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Landsat-based analysis of mega dam flooding impacts in the Amazon compared to associated environmental impact assessments: Upper Madeira River example 2006–2015

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ABSTRACT

Hundreds of dams are currently under construction or have been built in the Brazilian Amazon with the purpose of fueling social development via hydroelectric power and the transport of goods along rivers. However, many times the environmental impact assessments used to approve these projects have omitted or grossly underestimated the impacts of these dams, leading to severe and often irreparable damage. As such we conducted a case study of the Santo Antônio and Jirau mega dams on the Madeira River in Rondônia, Brazil and used Landsat TM and OLI data to determine area covered by water along a 539 km stretch of the Madeira River from 2006 to 2015 (covering before and after the dams' construction). The classification method used in this study was modified based off of previous methods and provided a highly accurate water classification suggesting it to be a valuable way of accurately classifying water along with other land cover classes. We compared the water areas calculated from Landsat land cover maps to the environmental impact assessment estimations used to approve the dams' construction. This analysis showed the reservoirs to be at least 341 km^2 (64.5%) larger than predicted with an additional 102 km^2 of unpredicted flooding outside of the planned reservoir areas and 160 km^2 more natural forest flooded than expected.

1. Introduction

In an effort to supply growing energy demands in Brazil, 452 dams are in the process of being planned or constructed in the Brazilian Amazon (Castello et al., 2013), ultimately damming all but three tributaries of the Amazon River (Macedo and Castello, 2015). Many of Brazil's largest dams remain controversial because of their immense and sometimes unforeseen environmental and social impacts, including the Belo Monte and São Luiz do Tapajós dams (Fearnside, 2006; Hess et al., 2016).

Around the world there have been claims that planned dams would have no negative impacts on the environment such as the Zangmu Dam on the Brahmaputra River (Krishnan, 2013), the Xayaburi Dam on the Mekong River (The Global Times, 2013), and the Mphanda Nkuwa Dam on the Zambezi River (Browne, 2009). Environmental consequences of many constructed dams were ultimately found to be far worse than predicted such as the Three Gorges Dam in China on the Yangtze River (Bosshard, 2009). Furthermore, a majority of these environmental impacts have proven to be irreversible and difficult to prevent because they were poorly predicted or not predicted at all (Tullos, 2009), highlighting the importance of detailed, comprehensive impact assessments. However, substantive evaluations from completed projects are uncommon, often having been poorly integrated throughout impact categories and scales or linked to other operations (WCD, 2000), lending to repetitive, unexpected, and massive environmental impacts following construction of many of these mega-structures.

At present, scientific literature on South American, African, and Southeast Asian fluvial systems is limited with tropical rivers generally underrepresented in studies (Bonthius, 2013). This is concerning because eight out of ten of the world's largest rivers, in terms of water discharge, are found in the tropics (Latrubesse, 2008), and two-thirds of the largest dams in the world are located in developing countries, most of which are in the tropics (WCD, 2000). Conversely, most knowledge on the impacts of impoundment comes from studies in temperate zones (Pringle et al., 2000). These circumstances make the implications of impoundment in tropical rivers uncertain and likely larger than impact

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assessments predict.

With hundreds of dams rapidly springing up across the Brazilian Amazon (Castello et al., 2013), broad environmental impacts are inevitable, making accurate, comprehensive impact assessments of individual dams crucial for larger-scale studies of combined, possibly synergistic, effects on the Amazon River and Amazon Basin. However, the environmental impacts of these dams have gone largely unquantified because many of them were constructed before baseline ecological data could be collected (Gunkel et al., 2003; La Rovere and Mendes, 2000), or because the impact assessments themselves weren't detailed enough due to the cost of conducting the assessments (Douglas, 2016).

In this article, we aimed to present findings of realized impacts from two recently constructed mega dams in the Amazon compared to the forecasted conditions from the original environmental impact assessment (EIA) used to approve implementation of the dams. We also aimed to describe areas not covered in the EIA at all, including impacts on várzea (seasonally flooded forest) as a result of prolonged flooding, transnational impacts into Bolivia, and the eventual decommissioning of the dams. The Santo Antônio and Jirau mega dams near Porto Velho, Rondônia were selected because they produce notable impacts on the Madeira River and surrounding ecosystems, and because their proximity to Bolivia allowed us to investigate if impacts transgressed international boundaries. The Madeira is the fifth largest river in the world in terms of water discharge (Latrubesse, 2008), the largest tributary of the Amazon River (Macedo and Castello, 2015), and the most heavily sedimented, whitewater river (Castello et al., 2013) in the Amazon Basin. As such, the Madeira River is a prime target for quantifying the environmental impacts of dams in the Brazilian Amazon.

