Acre	186,113.2	809.0	631.8	7742.3	4.2	6.1	79.1	214.5	3870.5
Amapá	144,852.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Amazonas	1,781,863.9	568.4	456.3	5905.4	0.3	115.2	1454.1	222.3	3296.8
Maranhão	262,313.1	1186.8	922.6	11,195.4	4.3	69.3	870.6	94.3	1073.1
Mato Grosso	936,913.8	1834.3	1419.9	17,500.2	1.9	13.9	184.8	139.6	2631.2
Para	1,275,339.2	5517.3	4222.2	43,960.1	3.4	9.9	452.8	814.0	11,410.1
Rondônia	261,343.7	550.2	436.0	5542.8	2.1	0.0	65.0	79.1	1522.3
Roraima	243,605.1	490.7	392.7	4915.5	2.0	61.5	752.9	120.6	2588.6
Tocantins	272,351.8	3580.9	2852.3	33,457.6	12.3	78.2	1025.6	15.2	263.9
Total	5,364,695.9	14,537.4	11,333.8	130,219.4	2.4	354.2	4884.8	1699.7	26,656.5

C

State	State area (km^2)	Current extent of other infrastructure	
		Roads (km)	Hydroreservoirs (km^2)
Acre	186,113.2	6074.4	NA
Amapá	144,852.2	4251.8	NA
Amazonas	1,781,863.9	10,209.9	NA
Maranhão	262,313.1	43,173.8	NA
Mato Grosso	936,913.8	131,850.6	NA
Para	1,275,339.2	87,053.2	NA
Rondônia	261,343.7	27,932.7	NA
Roraima	243,605.1	12,834.4	NA
Tocantins	272,351.8	42,600.1	NA
Total	5,364,695.9	365,980.8	12,171.0

Appendix C

Upon visual inspection of the EPE and the verified dataset, the discrepancies between this dataset and our verified dataset were due to three factors: 1) there were several instances where the EPE dataset captured two lines immediately parallel to each other, while the verified dataset showed one line in the same location (we were unable to visually confirm the presence of the extra line in these locations). Thus, the verified dataset covered more land area and captured more lines than were present in the EPE dataset, but the EPE dataset was only slightly shorter in length due to these instances of unconfirmed or undetectable parallel lines; 2) The EPE dataset does not include low voltage lines, which accounts for some of the discrepancy. We were unable to find a public dataset of distribution lines (lines with voltage less than 230 kV). However, these lines likely still cause disruption to the surrounding ecosystem from their construction and operation, and thus were included in our dataset; and 3) The EPE dataset was several years old, and thus did not include some of the more recently constructed lines. In the ANEEL dataset, the transmission lines appeared to correspond to transmission lines that were verified by our work, but they were located at least 800 m (the size of the buffer around the same line for each dataset) from the verified location of the line in most cases. We confirmed that this shift was not due to the use of different reference systems, since the original geographic coordinate systems for each dataset were determined from the metadata and then all were projected to the same coordinate system and the misalignment could not be corrected by a simple shift of 800 m throughout the basin. Upon visual inspection, this dataset is mostly composed of straight lines without contouring to the real transmission route, and thus may be meant only as a general reference point rather than a detailed dataset.

Appendix D

The scale of the impact of the transmission system varies greatly between Amazonian states (Fig. 3), with the greatest total impact currently in states within the Arc of Deforestation such as Mato Grosso and Pará, and the least total impact in more isolated states such as Acre, Amapá, Amazonas, and Roraima. The highest percentage of a state currently impacted occurs in Maranhão (12.6%). The greatest length of planned lines is also in this area, especially in the states of Pará and Tocantins. However, the new lines will nearly double the length of transmission lines in the northern Amazon and add the first transmission lines in the far western Amazon. In the state of Acre in the western Amazon, the length of transmission lines will triple in the next ten years. Amapá is the only state with no new lines planned in this timeframe. After the construction of all planned lines, the state of Tocantins will host the most impacted land area from transmission lines, with 22.3% of the land area in the state under indirect impact (Fig. 3).

