SEDIMENT RESPONSE TO DEFORESTATION

IN THE AMAZON RIVER

BASIN

by

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ABSTRACT

The Amazon River Basin is the largest river basin in the world (6,300,000 km^2) and serves as a home to approximately 26 million people across the South American continent. Renowned for its biodiversity, the Amazon River Basin is home almost 50,000 vascular plant species, 2,000 species of freshwater fishes, and was once one of the Earth's largest carbon sinks. Despite its anthropogenic and ecological importance, the Amazon experiences thousands of kilometers of deforestation annually with recent rates increasing to levels unseen since the late 2000s. These increased rates of deforestation within the basin have led to changes in sediment concentration within its river systems, affecting both the ecological balance and freshwater availability within the system. Furthermore, sediment plays an important role in river channel morphology and landscape development, effectively influencing the future topography of the basin. Therefore, it is important to closely examine the relationship between deforestation and suspended sediment in order to characterize the extent of influence anthropogenic activities, such as deforestation, have on rivers.

In this study, I analyze the impact of deforestation from 2001 to 2020 on suspended sediment throughout the Amazon River Basin. These impacts are studied by quantifying the spatiotemporal relationships between observed suspended sediment and changes in land cover over time. In the southeast region of the Amazon, where deforestation rates are high, I observed strong correlations between deforestation and total suspended solids concentration. Basin wide, I determined that 26% of the temporal variability in sediment is attributed to deforestation. Sub-basins subject to large amounts of deforestation during the study period were shown to have

sediment spatial dynamics more heavily influenced by deforestation than their more pristine counterparts. Further, at local scales, large amounts of deforestation were observed to be associated with increases in total suspended solids. The results of these analyses reveal that large scale deforestation of the Amazon during the 2001-2020 period may have led to significant changes in sediment dynamics predominantly in the eastern portion of the basin. These findings suggest severe implications for future sediment dynamics across the Amazon if deforestation is to further expand into the basin.

LIST OF ABBREVIATIONS AND SYMBOLS

TSS	Total Suspended Solids
mg	Milligram
L	Liter
mg/L	Milligrams per liter (concentration)
km	Kilometer
km^2	Kilometers squared
α	Significance level
p	Probability of occurrence under the null hypothesis of obtaining a value as extreme or more extreme than the observed value
RMSE	Root mean squared error
MAE	Average magnitude of error
SMAPE	Symmetric mean absolute percentage error
Pbias	Percent bias
MW	Mega watts
MCM	Million cubic meters
t/year	Tons per year
BR	Brazil
Std. Dev	Standard Deviation
ArcGIS	Geographical Information System Software
H1	Hypothesis 1

H2	Hypothesis 2
H3	Hypothesis 3
=	Equal to
<	Less than
%	Percent

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CHAPTER 1

INTRODUCTION

The Amazon River Basin is the largest river system in the world, accounting for roughly one-fifth of global freshwater discharge (Callède et al., 2010) and supplying 40% of the Atlantic Ocean's sediment flux (Milliman and Farnsworth, 2011). Though the Amazon River Basin is most often recognized for its rich biological diversity, it also performs a suite of ecosystem functions such as local climate modulation and carbon sequestration (Foley et al., 2007). Despite its ecological importance, the Amazon experiences thousands of kilometers of deforestation annually with 2020 rates increasing to levels unseen since 2008 (Silva et al., 2021; Instituto Nacional de Pesquisas Espaciais, 2020)

Between tropical, subtropical, temperate, and boreal climate domains, the tropics experience the largest total forest losses and gains as well as the greatest loss to gain ratio (Hansen et al., 2013). From 1975 to 2018, the Amazon experienced an accelerated rate of deforestation with roughly 20% (788,353 km^2) of the Amazon deforested during this 43-year span (da Cruz et al., 2020). Mato Grosso, a state located in western Brazil, is known as Brazil's agribusiness powerhouse with a count of 30.2 million head of cattle in 2017 (Vale et al., 2019). In the year 2000, the total amount of deforested land in Mato Grosso comprised of 18.8% of the total area, however in 2015 this percentage increased to 37.1% (Grecchi et al., 2017). In central Brazil, the savannah environment locally known as Cerrado has more than 50% of the original 2 million km^2 of land converted and fragmented through deforestation and expansion of the agricultural industry (Coe et al., 2011). With increasing global demands for soy and beef, and the expansion of sugarcane and palm oil production in the Amazon, deforestation is only predicted to increase.

The effects of deforestation extend far beyond the immediate impacts on the environment, carrying long term, severe implications for local and global climate change (Longobardi et al., 2016), hydrologic cycling (Vergopolan and Fisher, 2016), and the welfare of indigenous peoples (Laudares and Gagliardi, 2020; Ellwanger et al., 2020). The conversion of forest to pasture may unintendingly cause forest loss in other regions through a process called indirect land use change (ILUC). Previously, ILUC was only a hypothesized phenomenon, difficult to measure due to the complexity of establishing a relationship between distal land cover drivers and impacted sites however, Arima et al. (2011) observed that from 2001-2008, a 10% reduction of soy in previously deforested areas would have prevented as much as 40 % of new deforestation in heavily forested Brazilian counties; broadly, as much as 32% of the Brazilian Amazon's deforestation is *indirectly* attributable to soybean production (Richards et al., 2014).

Deforestation alters the geomorphological, biochemical, and hydrological states of streams by decreasing land surface evapotranspiration and increasing surface runoff and river discharge, erosion rates (Horton et al., 2017), and sediment fluxes from land surfaces (Coe et al., 2011). A 2003 study conducted within the Tocantins sub-basin (of the Amazon), noted a 24% increase in mean annual discharge and a 28% increase in high-flow season discharge not attributed to changes in precipitation, but rather by changes in land cover (Costa et al., 2003). A 2009 model simulation study using the same watershed determined that the increase in discharge could not be solely attributed to climate variation (Coe et al., 2009) but rather, two-thirds of the observed 25% increase in discharge was attributed to deforestation that occurred during that period (Coe et al., 2011).

Deforestation’s effects on suspended sediment can be measured years after forest removal has occurred. A deforestation-sediment study conducted on the Noto Peninsula of Japan concluded that 15 years after a deforestation event, the sedimentation rate remained high due to an increase in the erosion rate of soil and organic matter (Ochiai et al., 2015). Additionally, 35 years after the deforestation event, there remained a change in the transport of organic matter. These effects on sediment and organic matter levels can be attributed to a combination of bare soil exposure, forest management activities to remove understory vegetation, and heavy rainfall (Ochiai et al., 2015).

Although sedimentation is a natural part of river systems, changes in the quantity and quality of sediment can have major effects on ecosystems and communities (Wohl et al., 2015) and basin topology (Ahmed et al., 2019). Sediment increases have been shown to affect fish migration patterns, clog fish gills, destabilize mangroves, and reduce irrigation reservoir capacity (Kjelland et al., 2015; Ellison, 1999). Additionally, communities in and around deforested areas experience an increased flood hazard risk, a reduced infrastructure lifespan, and a decreased level of water quality (Vercruysse et al., 2017). The extent of the relationship between deforestation and sedimentation must be investigated on a large-scale to plan for future changes in land cover and offset the current effects of deforestation on the environment and communities.

Research Gaps

Previous studies have observed significant increases in sediment load and concentration attributed to deforestation. However, these studies have been limited in scale, focusing on smaller basins or study areas (Bringhurst and Jordan, 2015; Latrubesse et al., 2009; Ochiai et al., 2015; Maina et al., 2013; Maeda et al., 2008). Further, these studies do not focus on the quantification of deforestation, rather they tend to discuss deforestation in a broad sense or explore general trends following deforestation and sedimentation rates. A quantitative analysis between deforestation and sediment has yet to be conducted on a large basin such as the Amazon.

Studies conducted within the sub basins of the Amazon have observed significant increases in sediment due to deforestation. Within the Suiá-Miçu River Basin (located in the northeast region of Mato Grosso) deforestation was observed to increase annual average sediment yields by 7 ton/ha (Maeda et al., 2008). This was assessed by examining land cover changes during three periods in time (1973, 1984, and 2005) and using the Universal Soil Loss Equation (USLE) to identify changes in sediment yield. Although this study concluded that deforestation had resulted in significant increases in the sediment load, examining shifts between only three points in time introduces some uncertainty in deforestation-sediment dynamics between these years. That study is further limited by its use of only modeled sediment data. The USLE calculates soil loss using relatively simple inputs such as: annual average soil loss, rainfall erosivity factor, soil erodibility, topographical factor, vegetation cover, and erosion control practices. These data inputs offer a high degree of flexibility, making it one of the most widely used soil loss equations (Alewell et al., 2019). Despite its relative simplicity, however, it has no input factor for soil deposition (sedimentation) making it somewhat of an unrealistic model.

Further, more than three quarters of all studies (conducted between 1977 and 2017) utilizing the USLE are focused on North America, Europe, or Asia; only eight percent of all studies during this period had been conducted in South America (Alewell et al., 2019). As the usability of the USLE is not well documented in the tropics, it may be inappropriate to apply these types of equations to complex tropical regions like the Amazon.

In the Magdalena River Basin (outside of the Amazon River Basin), deforestation in the Columbian Andes was also observed to increase the basin's sediment load (Restrepo et al., 2015). They estimated that 9% percent of the sediment load in the Magdalena River Basin was due to deforestation (Restrepo et al., 2015). In this study, the total area of deforestation was assessed for each of the Magdalena's sub-basins during the 1980-2010 period; this data was used to modify the anthropogenic induced erosion factor (E_h) of the BQART sediment modeling equation. By altering the E_h factor, Restrepo et al (2015) observed a 11% increase in model accuracy. Though this method allows for comparison of sediment load with and without anthropogenic input, it does not consider the likelihood of deforestation derived sediment entering streams and rivers. Rather, it assumes that all deforestation has some effect on the sediment load regardless of its proximity to rivers and streams.

The number of readily available observational datasets within the Amazon has increased significantly in recent years (Crochemore et al., 2019) however, it is likely that deforestation-sediment studies within the Amazon River Basin remain limited due to a lack of high-quality datasets, especially for sediment. For example, Brazil's national hydrologic dataset, ANA Hidroweb (Water Resources National Agency (ANA)), contains data on hundreds of river gauging stations. These stations collect discharge and sediment concentration data throughout the country however, much of the data collected is incomplete or contains duplicate entries. Further, data collection is inconsistent with many stations having only one recorded observation for an entire year or at seemingly random points in time throughout the year. Examining sediment data availability for stations within the Brazilian Amazon starting at 2001, I observe that more than half of the stations lack data prior to 2007 (**Fig. 1**). Only a handful of stations in this area contain observations for each year from 2001-2015 (though this does not mean that observations for these stations are consistently recorded).