We used annual Landsat satellite imagery (2006–2015) to measure upstream and downstream flooding before, during, and after the dams were installed. 2006–2008 were used as control years from before either of the dams were constructed. Construction continued until 2011 for the Santo Antônio dam and 2012 for the Jirau dam, with subsequent reservoir filling during 2013–2015. Observed areas of flooding were compared to estimated areas from the impact assessment.

2. Methods

2.1. Study area

The research area included 32,872 km^2 of the Brazilian Amazon within the state of Rondônia, Brazil, and northeastern Bolivia as delineated by a twenty kilometer buffer to either side of the Madeira, Mamoré, and Madre de Dios Rivers located within three Landsat scenes (path/row 232/66, 233/66, and 233/67). The study area was divided into four subsections defined as: 1) the impact assessment area, containing the entire area studied by the EIA used to approve the construction of the dams; 2) the downstream section of the Madeira River below the Santo Antônio dam; 3) the upstream Bolivia section which includes portions of the Madeira and Madre de Dios Rivers outside of the original impact assessment area, and; 4) the upstream Rondônia section which includes portions of the Madeira and Mamoré Rivers within Brazil (Fig. 1). These subsections were created to better allow for a comparison of predicted and observed impacts in only area 1 (impact assessment area), and a comparison of predicted impacts to observed impacts that extend beyond area 1 (area 1 plus areas 2, 3, and 4). Areas 3 and 4 were split to allow for an analysis regarding flooding in Bolivia.

The following comes from (RONDÔNIA, 2000) unless otherwise noted. The climate is tropical with distinct dry and wet seasons from May to September and October to April respectively. Annual peaks of dry and wet seasons occur in August-September and January-February respectively with an average annual temperature of 27° C and precipitation of 2300 mm. The study area is mostly covered by tropical, open forests (58.9%), *várzea* forests[1] (10.2%), and *cerrado*[2] (10.3%). A portion of the native vegetation has been converted to pasture, agriculture, and flooded lands, and the study region is considered a deforestation frontier within the Brazilian Amazon.

The Madeira River drains tropical rainforest and shows high, variable peak discharges during the wet season and low water flows during the dry season with maximum river levels in March-April (10.68 m) and minimum levels in September (8.31 m) on average as recorded by the Porto Velho gaging station. It is the largest tributary of the Amazon River with an average discharge of 32,000 m^3/s/year, and is 3400 km long with an average width of about 2.4 km (Latrubesse et al., 2005).

2.2. Landsat data processing

To quantify areas of flooding in our study region over a period of ten years (2006–2015) covering pre- and post-dam construction, we performed Landsat land cover mapping using the methodology of Souza et al. (2013) which combines Spectral Mixture Analysis (SMA) and Decision Tree Classification (DTC). A detailed description of the land cover classification methods used in this study can be found in Souza et al. (2013). Landsat TM and OLI L1T satellite images (Table 1) covering a portion of the Rio Madeira located over three Landsat scenes were obtained from the United States Geological Survey (USGS) (earthexplorer.usgs.gov) (Table 2). Dry season images were selected to limit cloud cover, and imagery from 2012 was excluded due to image scanline errors. The software Image Tools was used to perform haze correction and strip away thin clouds and aerosols, followed by conversion of digital numbers (DN's) into radiance (watts/m^2). FLAASH, the atmospheric correction module of ENVI version 4.8 (Harris Geospatial), was subsequently used to convert radiance into surface reflectance. SMA was performed to determine Green Vegetation (GV), Non-Photosynthetic Vegetation (NPV), shade, and soil fractions. These fractions were used as input variables for DTC to generate land cover maps with four classes of land cover: deforestation, water, forest, and cloud.

2.3. Classification enhancement

While the land cover maps generated by Souza et al. (2013) have a good overall accuracy (kappa of 0.92), the water class was not assessed, and we observed water areas misclassified as forest in the land cover maps. To enhance water classification, we included the shade fraction input variable that was discarded in the Souza et al. (2013) decision tree model since this fraction has been found to be useful when characterizing water areas (Roberts et al., 2002). We also observed burned areas misclassified as water. To distinguish misclassified burn areas from water, misclassified burn areas were manually indicated and used to mask the classified image, with all masked water pixels reclassified as deforestation. We used ArcGIS to create a twenty-kilometer wide buffer around the Madeira River that was large enough to encompass the growth of the reservoir through 2015 (Fig. 1) while excluding the reservoir of another nearby dam.