Pará and Mato Grosso, large states with the most transmission lines (Appendix B), contained the most impacted forest, despite the large amount of deforestation that has already occurred in these states (Morton et al., 2006). However, in more isolated states, the proportion of direct impact to forests will increase dramatically, by 1535% in Acre, by 470% in Roraima, and by over 100% in Amazonas and Pará (Appendix B). The transmission system currently indirectly influences 5,147 km^2 of protected or indigenous areas in the state of Pará, and planned lines will indirectly impact over 1000 km^2 of land in these categories in the states of Amazonas and Tocantins. Although the planning process attempts to avoid building transmission projects in conservation areas (Plano Decenal de Expansao de Energia 2026, 2017), new lines will directly impact 354 km^2 of protected or indigenous areas.

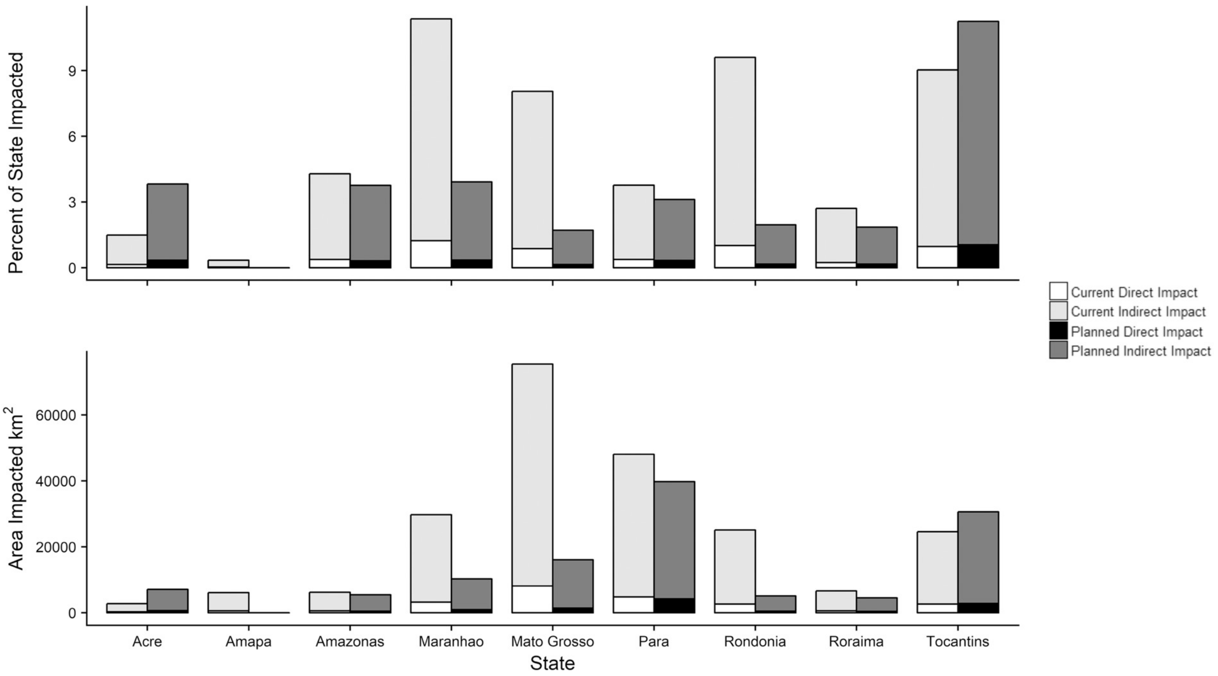

Fig. 3. The land area (bottom) and percent of the state land area (top) directly and indirectly impacted by current and planned transmission lines in each legal Amazon state. For states that are only partially inside the legal Amazon boundary, only the transmission lines inside the boundary are included.