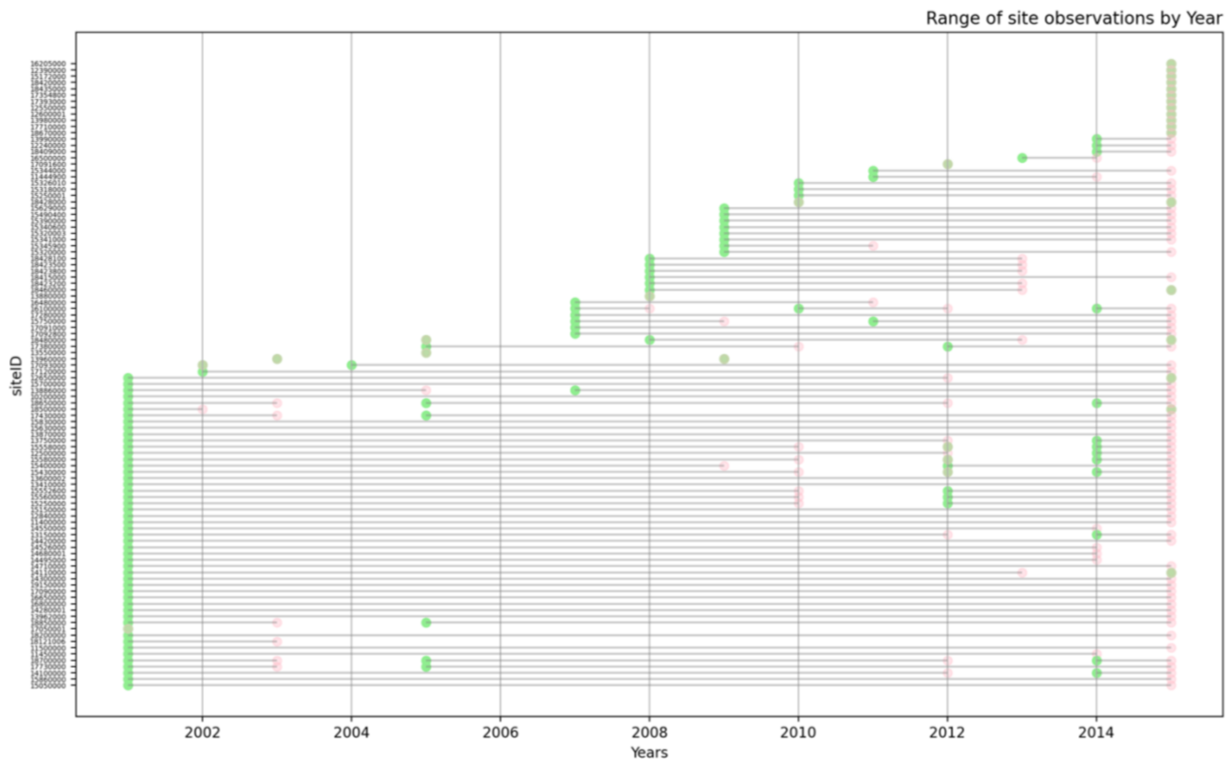


Figure 1. Sediment data availability for stations within the Brazilian Amazon River Basin starting at 2001. Green points indicate the start of data collection. Red points indicate the end of data collection.

Other datasets, such as SO-HYBAM (Institut national des sciences de l'Univers, 2021) contain consistent, long-term observations and is updated frequently, however this dataset contains only fourteen stations spread throughout the Amazon River Basin forcibly limiting the scale of studies to smaller catchments. Depending on their research goals, many studies in the

Amazon instead, use sediment modeling equations in place of in-situ data (Maeda et al., 2008, Restrepo et al., 2015). As the Amazon River Basin falls within the boundaries of eight different countries, it is difficult to compile the various national datasets available for a basin wide analysis due to variations in data collection methods and the temporal availability of data.

Despite improvements to hydrologic models in recent years, using traditionally modeled data introduces some sources of error due to uncertainties in parameters, model structure, calibration, and input data (Moges et al., 2020). To overcome these uncertainties, sediment data in this study was derived from a novel remote sensing observation. Though predictive uncertainties do still exist within remote sensing datasets, the data was shown to provide accurate sediment concentration data.

Goals and Objectives

The goal of this study is to analyze the impact of deforestation from 2001 to 2020 on suspended sediment throughout the Amazon River Basin. These effects are studied by quantifying the spatiotemporal relationships between observed suspended sediment and deforestation using spatially and temporally explicit, basin-wide, remote sensing products.

Objectives

1. Investigate temporal trends and variability in sediment within the Amazon River Basin's major tributary, minor tributary, and sub basins.
2. Analyze the spatial and temporal dynamics and influence of deforestation on suspended sediment within the Amazon River Basin's major tributary, minor tributary, and sub basins.
3. Identify regions within the Amazon where deforestation has produced the greatest impact on sediment dynamics.

Hypotheses

H1: Deforestation will lead to significant increases in suspended sediment load in deforestation hot spots.

In a number of small-scale studies, deforestation has been shown to increase suspended sediment in fluvial systems (Restrepo et al., 2015; Ochiai et al., 2015; Latrubesse et al., 2009; Bringhurst and Jordan, 2015, Xing et al., 2014, Kettner et al., 2007). I hypothesize that streams closer to deforestation hotspots will experience an increase in suspended sediment loads compared to more pristine locations.

H2: Significant amounts of deforestation are required to produce a discernable effect on suspended sediment.

For deforestation to produce a discernable effect on sediment, the influence of deforestation must be greater than that of other environmental drivers. Within large basins, small parcels of deforestation are not expected to produce significant effects on sediment.

H3: Stronger relationships between deforestation and sediment will be observed in smaller Amazonian basins.

Globally, sediment is observed to be more responsive to land use changes in smaller basins compared to larger basins (Dearing and Jones, 2003). Due to their lower buffering capacity, smaller basins are expected to have a higher sediment delivery ratio[1] (Walling, 1983; Walling 1999), therefore I expect to observe the presence of stronger deforestation-TSS relationships within smaller basins.

[1] Ratio of sediment yield to gross erosion

Study Area

Since the late 1960s, the Amazon River Basin has experienced significant amounts of forest loss with nearly 1/5 of its original forest (1,000,000 km^2) deforested (Nobre et al., 2016). Anthropogenetic activities such as cattle ranching, soybean cultivation, and river damming cause significant changes within the forest leading to serious forest degradation and rising global CO_2 emissions (Exbrayat et al., 2017). As the tropics continue to be the most heavily deforested biome on the planet, I examine the relationship between deforestation and sediment within the Amazon River Basin (**Fig. 2**).

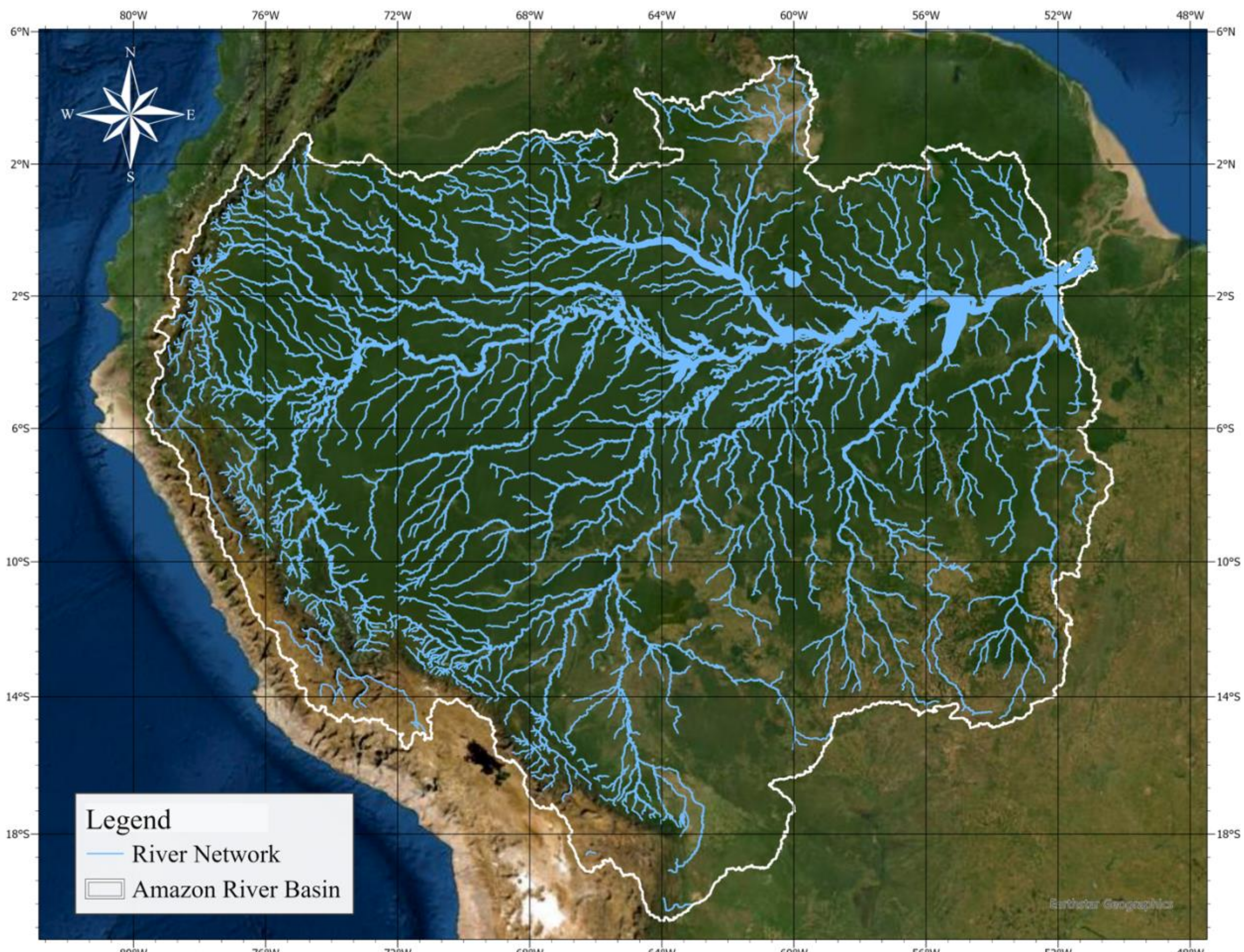


Figure 2. The Amazon River Basin with major streams and rivers. Line width symbolize the river size using the layer's river width attribute.