2.4. Accuracy assessment of classification

To assess the accuracy of our land cover maps, three, high-resolution (5 m pixel size), RapidEye images (Table 2) (image identification numbers 2034807, 2034909, 2035010) provided by MMA (2016) from 2015 were acquired to validate classified land cover classes in the study area. Systematic-random sampling was used to

[1] Várzea forests include various types of seasonally flooded forests that occur around sedimented rivers in the Amazon.

[2] Cerrado is tropical savanna vegetation occurring widely in Brazil.

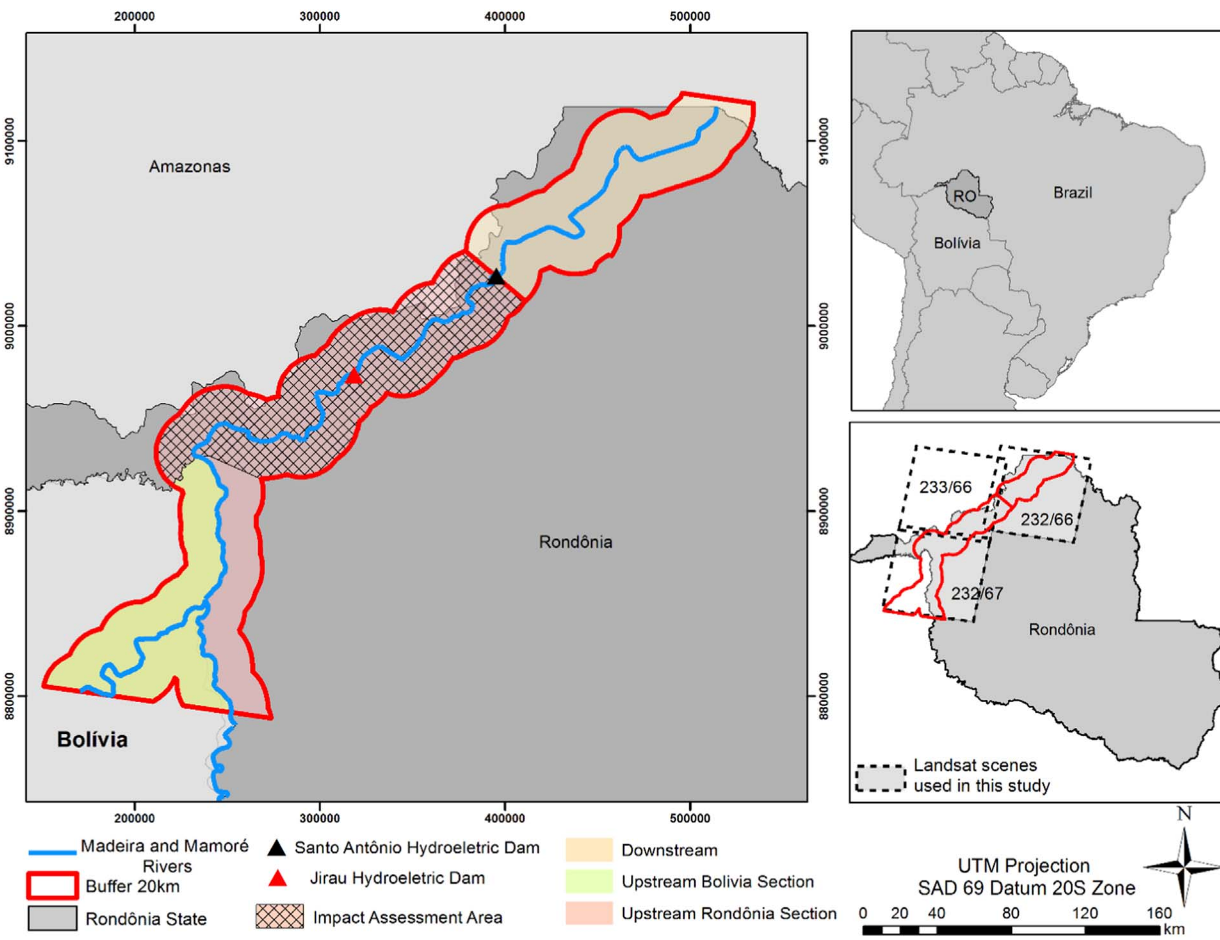

Fig. 1. The study area in context of South America (top right) and the Brazilian state of Rondônia (bottom right), and studied subsections (left).