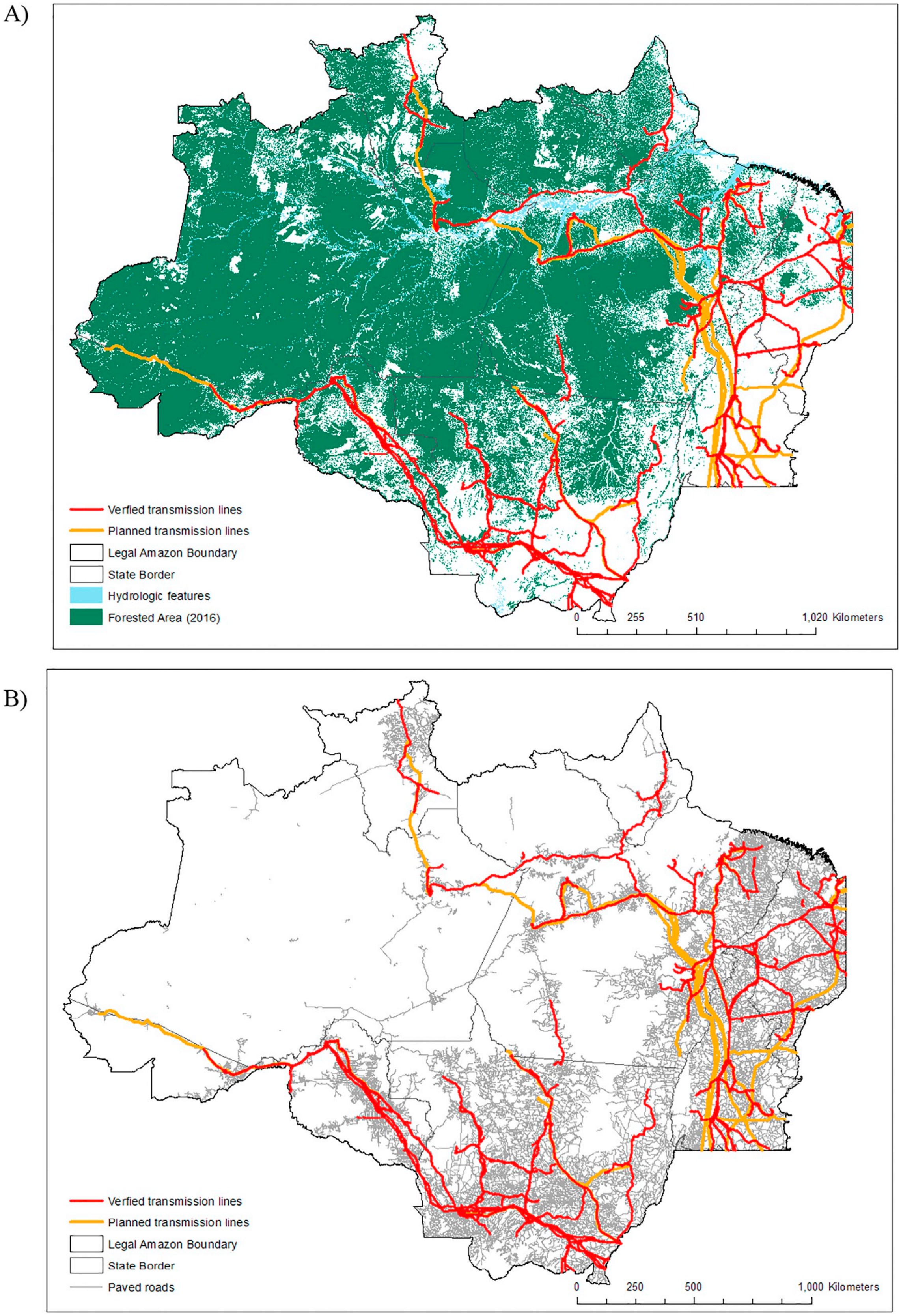

Fig. 4. Transmission lines in relation to A) areas of intact forest (includes cerrado habitat) and hydrologic features, and B) paved roads in the Amazon region.