Despite its incredible size (6,300,000 km^2), the Amazon River Basin has a relatively homogenous climate due to its large tropical rainforest and its location situated along the equator between 10°N and 20° S (**Fig. 2**). The basin is characterized as a tropical rainforest (*Af* by the Köppen-Geiger system) with average temperatures ranging between 24-26 °C throughout the year (Barthem et al., 2005). Typical of the *Af* climate type, the Amazon experiences large amounts precipitation annually. However, the spatial distribution of its receiving precipitation varies largely (1,000-3,600 mm) with annual rainfall exceeding 8,000 mm in the Andean coast and ranging from 1,500 to 1,700 mm in the drier regions of Roraima (BR) through the Middle Amazon to the state of Goiás (BR) (Barthem et al., 2005).

Humid tropical forests are the largest biome in the Amazon River Basin encompassing almost 80% of the region. Other biomes, such as dry forests/savannas, cloud forests, várzea forests, and puna grasslands are also present within the basin although these biomes constitute a far smaller percentage of area than the rainforest (Barthem et al., 2005). Despite being the most dominant biome in the Amazon, 40% of the Amazon's tropical forests are at risk of conversion to a savanna state due to a combination of deforestation (causing a negative rain-forest feedback loop) and climate change (Staal et al., 2020).

Topographic characteristics, such as hillslope steepness, can significantly influence soil erosion rates (Zhang et al., 2015), however most of the Amazon appears uninfluenced by steep slopes (**Fig. 3A**). The Andean region of the Amazon River Basin is subject to natural erosive process, producing approximately 93% of the Amazon's sediments (Naziano and Guyot, 2009). Much of this region is influenced by slopes greater than 30 degrees (**Fig. 3A**). Apart from this region however, the Amazon is a fairly flat river basin (**Fig. 3A, 3B**) with a basin wide median slope of 2.78 degrees and an average slope of 5.32 degrees (**Fig. 3B**).

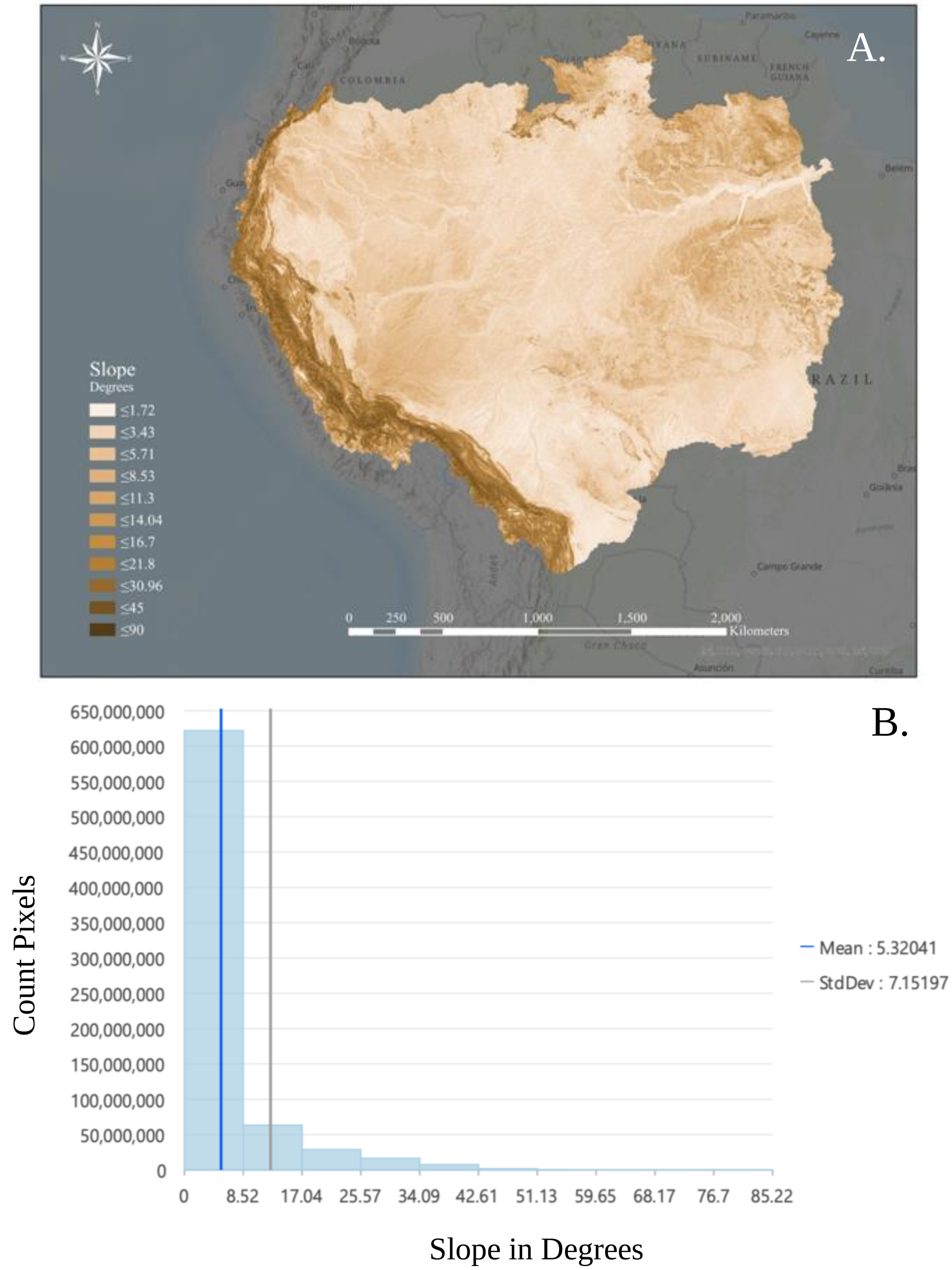


Figure 3. Slope **(A.)** and distribution **(B.)** of slopes (in degrees) in the Amazon River Basin. The average basin wide slope is 5.32 degrees with a standard deviation of 7.15 degrees and a median slope of 2.78 degrees.

Throughout the Amazon, over a hundred hydroelectric dams exist along rivers and streams (Latrubesse et al., 2017). Examining the annual trapping efficiency of four Amazonian dams however, I observe that these dams are somewhat inefficient at trapping sediment (**Table 1**). Although this sample is limited, most dams in the Amazon are very small (most with an installed capacity of less than 1000 MW; **Fig. 4**) and therefore are expected to have a low trapping efficiency. Potentially, mega dams and dams with high trapping efficiencies may affect results by reducing transport of deforestation sourced sediment. Latrubesse et al. (2017) identified the planned installation of 288 dams within the Amazon River Basin; of these planned dams, 48% were considered to be small (0-30 MW), 45% to be large (30-1,000 MW), and 7% to be “mega-dams” (>1000 MW). At the time of the study, three of the ten largest mega dams were at or near completion. Two of these mega dams, the Santo Antônio and Jirau, were observed to reduce the mean surface suspended sediment concentration of the Madeira River by approximately 20% (Latrubesse et al., 2017). With the completion of the remaining mega dams, it can be expected that deforestation-sediment dynamics will be more difficult to assess due to upstream reservoir trapping.

Table 1. Selected Dams and Estimated Trapping Efficiency

Dam Name	Size	Reservoir Capacity (MCM)	Installed Capacity (MW)	Calculated Trapping Efficiency (%)
Primavera	Small	8,400	18.2	14.64
Teles Pires	Large	897,220	53	15.94
Balbina	Large	9,755,000	250	22.06
Jirau	Mega	2,746,700	3,750	19.87

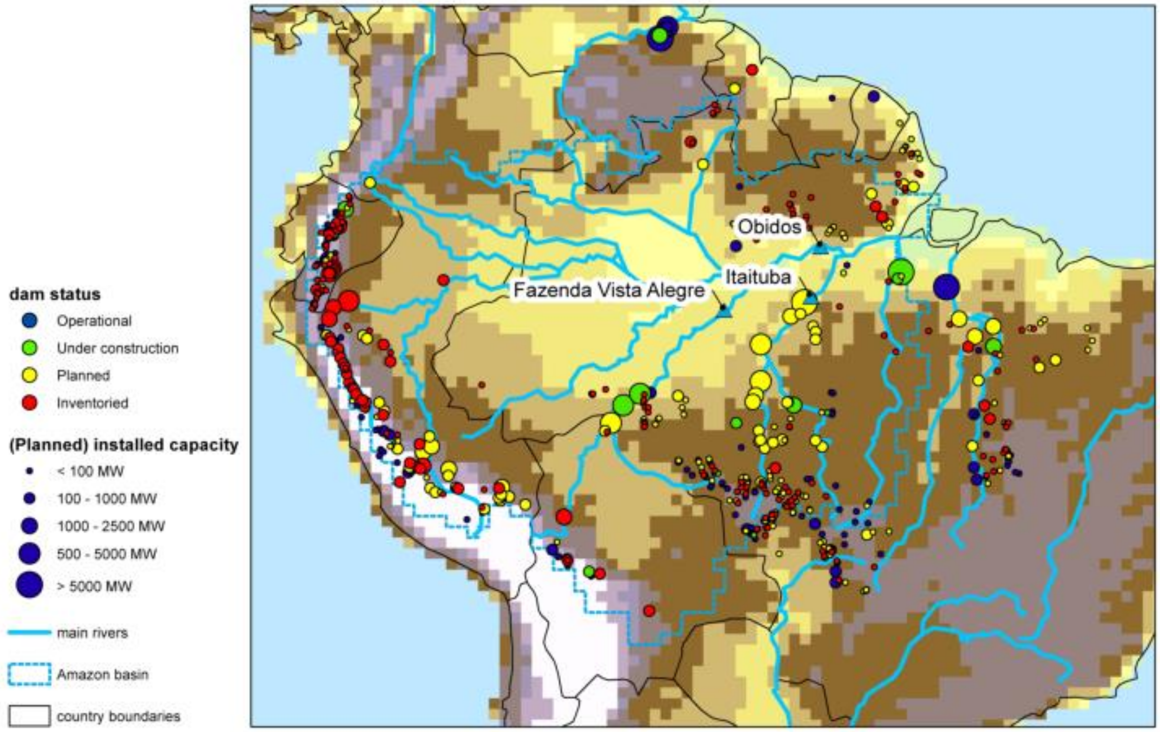


Figure 4. Locations and capacity of planned and installed dams within the Amazon River Basin; adapted from Von Randow et al. (2014)[2].