Table 1
List of images classified for the study by scene and acquisition date.

Path/Row			Satellite/Sensor
232/66	233/66	233/67	Landsat-5 TM/ Landsat-8 OLI
6/1/2006	7/14/2006	7/14/2006	Landsat-5 TM
6/24/2007	7/1/2007	7/1/2007	Landsat-5 TM
7/28/2008	7/3/2008	6/17/2008	Landsat-5 TM
7/15/2009	6/4/2009	6/4/2009	Landsat-5 TM
8/19/2010	7/25/2010	9/27/2010	Landsat-5 TM
7/21/2011	8/13/2011	8/13/2011	Landsat-5 TM
7/26/2013	8/18/2013	8/18/2013	Landsat-8 OLI
6/11/2014	6/18/2014	8/21/2014	Landsat-8 OLI
6/30/2015	6/21/2015	6/21/2015	Landsat-8 OLI

collect 245 co-located points from both RapidEye and the 2015 classified Landsat data for visual class comparison. The confusion matrix, kappa value, z statistic, and p value were calculated according to Congalton and Green (2002).

2.5. Change detection analysis

The three research-area Landsat scenes were mosaicked for each of the ten study years. Change detection of land cover classes including water, forest, and deforestation area was performed from the time series of mosaicked, classified images to quantify changes in area (km^2) of each land cover type in our study area from 2006 to 2015, using the Post-Classification feature of ENVI.

Table 2
List of datasets used in the study and their corresponding characteristics.

Dataset	Features	Format	Spatial resolution/ scale	Source	Period of analysis
Landsat Data	Landsat Imagery Bands 1–6	TIFF	30 m	USGS	2006–2015
Santo Antônio and Jirau Dams	Limits of the dams' reservoirs and areas of impact	Shapefile	1:50,000	EIA/RIMA[a]	2014
RapidEye	RapidEye Imagery Bands 1–5	TIFF	5 m	MMA[b]	2015
Vegetation Map	Vegetation types along the Brazilian Madeira River	Shapefile	1:250,000	RONDÔNIA[c]	1998

[a] EIA/RIMA: Environmental Impact Assessment and Environmental Impact Report prepared by the dam' s constructors and approved by the Brazilian Institute of Natural Resources and Renewable Resources (IBAMA).
[b] MMA: Brazilian Ministry of the Environment.
[c] RONDÔNIA: Amazon State of Rondônia Government.

Table 3
Results of the accuracy assessment with calculated users and producers accuracy.

		Classification				
		Forest	Deforestation	Water	Σ	PA
True	Forest	149	5	2	156	0.96
	Deforestation	7	49	0	56	0.88
	Water	1	0	32	33	0.97
	Σ	157	54	34	245	
	UA	0.95	0.91	0.94		

2.6. Várzea calculations

A 1998 vegetation map from the (RONDÔNIA, 2000) (Table 2) was used to distinguish várzea from other vegetation types in the Brazilian portion of our study area. This map was then intersected with our classified images to delineate várzea areas (which are considered forest in this study) (Fig. 4). Forest classifications from this area each year were assumed to be várzea that had survived or regrown. Change detection between 2006 and 2015 was used to estimate net várzea area converted to water. Because the (RONDÔNIA, 2000) dataset did not include vegetation in Bolivia, only várzea in Brazil was included in our study.

3. Results

3.1. Accuracy assessment

The accuracy assessment showed high overall fidelity of land cover classifications (Table 3) with a kappa of 0.88, and a highly significant Z statistic of 30.35 ($p < 0.0001$). The water class upon which our results heavily depend had extremely high users and producers accuracies of 0.94 and 0.96 respectively, showing the modifications of the Souza et al. (2013) method based off of Roberts et al. (2002) to be highly effective at producing quality water classifications while maintaining the accuracy of the forest and deforestation classes.