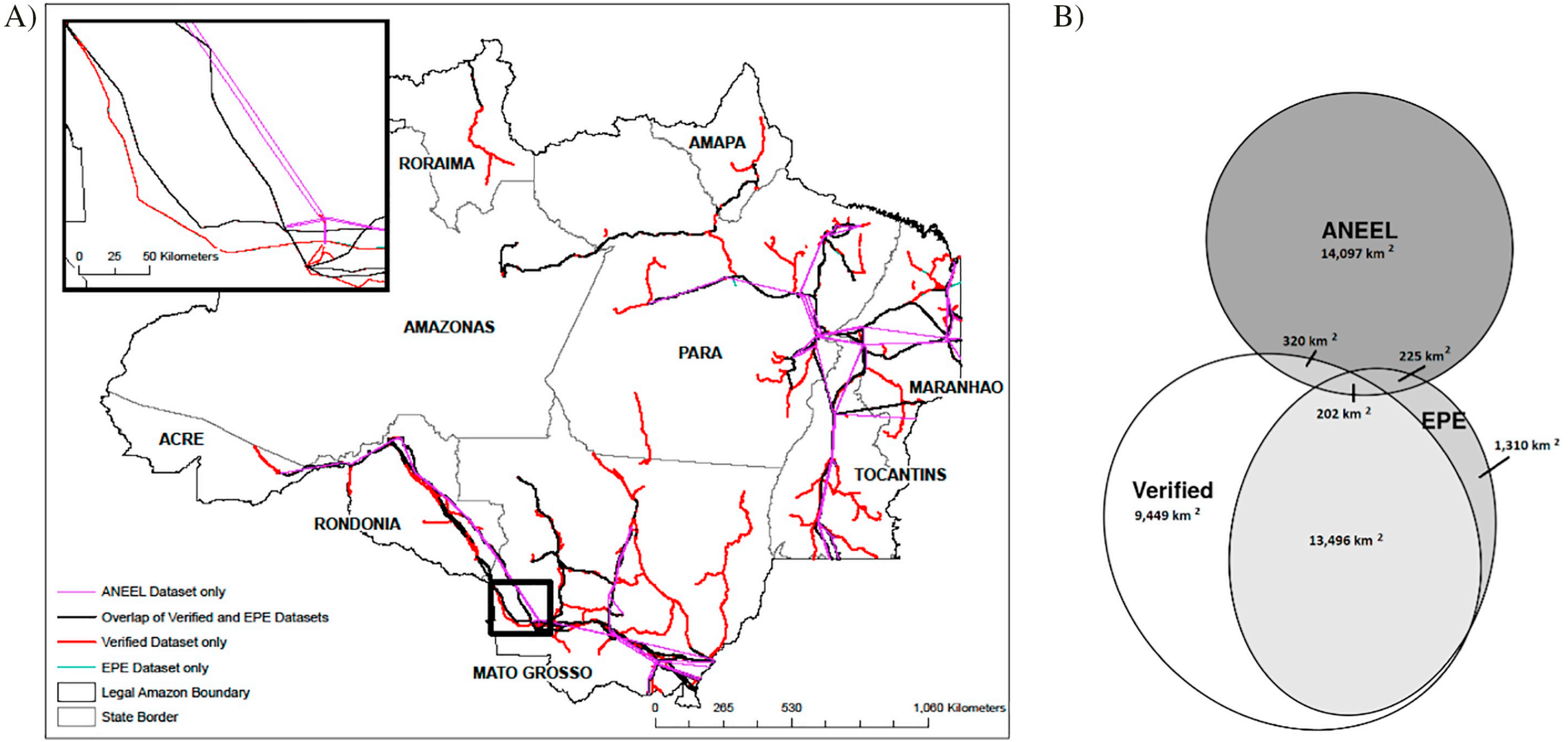

Fig. 5. A) The verified dataset compared to the ANEEL and EPE datasets. Much of the verified dataset overlaps with the EPE dataset (overlap shown in black); the red areas show where the verified dataset captures lines that are not shown in the EPE or ANEEL dataset. The inset illustrates that (1) multiple lines can be present in a small area and (2) the ANEEL dataset shows some lines verified in our data set, but the lines are not in the correct location. B) The size of the impact areas (km^2) calculated from each dataset (based on a 400 m impact area buffer) and the geographic overlap of the predicted impact areas with the impact area of the verified dataset. The size of the circle corresponds to the overall impact area estimated from each dataset. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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