More than half (54%) of the Amazon River Basin falls within Brazil, therefore conservation and protection policies enforced within Brazil's Legal Amazon have significant implications for forest management goals basin wide. Launched in 2004, the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) is Brazil's main governance plan to reduce deforestation rates continuously while allowing for sustainable development. PPCDAm was widely successful during the first two phases of the plan (2004-2008 and 2009-2011), reducing deforestation rates by 84% from 2004 to 2012 (Silva Junior et al., 2021). PPCDAm III (2012-2015), also had positive results, leading to the creation of 50

[2] Note a typo in the legend under the installed capacity. Range for tier four says "500-5000 MW", should say "2500-5000 MW"

million acres of conservation units and of the Amazon Protected Areas Program (Pereira, n.d). Despite the success of these phases, beginning in 2012, deforestation rates began to climb yet again.

In 2012, the Native Vegetation Protection Law (Law no. 12.651, 2012) replaced Brazil's 1965 Forest Code (Law no. 4.771, 1965) allowing for greater leniency in terms of environmental regulation (Brancalion et al., 2016). Previously, the 1965 Forest Code required landowners in the Amazon to maintain 35-80% of their property under native vegetation. The 2012 law, which was heavily supported by Brazil's agribusiness lobby, *bancada ruralista*, (Hurwitz, 2012) allowed for the removal of protection for certain environmentally fragile areas, the forgiveness of fines for violations under the previous code, and the allowance for continuous farming in protected areas (Brancalion et al., 2016). These environmental setbacks allowed for further degradation of deforested land and encouraged the continuance of illegal logging.

From 2004 to 2011, one of the most efficient courses of action to reduce deforestation was "monitoring and control". The DETER and PRODES satellite forest monitoring systems allowed for deforestation to be monitored at both daily (DETER) and annual (PRODES) time scales. Despite these advancements, over time illegal loggers developed methods of deforesting areas while remaining undetected by satellites. These methods include removing only the understory of the forest, leaving the tallest trees, deforesting in smaller parcels (DETER can only detect parcels greater than 25 ha; PRODES greater than 6.25 ha), and deforesting during the rainy season when cloud cover obstructs the satellite's view (Pereira, n.d.).

Origins of Amazonian Deforestation

Large-scale deforestation in the Brazilian Legal Amazon began in the mid 1960s with the construction of the Brazilian Belém–Brasilía (BR-010) highway in 1958. Stretching from the city of Belém, Para, through the Tocantins River Basin (adjacent to the Amazon River Basin), this highway segment would be the first of a series of road developments aimed at joining the western and northern states of Brazil with the remainder of the country (Moran, 1993). Within the first twenty years of the road's completion, over 2 million people settled along the almost 2,000 km road. Land alongside this road was quickly put to use through a number of low-quality cattle ranches (Moran, 1993); during this period, the cattle population in Brazil would grow from 0 to 5 million head of cattle.

In 1968, another major highway, the Cuiabá–Porto Velho (BR-364) highway, was constructed, expanding access to the southern portion of the Amazon linking the Brazilian states of Amazonas to Mato Grosso. The Belém–Brasilía and the Cuiabá–Porto Velho highways helped carve through the Legal Amazon in the 1950s and 1960s and would later be responsible for a focal region of Brazilian Amazonian deforestation- the "arc of deforestation" (Kirby et al., 2006).

The 1964 Brazilian coup d'état put into place a military dictatorship within the country. Fearing the largely unpopulated Amazonian region of the country would be subject to foreign invasion and domestic insurgency, the new military government offered tax incentives and subsidized credits to those who migrated into the Amazon and cleared the land (Wood and Schmink, 1933). Originally, land development near these roads was planned to be executed largely by individual farmers and their families. Fueled by the 1973 Oil Crisis however, efforts by the Brazilian military government to create planned settlements and communities along road developments were halted due to rising transportation costs. Instead, the task of developing the newly accessible Amazon was assigned to large scale, private operators who were given significant tax incentives and loans to encourage development (Moran, 1993).

Within the Brazilian Amazon, large-scale cattle ranching and agricultural operations constituted the largest percentage of deforestation; in fact, only 4% of total deforestation in the 1970s had come from small-scale operations (Browder, 1988). Most of the deforestation observed in the southeast region of the Amazon River Basin (**Fig. 5**) can be tied to tax incentives and development plans encouraging land clearance by large-scale operators. Drivers of deforestation throughout the Amazon River Basin can vary based on local economics, governmental subsidies and incentives, and natural resource availability- in Guiana, goldmining is the dominant driver, in Columbia, illegal land-grabbing. Overall, however, in the Amazon River Basin, the key drivers of deforestation remain to be cattle ranching and soybean production.

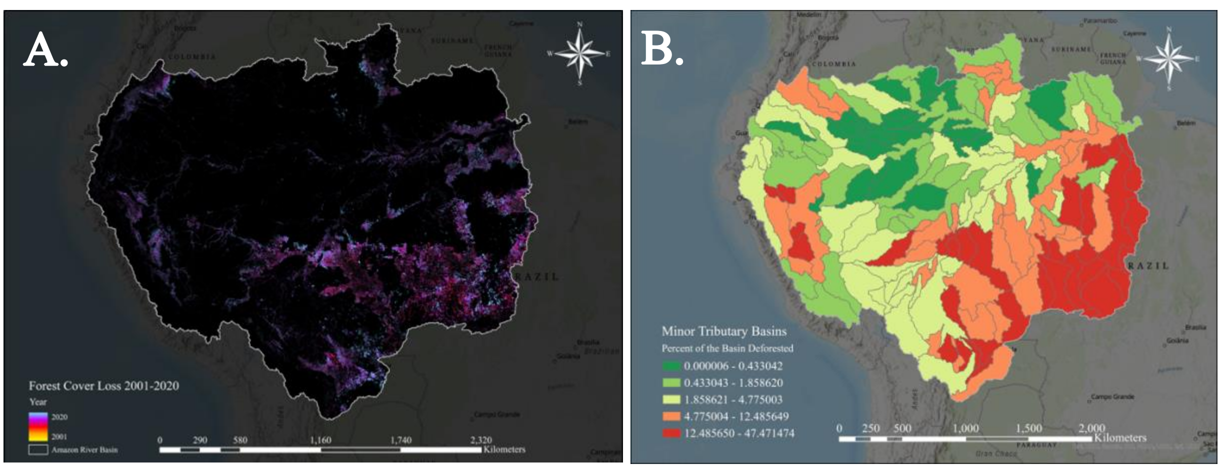


Figure 5. Forest loss within the Amazon River Basin **(A.)**, and Percent Forest loss within Amazon Minor Tributary Basins **(B.)** between 2001-2020. Each category in (B) is broken into groups containing an equal number of basins. Forest loss data was acquired from the Global Forest Change Dataset (Hansen et al., 2013).

CHAPTER 2

METHODS

To analyze sediment dynamics, I use a remotely sensed total suspended solids (TSS) dataset and in-situ observations (for validation). Sediment data is averaged annually for each river reach within the Amazon River Basin. Spatial and temporal trends in deforestation are derived from an existing satellite-based, forest clearing detection dataset. Deforestation and sediment data are grouped by sub basins to allow for a clearer trend analysis. Significant trends in precipitation and sediment are identified with a Mann-Kendall test. Sub basins with significant trends in precipitation are removed from the analysis to isolate trends due to land use. Correlations between trends in sediment and deforestation are examined with the Pearson's correlation test. These methods are illustrated in Figure 6.

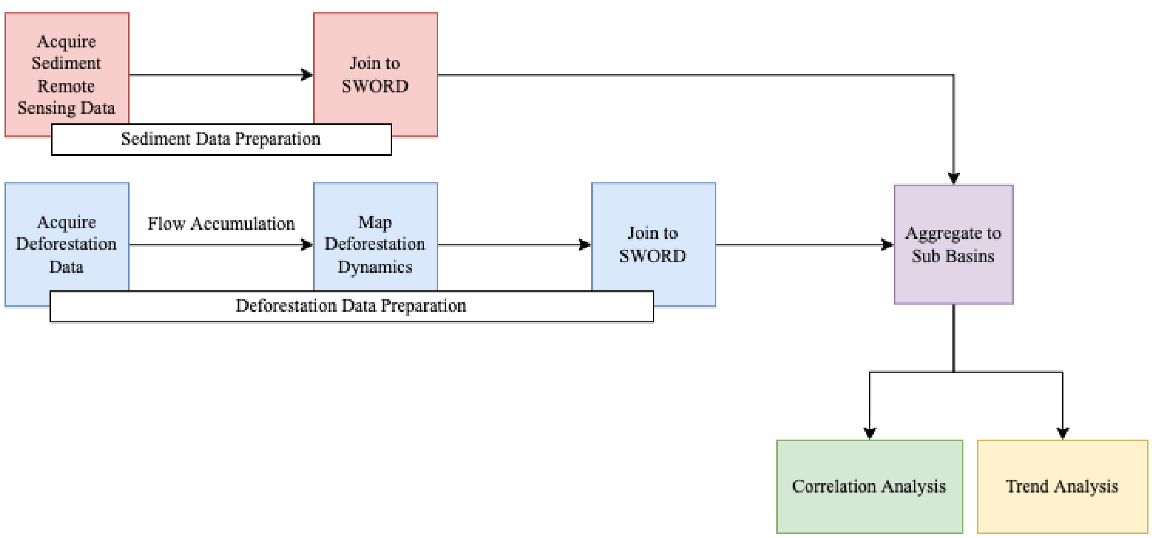


Figure 6. Flowchart of the Methodology.

Remote Sensing of Sediment

TSS data was acquired using a sediment model developed for the Amazon River Basin by Dr. John Gardner at the University of Pittsburgh. Surface reflectance values were extracted from satellite imagery from Landsat 5 Thematic Mapper I, Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Landsat 8 Operational Land Imager (OLI) using Google Earth Engine (GEE). The model was then calibrated using supervised machine learning techniques and roughly 1200 sampling points from gauging stations (Water Resources National Agency) and grab samples (Institut national des sciences de l'Univers, 2021) located throughout the basin. Satellite imagery was captured mostly during the dry season (June-September) due to cloud coverage, coinciding with the same period deforestation data is collected. Though the number of training points is relatively small for a basin as large as the Amazon, overall, the model performs extremely well (Root Mean Squared Error (RMSE) = 21 mg/L, Average Magnitude of Error (MAE) < 5 mg/L, Symmetric Mean Absolute Percentage Error (SMAPE) = 7%, Percent Bias (Pbias) = 0.01%) (**Fig. 7A**).