3.2. Area changes along the Madeira River 2006–2015

Water, forest, and deforestation area changes throughout 2006–2015 can be found in Table 4 and show there was a net 60.5% (576 km^2) increase in water area. Of the 606 km^2 area that had been non-water in 2006 and became water in 2015, 78.0% (473 km^2) had originally been forest and 22.0% (133 km^2) had originally been deforestation. In the area upstream of the Santo Antônio dam (including the Jirau dam and Bolivian section of the Madeira River), water area increased by 87.2% (502 km^2), 82.1% (421 km^2) of which was originally forest and 17.9% (93 km^2) of which was originally deforestation. Downstream of the Santo Antônio dam, water area increased by 19.6% (74 km^2) during this time, 53.9% (47 km^2) of which was originally forest and 46.1% (40 km^2) of which was originally deforestation.

3.3. Water area changes upstream of the Santo Antônio Dam 2006–2015

We divided our classification of the Madeira River above the Santo Antônio dam into two parts: the original impact assessment area (water area above the Santo Antônio dam and below the Bolivian border) and the Bolivian area (water area upstream of the Bolivian border), both of which are depicted in Fig. 1. According to our classification, there was a 120.1% (475 km^2) increase in water area in the area described by the Santo Antônio and Jirau EIA during this ten year period. The Bolivian section of the Madeira River within our study area experienced a 15.3% (28 km^2) increase in water area during the same period.

3.4. Várzea area changes in Brazil 2006–2015

Between 2006 and 2015, 89 km^2 of várzea was completely submerged in the impact assessment area. A negligible area of 0.9 km^2 water became non-water in this region, 0.8 km^2 of which became várzea. In the downstream section of the Madeira River, 29 km^2 of várzea was submerged completely during this time period, and 4 km^2 of water became non-water, 3 km^2 of which was várzea.

4. Discussion

In 2005, RIMA, the official EIA for the Santo Antônio and Jirau dams, was submitted to IBAMA (Switkes, 2008), the Brazilian Institute of Natural Resources and Renewable Resources. Additional studies were requested by IBAMA throughout 2006 (ANEEL, 2010) before the agency published a technical report in 2007 that recommended a non-issuance of a preliminary license due to insufficient studies primarily relating to potential transboundary impacts in Bolivia as a result of the dams' construction. However, the license was granted only a few months later with a number of conditions after the site of the Jirau dam was moved from Cachoeira de Jirau to Ilha do Padre (Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis, Ibama, 2008) 12.5 km downstream of its originally proposed location, and several key IBAMA authorities were removed (Molina, 2012).

Even after the Santo Antônio and Jirau dams received their preliminary licenses in 2008 and 2009 respectively, the Madeira River Hydroelectric Complex (MRHC), to which the dams are a major part, has remained among the most controversial projects with predictions that it will cause the greatest impacts of any infrastructure project ever built (Mego, 2008). The dams themselves have also faced widespread criticism on many fronts, including how political pressure seems to have been used to push it through the licensing procedure (Switkes, 2008), their many impacts (Fearnside, 2013a, 2014), and concerns about the scale and accuracy of the mitigation methods (Tucci, 2007) and EIA used to approve the project (Fearnside, 2007, 2013b; Forsberg and Kemenes, 2007; Molina, 2008; Tucci, 2007; Tundisi and Tundisi-Matsumara, 2007).

We have provided quantification of dam-related flooding and forest losses as of 2015 and compared them to predictions from the 2005 EIA, showing that impacts from the dams have been substantially underestimated. Because our imagery is from the dry season, when water levels are at their lowest, and flooding beneath living forest canopies (waterlogged forest) along the rivers is not yet visible to our methodology, these are conservative impact estimations. Forest impacts will increase further in coming years as water tables surrounding the reservoir rise, flooding roots and killing unknown amounts of forest farther inland.

Table 4
Water, forest, and deforestation area changes each year from 2006 to 2015.

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Water Area (km^2)	952	966	952	987	827	884		1105	1468	1528
Forest area (km^2)	20,503	20,668	20,601	20,940	18,786	18,993		19,849	19,169	20,097
Deforestation area (km^2)	3585	3406	3487	3113	5427	5163		4086	4402	3414