The TSS remote sensing model outputs were aligned with river reaches based on the Surface Water Ocean Topography (SWOT) River Database (SWORD) centerlines (Altenau et al., 2021). SWORD (V.1) combines river centerline locations and include the following attributes: river width, water body type, and number of channels attributes derived from the Global River Widths from Landsat (GRWL) dataset (Allen & Pavelsky, 2018), elevation and flow accumulation at 3 arc-second resolutions from MERIT Hydro (Yamazaki et al., 2019), Pfafstetter basin codes from HydroBASINS (Lehner & Grill, 2013), and the Global Reservoir and Dam Database (GranD) (Lehner et al., 2011). Of the 17,182 river reaches in the Amazon, 10,932 reaches had at least one year of TSS data during the twenty-year period (2001-2020).

Roughly 60% of reaches with TSS data had at least 80% of complete data (at least 18 years). Reaches ranged in length from 115 meters to 20 km, with 58% of reaches falling between 10 and 15 km in length **(Fig. 7B)**.

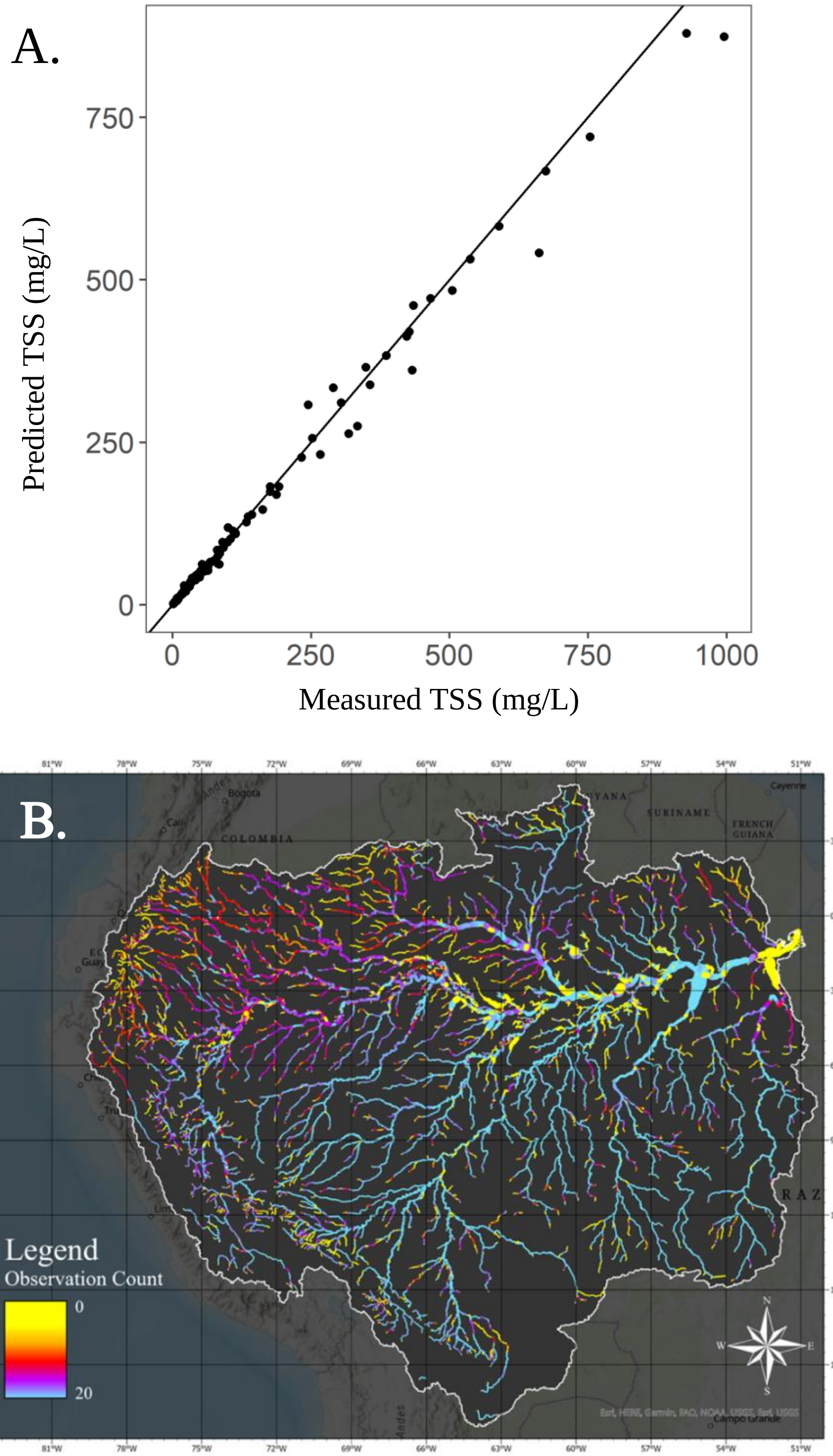


Figure 7. (A) Remote sensing derived (predicted) TSS (mg/L) vs. in situ TSS measurements (mg/L); Generated by Dr. John Gardner, University of Pittsburgh, and **(B)** Number of annually averaged TSS observations during the 2001-2020 period.

Deforestation Dynamics

The Global Forest Change (GFC) dataset is a remotely sensed, forest loss detection dataset developed by Hansen et al. (2013) in GEE. Using growing season imagery collected from the Landsat satellite series, the GFC dataset identifies changes in forest cover from the year 2000 to 2020 (v1.8) at a 30-meter resolution. Forest loss is defined as a stand-replacement disturbance, or a change from forest to non-forest (Hansen et al., 2013). In this context, the term "forest loss" does not equate loss caused exclusively by deforestation as forest loss induced by natural disasters such as tornadoes, wildfires, and hurricanes are also included. Though the purpose of this study is to investigate the effects of deforestation on suspended sediment load, the GFC dataset is used to identify areas affected non-natural forest loss (deforestation). In the Brazilian Amazon, eighty-five percent of forest loss during the 2001-2013 period occurred as a direct result of deforestation (Butler, 2021). Because most forest loss in the Amazon is not cause by natural events but rather by deforestation, I use this dataset to assess deforestation. Other datasets such as the Program to Calculate Deforestation in the Amazon (PRODES; National Institute for Space Research) and the Palsar Global Forest/Non- Forest Maps from ALOS PALSAR (Shimada et al., 2014) were considered; however, these datasets did not have the spatial coverage (National Institute for Space Research) or the temporal range (Shimada et al., 2014) desired for this analysis. The large spatial scale, temporal continuity, and high resolution of the GFC dataset remains unmatched to other forest clearing datasets available, making it the most suitable choice for this study.

To analyze the influence of deforestation on sediment dynamics, deforestation is quantified along stream networks using the ArcGIS Pro Flow Accumulation tool. Using the MERIT Hydro (Yamazaki et al., 2019) Flow Direction dataset as input into the tool, a raster is generated containing a downstream-accumulated annual deforestation “signal” along rivers from a rasterized version of the GFC dataset. The accumulation is then normalized [0,1] by dividing it by a regular flow accumulation raster (depicting the total number of accumulated grid-cells). To align the output of the annual deforestation signal to the TSS data, a 500-meter buffer was created around each river delineated in the accumulation. This was done so that river centerlines would fall within the raster delineated rivers. Using the Zonal Statistics as Table tool (ArcGIS Pro 2.8.0), the values of the annual deforestation signal is extracted by reach identification numbers. These values were then joined to the SWORD centerlines.

Not all reaches within the basin, however, contain 20 complete years of TSS data. To correct for this, deforestation signals are temporally aligned to match the presence/absence of TSS data by removing deforestation data along reaches where no TSS data exists.

Precipitation Trends

To account for potential changes in sediment unrelated to deforestation, precipitation trends during the 2001-2020 period are examined. Precipitation data was acquired from CHIRPS Daily: Climate Hazards Group InfraRed Precipitation with Station Data (Version 2.0 Final) and was processed in GEE using a statistical framework developed by Peter et al. (2021). To identify significant trends, Mann Kendall tests were performed on each minor tributary basin for each month in the 20-year period using the python statistical package pyMannKendall (Hussain et al., 2019). River reaches within significantly trending basins are removed from the final analysis to isolate changes in TSS due to deforestation rather than precipitation.

Sub-basin Aggregation

TSS and deforestation signals for each reach are aggregated into sub-basins delineated by the *Amazon GIS-Based River Basin Framework* (Venticinque et al., 2016). The framework delineates basins and sub-basins on seven different spatial scales, with basins decreasing in size as the basin level increases. Reaches are aggregated by the catchments they fall within; we examine three basin levels outlined in Table 2 and shown in Figure 8. Performing a direct reach-to-reach analysis introduces a significant amount of noise. As deforestation is predominantly concentrated in the eastern portion of the basin, the remaining central and western regions have comparatively small deforestation signals. Preliminary observations revealed that this phenomenon resulted in large amounts of clustering towards zero and negative correlations between deforestation and sediment. Aggregating the data through their respective basins is expected to reduce this noise, allowing a clearer analysis of co-variability in sediment and deforestation.