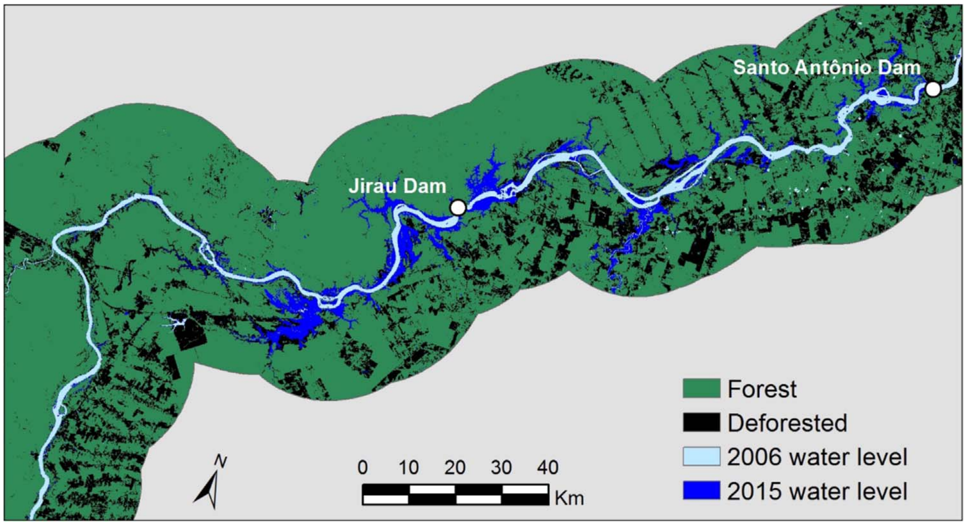

Fig. 2. Classified image of the upstream study area that compares the 2006 water area from before the dams were built to the 2015 water area from after the dams' construction.

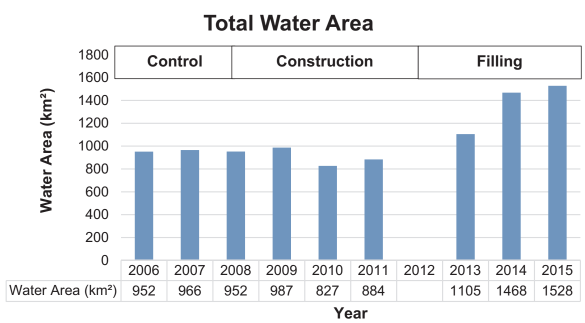

Fig. 3. Total water area (km^2) from 2006 to 2015.

4.1. *Extent and causes of flooding*

As of 2015, we can assume that flooding (Fig. 2) has primarily resulted from implementation of the Santo Antônio (2011) and Jirau dams (2013), being only peripherally compounded by abnormally high precipitation in the 2013–2014 wet season (Espinoza et al., 2014) because 2015 received average precipitation amounts and still had the highest water levels in this dataset (Fig. 3). However, considering both of the mega dams' reservoirs have been completely filled since then, the flood of 2013–2014 should serve as a cautionary tale for future flood years that could build on the already heightened water levels of the completely filled reservoirs.

4.2. *Planned versus observed impact*

According to the 2005 EIA, the combined reservoirs of the Santo Antônio and Jirau dams were expected to cover 529 km^2. Within this anticipated EIA region, the area impacted has already substantially exceeded this estimate within the first few years of operation. The reservoir water area progressed from 554 km^2 in 2013 to 747 km^2 in 2014 and 870 km^2 in 2015, exceeding the EIA area estimates used to apply for the environmental license to build the dams by 64.5% as of 2015.

Moreover, our results indicate that the environmental impacts were not contained within the EIA region. In fact, flooding extended beyond Brazilian borders despite mitigation strategies and will only increase in magnitude as sediments build up in the reservoirs, causing water to be displaced into Bolivian territory (Fearnside, 2013b). An additional 28 km^2 of lands were flooded in the Bolivian section within our study area, bringing the total flooded area to 898 km^2 (69.8% larger than estimated in 2005). Furthermore, 74 km^2 of downstream flooding during the dry season can also be observed, raising the total flooded area to 972 km^2.

The 2005 EIA also estimated a total of 30,800 ha (308 km^2) of natural vegetation would be lost due to the dams. However, we show that 468 km^2 of forest (várzea and non-várzea) was completely submerged during this period, exceeding the impact predictions by 160 km^2 (52.0%) before considering deforestation related to construction or how rising water tables will degrade surrounding forests.

Furthermore, the gross amount of unplanned flooding has forced many families to vacate their flooded lands and move elsewhere (Matarésio, 2012). Within the study area, 133 km^2 of flooded land had originally been cleared forests which were potentially inhabited. The EIA was updated in 2013 to report that no more than 110 families would be displaced by flooding even if the reservoir and energy capacity of the dams were to increase because enough adjacent lands had already been bought to encompass the anticipated growth in water area. However, by 2012, 175 families had already been displaced by flooding and failing river banks (Matarésio, 2012), a number that has surely increased as the combined reservoir area grew by another 316 km^2 by 2015.

4.3. *Impacts on Várzea*

Várzea is the most biologically diverse floodplain forest in the world with over 1000 flood-tolerant tree species (Wittmann et al., 2006) and performs a number of ecological services including recycling nutrients, supporting a widespread range of freshwater fish and aquatic mammals, and stabilizing landscapes (WildlifeFund (WWF), 2016). It is known for being accessible, highly valuable in terms of resource extraction and agriculture, and colonized by considerable human populations. These characteristics combine to make várzea disproportionately important for the small area they cover (2% of the Amazon Basin) and, economically, the most important type of land in the Amazon (Brookfield, 1996). However, vital ecosystems such as várzea have been neglected entirely in the dams' EIA and their mitigation strategies which is why we quantify the area impacted and describe how prolonged submersion will likely affect these forests.

At this point, 89 km^2 of várzea upstream of the Santo Antônio dam and 29 km^2 of downstream várzea has remained flooded even in the dry season. Forests subjected to long-term submersion experience a number of stress factors including reduced oxygen (Kozlowski, 1984) and an increase in toxic compounds in the surrounding soil (Ponnamperuma, 1984). In addition, várzea upstream of the dams will experience heavy deposition of sediments which can prevent sunlight from reaching the

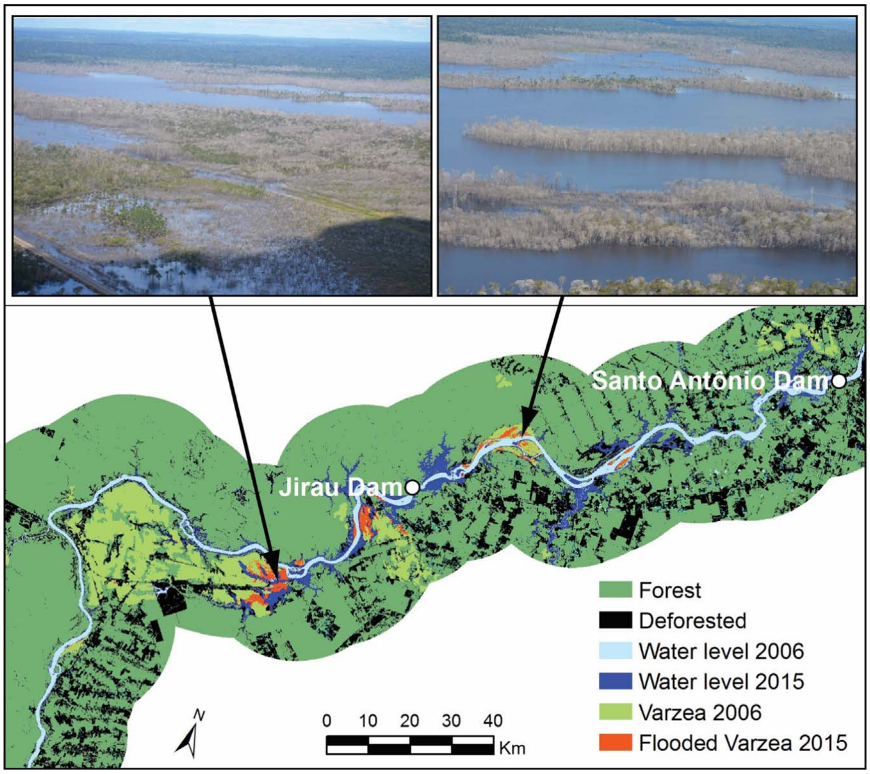

Fig. 4. Aerial photos (Source: Eraldo Matricardi) of várzea on the Madeira River. Extensive tree death as result of prolonged submersion appears as water or deforestation in our classified images (right). Areas in the process of dying from prolonged flooding or rising water tables still appear as forest or degraded forest in our classification (left). The photos for generalized locations of classified várzea (bottom) illustrate where these processes are ongoing.

trees' leaves (Ewing, 1996), further limiting oxygen availability to roots (Wittmann and Parolin, 2005). There has been little consensus regarding what would occur to várzea experiencing prolonged submersion, but aerial photos taken above the dams show that vast amounts of várzea are already dying as a result of the hydrological changes related to the dams (Fig. 4).