Table 2. General description of catchments system for Amazon region. *General descriptions adapted from Venticinque et al., (2016).*

General Description	Basin Level	N catchments	Average Area (km^2)
Major tributary basins > 100,000 km^2	BL3	39	178,847
Minor tributary basins < 100,000 km^2 & > 10,000 km^2	BL4	173	35,372
10,000 km^2 < sub-basins > 5000 km^2	BL5	911	1,589

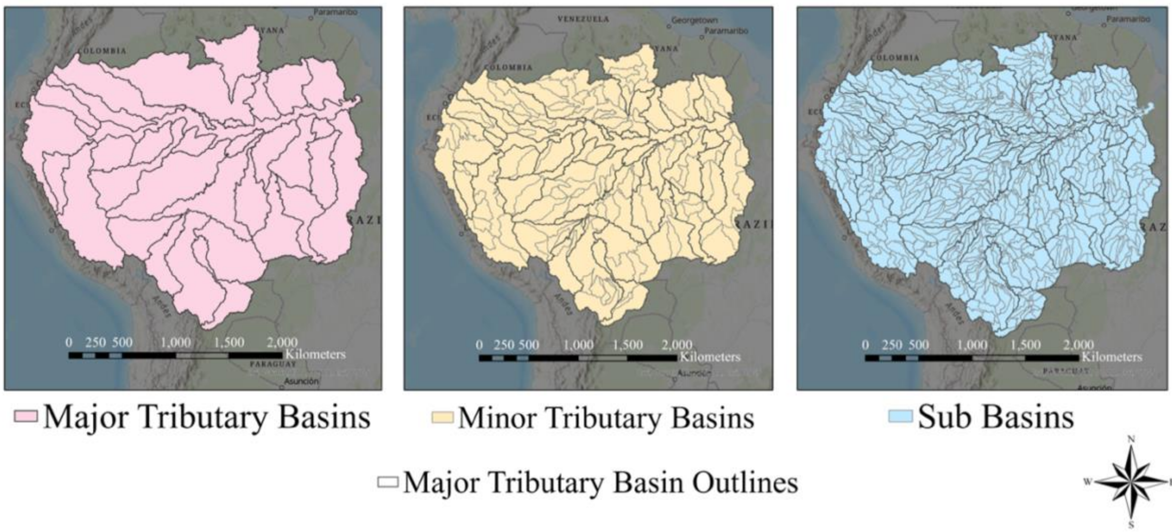


Figure 8. Basin Aggregation Levels 3 (left), 4 (center), and 5 (right).

Analysis of spatial and temporal trends in sediment

Sediment trends are analyzed throughout the basin by aggregating reaches through their respective minor tributary basins. Only reaches with at least 80% (18 out of 20 years) of complete annual TSS data are aggregated for the trend analysis to allow for a more statistically robust trend assessment. After the reaches are grouped by their respective minor tributary basins, TSS data within each basin is averaged together for each year during the 2001-2020 period. I then use a Mann Kendall test to identify significant TSS trends in each minor tributary basin with the python package, pyMannKendall (Hussain et al., 2019; **Fig. 9**)

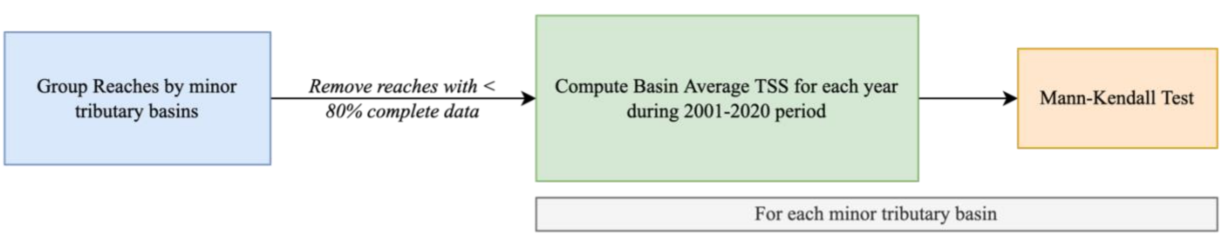


Figure 9. Sediment trend analysis methods

The overall (basin-wide) relationship between deforestation and sediment is examined by calculating the basin wide average deforestation signal and TSS for each year. A Pearson correlation is used to determine the strength of the relationship. The significance of the correlation is assessed at the 95% confidence level ($\alpha = 0.05$).

Deforestation-sediment temporal dynamics are also examined at the major tributary (BL3), minor tributary (BL4), and sub-basin (BL5) level. Reaches are grouped by their respective sub-basins (BL3, BL4, BL5); the average TSS and deforestation signal is then calculated for each basin aggregation unit, for each year. Using a Pearson's correlation ($\alpha = 0.05$), I examine the strength of the relationship between deforestation and sediment over the 2001-2020 period, within each major tributary, minor tributary, and sub-basin (**Fig. 10**).

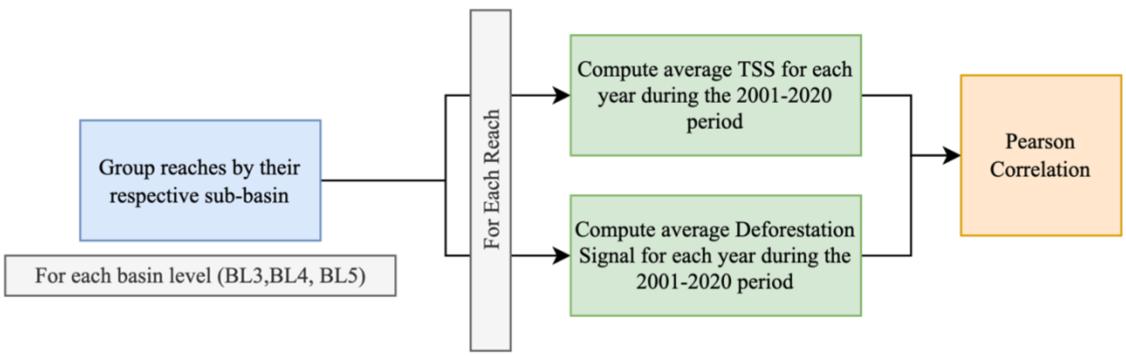


Figure 10. Methods for Temporal Analysis. This method is applied to each of the aggregation units (BL3, BL4, BL5).

To examine the spatial variability of deforestation-sediment dynamics, I compute the long-term average TSS and deforestation signal for each reach. Reaches are then grouped by their respective sub basins at the BL3, BL4, and BL5 level. A Pearson's correlation analysis (α = 0.05) is then performed within each sub-basin (with each reach equaling one data point) to assess the relationship (**Fig. 11**).

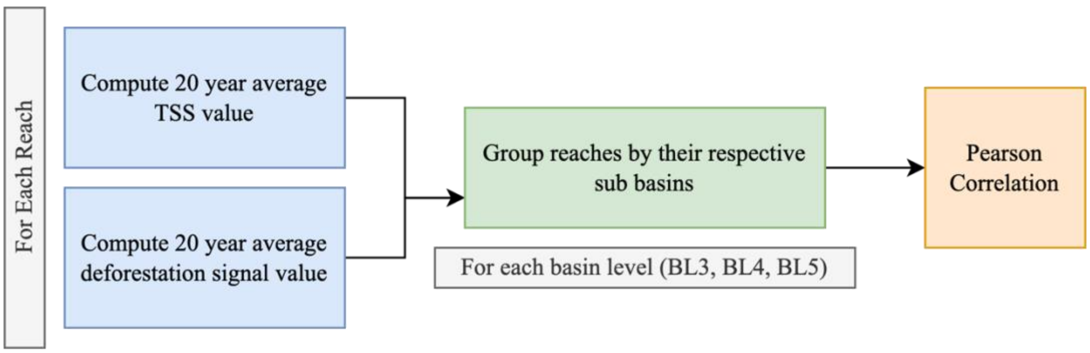


Figure 11. Methods for Spatial Analysis. This method is applied to each of the aggregation units (BL3, BL4, BL5).

CHAPTER 3

RESULTS

Trends in Precipitation

Previous studies on deforestation's effects on precipitation have produced mixed results. On a small scale, deforestation has the potential to increase local precipitation (D'Almeida et al., 2007; Satyamurty et al., 2009) due to enhanced local or mesoscale circulations. At a large scale however, the opposite effect takes place. One tropical simulation revealed that large scale deforestation in the Amazon results in an overall precipitation decrease of 138 mm/y (Bathiany et al., 2010); another described decreases of up to 266 mm/y (Sud et al., 1996). These decreases may be further exacerbated by rising CO_2 levels in the atmosphere (Kooperman et al., 2018) creating feedback loops that may further alter basin climate. As the Amazon has been subject to large-scale deforestation since the 1960s, it is to be expected that decreasing precipitation trends would be observed in the eastern region of the basin, however much of the region had no significant trends.

Of the 173 minor tributary basins analyzed, twelve basins had significant increasing precipitation trends between 2001 and 2020, while one had a decreasing trend; the remaining 160 basins had no trend (**Fig. 12**). Only in the western region of the Amazon nearing the Andes are significant trends observed (**Fig 12**). Consistent with previous observations (Baker et al., 2021), these significant trends are generally positive. Although these trends cannot be solely attributed to deforestation and examining the effect of deforestation on precipitation patterns is beyond the scope of this study, it is interesting to note this increase in the western region where deforestation is not so prolific (compared to the eastern region). To reduce the effects of precipitation on sediment trends and the deforestation-TSS analysis, reaches falling within trending sub basins are excluded in the following analyses results.

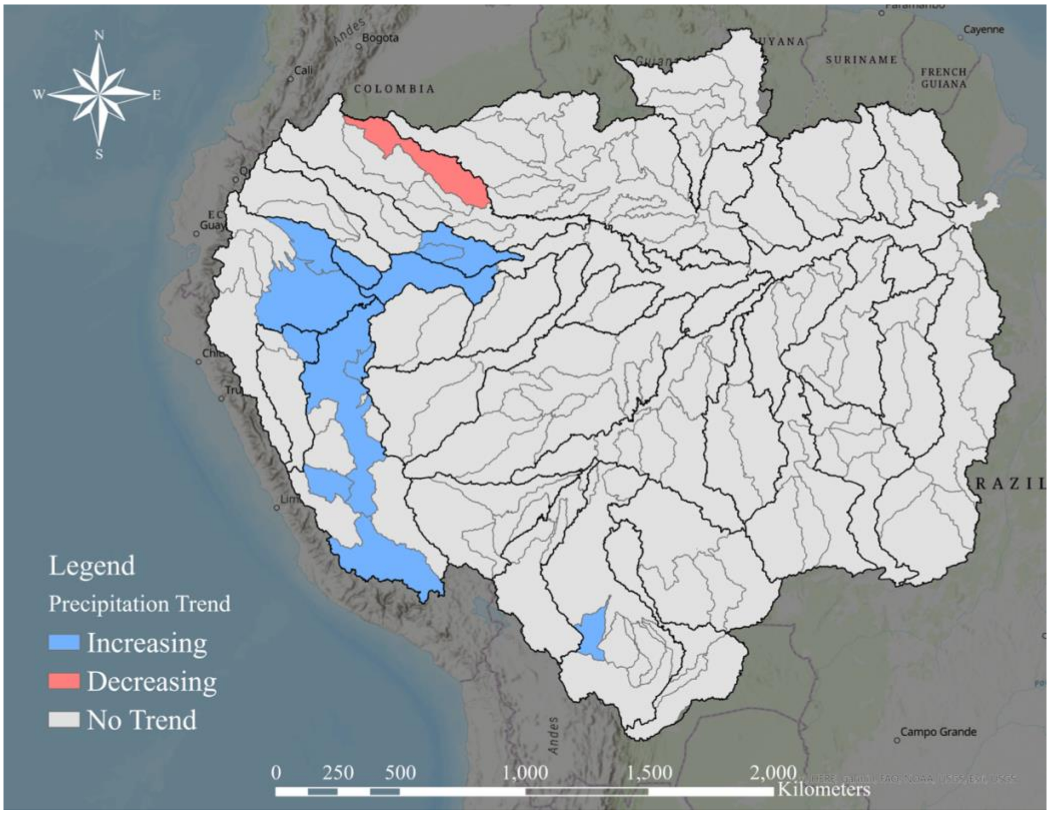


Figure 12. Precipitation trends within during the 2001-2020 period within the Amazon River Basin's Minor Tributary Basins.