Várzea regrowth faces harsh set of conditions. Flood pulses characterize (Junk et al., 1989) and are critical to reproduction cycle of várzea. Várzea fruits typically mature at high water levels (Kubitzki and Ziburski, 1994) with their seeds submerged or floating for a maximum of several weeks before dying. Germination begins once waters recede (Parolin et al., 2004). However, dams, such as the Santo Antônio and Jirau, interfere with seasonal flooding (Stevaux et al., 2009), preventing fish from feeding on and dispersing seeds (Kubitzki and Ziburski, 1994), and substantially increasing seedling mortality in waterlogged areas (Parolin, 2009) and dry conditions (Ziburski, 1990). Whether the plasticity of várzea species will prove to be great enough to adapt to shifts in these seasonal cues is still unknown. If not, it is possible that várzea reproduction may become severely limited, and many more square kilometers of várzea will die as a result of prolonged flooding.

4.4. Social Impacts related to dam failures

The EIA estimated the lifespans of the Santo Antônio and Jirau dams to be seventy years. However, severe flaws have been found in the methodology used to determine the rate of sediment accumulation and dam lifespan, leading to concerns that the lifespan is likely shorter than expected (Forsberg and Kemenes, 2007; Tundisi and Tundisi-Matsumara, 2007). Given that the Madeira River is one of the world's most heavily sedimented rivers, this is a critical factor since dam failure risk primarily increases as a function of reservoir sediment levels (Morris and Fan, 1998).

Very little literature exists regarding removal of large dams, but, regardless of financial costs or technical difficulties, dam removal plans should not be overlooked due to the social costs of potential dam failures. For example, when the Banqiao dam on the Huai River in China failed in 1975 as a result of a typhoon it led to the cascading failures of as many as 62 more dams and the deaths of 230,000 people (McCully, 2001). On the Madeira River the Santo Antônio dam sits just upstream of Porto Velho, a city of more than 500,000 people (IBGE, 2015), making critical failure of either the Jirau or Santo Antônio dams potentially catastrophic for the city.

5. Conclusions

The modification of the Souza et al. (2013) method based off of Roberts et al. (2002) has proven to be highly successful at improving water classification while maintaining the accuracy of forest and deforestation classifications. As a result, we were able to determine that the direct impacts of damming the Madeira River were substantially underestimated in the EIA for the Santo Antônio and Jirau dams with 52.0% more natural vegetation affected and reservoirs at least 69.8% larger than predicted. Many additional impacts were not addressed at all, including, but certainly not limited to prolonged submersion of várzea, transnational impacts into Bolivia, and the potential for dam failure.

While the central conclusion from this study is that the EIA grossly underestimated the flooding caused by both dams and omitted several other important impacts, this does not appear to be a unique case among the 452 constructed or soon to be built dams across the Brazilian Amazon (Hess et al., 2016). However, of more concern is the fact that the combined impacts of these dams on Amazonian river systems, most notably through sediment loss, will increase along each tributary and act cumulatively in the main stem of the Amazon river with huge, unknown ramifications for the surrounding deltas and ocean itself (Syvitski et al., 2005) along with unique ecosystems adapted to these specific, sedimented conditions such as the newly discovered coral reef at the edge of the Amazon river (Vidal, 2016). Handling these immense impacts calls for a meta-assessment of the cumulative and potentially synergistic impacts of damming throughout the Amazon Basin that would potentially benefit from using the methods applied in this study on a larger scale to determine more accurate land cover changes resulting directly and indirectly from many dams.

Although this research has focused on impacts from two dams in the Brazilian Amazon, what has occurred here is indicative of problems occurring with many dams across the globe. Currently, there are more than 45,000 large dams around the world (WCD, 2000), making accurate quantifications of their individual and combined impacts, as well as the woefully understudied consequences of dam removal, crucial areas for future study. The limited collection of scientific literature on large fluvial systems and mega dam impact assessments has come together to pose a significant barrier to quantifying the effects that these dams have on ecosystems and larger river systems as a whole. This situation not only impedes the pursuit of more accurate impact assessments in the future, but also enables dams with unreasonably large impacts that often cannot be remediated, due to poor foresight within the planned assessments, to be constructed. Accurate, individual impact assessments will be vital for conducting future meta-analyses of the integrated impacts that dams cause, providing information critical for mitigating or preventing irreparable damage from occurring throughout the world's largest river basin.

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