Trends in Sediment

Results of the TSS trend analysis are shown in Table 3. Reaches with at least 18 years of annual TSS data were aggregated into a total of 33 major tributary, 147 minor tributary, and 542 sub-basins. Examining minor tributary basins, 28 basins, located primarily in the northern and eastern portions of the basin were identified as having a significant increasing trend in TSS (**Fig**

13). Five basins were identified as having a significant decreasing trend. The remaining 114 basins did not have a significant trend in TSS.

Although it is expected that significant deforestation will result in an increase in TSS, no differences in percent forest loss are observed between basins with increasing, decreasing, and non-trending TSS at the major and minor tributary basin scales (tested using ANOVA; **Table 4**). At the finer, sub basin level, differences are noted between TSS trends and the percentage of each sub basin deforested. Sub basins with increasing TSS trends are observed to have a greater percentage of their basin deforested compared to basins with decreasing or no trend (**Table 3**). When comparing the slope of the trend with the percent of the area deforested, no significant correlation is observed, signifying that this relationship may exist in a more general sense than a direct 1-1 relationship. Potentially, other factors influencing TSS trends that exist within each basin prevent the establishment of a strong relationship between trends and deforestation.

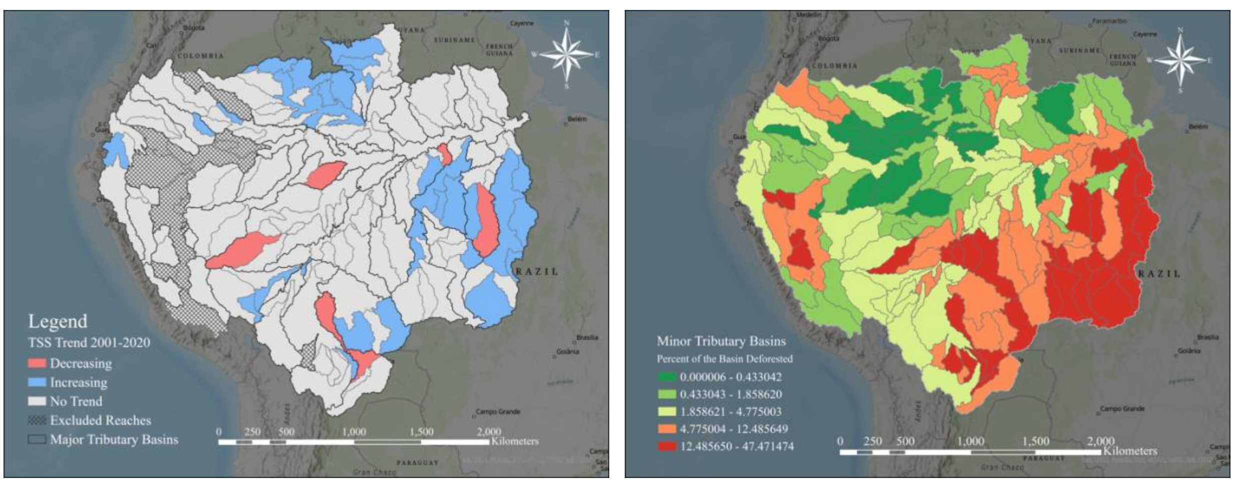


Figure 13. Significant Trends identified in annual TSS within the Amazon River Basin's Minor Tributary Basins **(A)** and Percent Forest loss within Amazon Minor Tributary Basins **(B)** between 2001-2020.

Table 3. Summary Statistics for TSS Trends and percent forest loss for major, minor, and sub-basins.

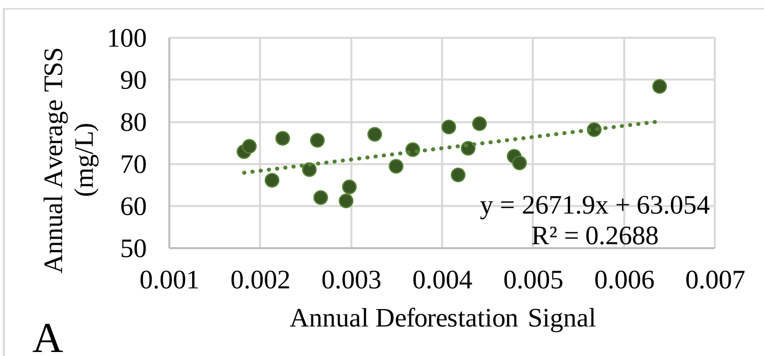
Basin	*TSS Trend*	*Count*	*Average % Deforested*	*Std. Dev*
Major Tributary	Increasing	6	7.7	5.86
	Decreasing	2	6.9	8.60
	No Trend	25	5.8	5.89
Minor Tributary	Increasing	28	8.7	8.90
	Decreasing	5	5.6	4.46
	No trend	114	6.9	8.25
Sub Basins	Increasing	44	8.3	8.41
	Decreasing	23	1.7	3.44
	No Trend	422	5.1	7.25

Table 4. ANOVA results for TSS Trends and percent forest loss for major, minor, and sub-basins. * Indicates a significant correlation

Basin	*Source of Variation*	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Major Tributary	Between Groups	18.26	2	9.13	0.25	0.77	3.31
	Within Groups	1079.59	30	35.98			
Minor Tributary	Between Groups	88.86	2	44.43	0.64	0.52	3.05
	Within Groups	9925.7	144	68.92			
Sub Basin	Between Groups	709.01	2	354.50	6.76	0.001*	3.01
	Within Groups	25463.3	486	52.39			

Deforestation-Sediment Temporal Relationship

In the Amazon River Basin, basin averaged TSS and deforestation signals do not appear to have a significant increasing or decreasing trend during the 2001-2020 period. This is to little surprise as basin wide deforestation trends only began to decline in 2004 (before increasing again in 2012) and no long-term trend in sediment has been observed at the most downstream gauging station on the Amazon (Óbidos; Montanher et al., 2018). Overall, there is a weak, yet statistically significant correlation between deforestation and sediment (**Fig. 14A**; $R^2 = 0.27$; $p = 0.019$). During the 2001-2020 period, annual TSS generally follows increases and decreases in deforestation signals. Exceptions to this generality occur in 2016 and 2017, where spikes in deforestation are observed with no corresponding response in TSS (**Fig. 14B**). When removing these two years, the correlation (R^2) increases from 0.26 to 0.33.



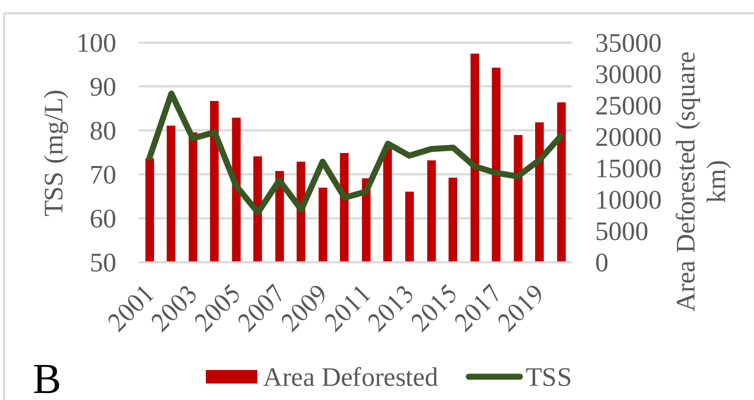


Figure 14. Basin Wide Annual TSS (mg/L) vs. Annual Deforestation Signal **(A.)** and Annual Basin Averaged TSS and Area Deforestation **(B.)** for the period of 2001-2020.

Coincidentally, until the passage of Brazil's Native Vegetation Protection Law, the relationship between deforestation and TSS was very strong with a correlation (R^2) of 0.60 compared to 0.15 after 2012 (**Fig. 15**). Potentially, land use changes as a result of the Forest Code revision may have affected this trend. As areas once protected were put to agricultural and developmental use, degradation of these fragile landscapes may have produced unexpected changes in sediment dynamics. Simultaneously, the relatively new illegal deforestation tactics developed to undermine satellite monitoring may have reduced the detection of deforestation parcels.

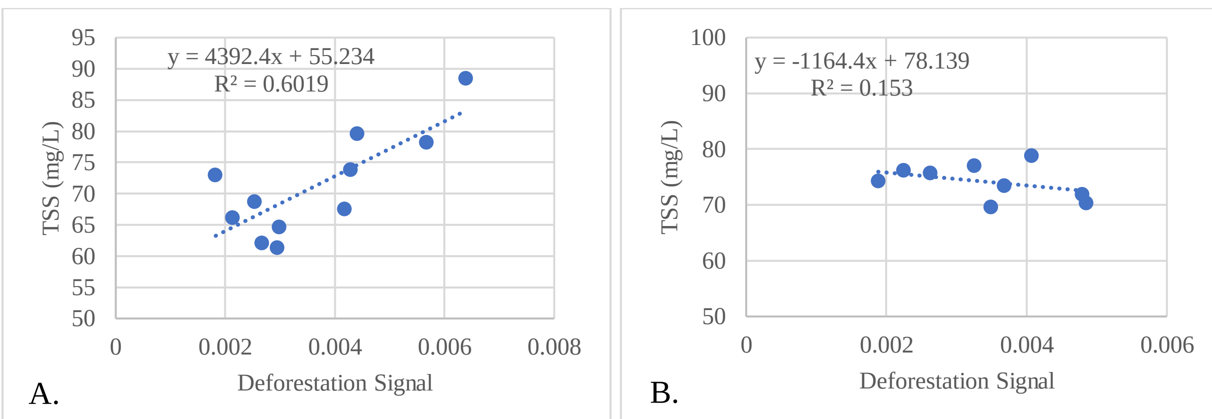


Figure 15. Basin Wide Annual TSS (mg/L) vs Annual Deforestation Signal for 2001-2011 **(A.)** and 2012-2020 **(B.)**

Within the Amazon's major tributary basins, only 15% (5 out of 33) of basins had a significant positive temporal correlation (**Fig. 16A**). These temporal correlations were determined by calculating a Pearson's Correlation between the basin averaged TSS and deforestation signal for each year. The percentage of significant correlations decreases within minor tributary basins; only 8% (12 out of 149) of minor tributary basins had a significant correlation (**Fig. 16B**). At the sub-basin scale, similar results are observed with 8.6% (58 out of 674) of basins having significant correlations (**Fig. 16C**). Although I expected to observe stronger temporal correlations within more heavily deforested basins, no significant correlations are observed at the major, minor, or sub basin scale.

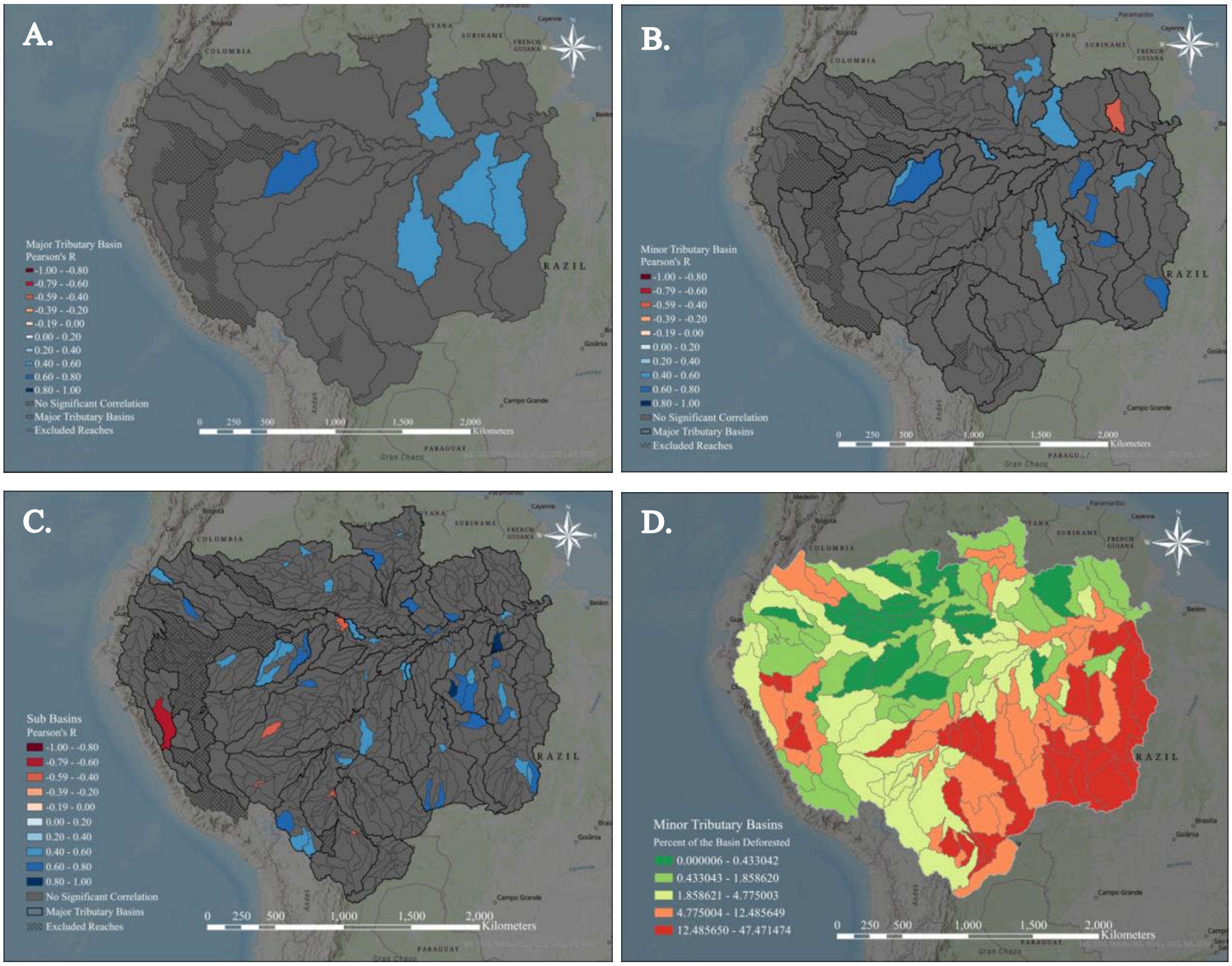


Figure 16. Significant Deforestation-TSS Temporal Correlations within Major Tributary Basins (**A**), Minor Tributary Basins (**B**), and sub-basins (**C**) of the Amazon River Basin Percent of each minor tributary basin deforested is shown in (**D**) for reference.

Deforestation-Sediment Spatial Relationships

Compared to temporal correlations, spatial correlations appear more prominent throughout the basin. While temporal correlations were determined by examining the basin averaged TSS and deforestation signal for each year, spatial correlations were determined by calculating a Pearson's Correlation between the long term average TSS and deforestation signal. Examining the Amazon's major tributary basins, most basins have a statistically significant, positive spatial correlation between deforestation and sediment (**Fig. 17A**). Stronger spatial correlations are generally found in the southern major tributary basins whereas weaker correlations are found in northern basins. Of the thirty-three major tributary basins analyzed, only six did not have a significant correlation.

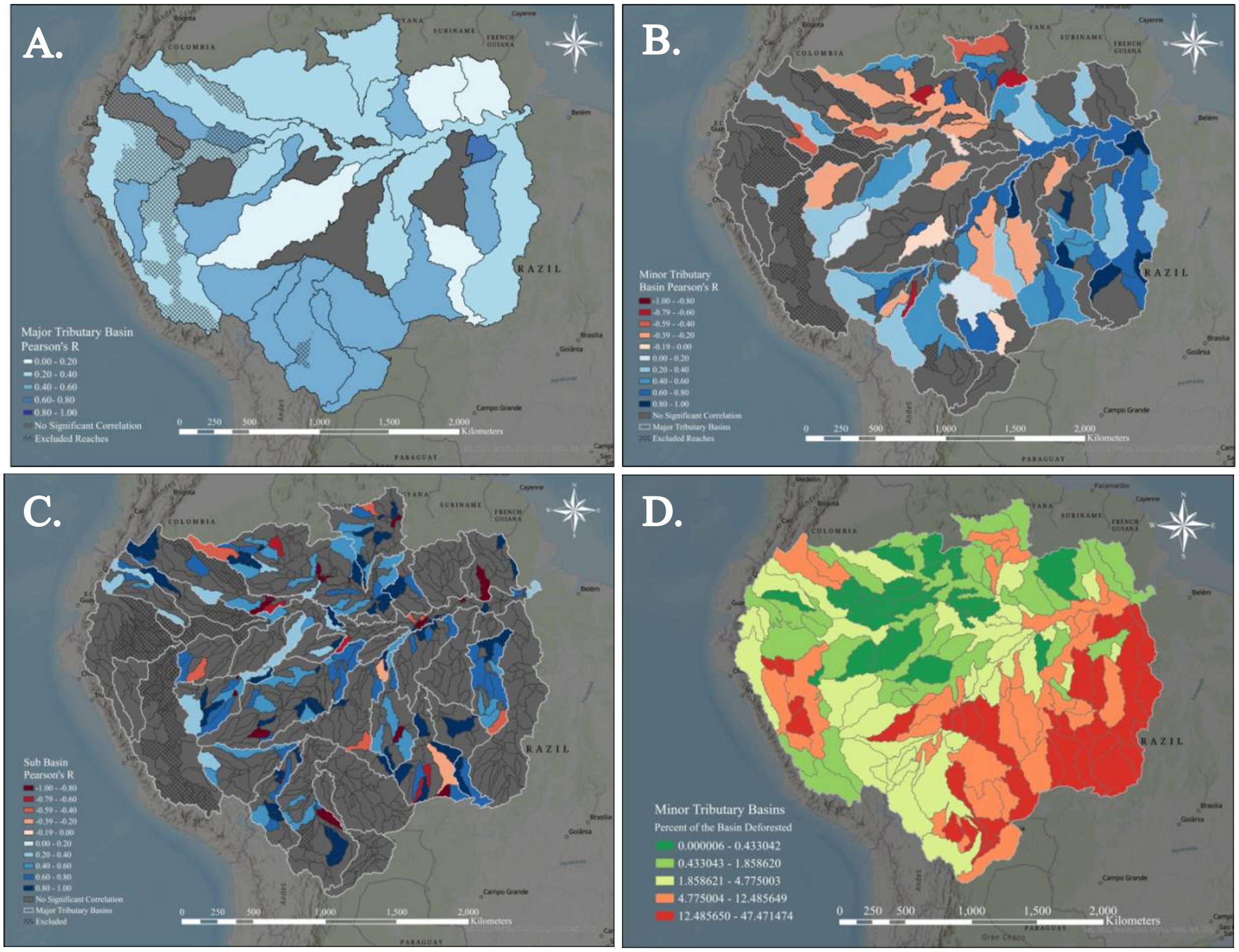


Figure 17. Significant Deforestation-TSS Spatial Correlations within Major Tributary Basins (**A**), Minor Tributary Basins (**B**), and Subbasins (**C**) of the Amazon River Basin. Percent of each minor tributary basin deforested is shown in (**D**) for reference.

Within minor tributary basins, 69 out of 159 total basins had significant spatial correlations; of which, 73.91 % had a positive correlation. Compared to major tributary basins, minor tributary basins are observed to have a greater variability in correlation strength and polarity. Strong, positive correlations are observed in southeastern basins where the incidence of deforestation is greater. Weak and negative correlations are found throughout the northwest and south-central basins, further away from the deforestation “hot zones” (**Fig. 17B**).

Sixty-three percent of the Amazon's sub-basins were found to have a significant spatial correlation; most of these significant correlations were positive (65%). Unusually, these correlations appear to fall along major rivers in the basin (**Fig 17C**). This was suspected to be the result of the propagation of deforestation sourced sediment downstream however, when comparing the average drainage area to the correlation strength, no significant relationship was observed.

Within minor tributary basins, a significant positive correlation ($p < 0.0001$) is observed between spatial correlation and percent forest loss (**Fig. 18**). Generally, sub basins with a large percentage of area deforested have a strong, positive spatial correlation; simultaneously, as deforestation increases, negative correlations become weaker.

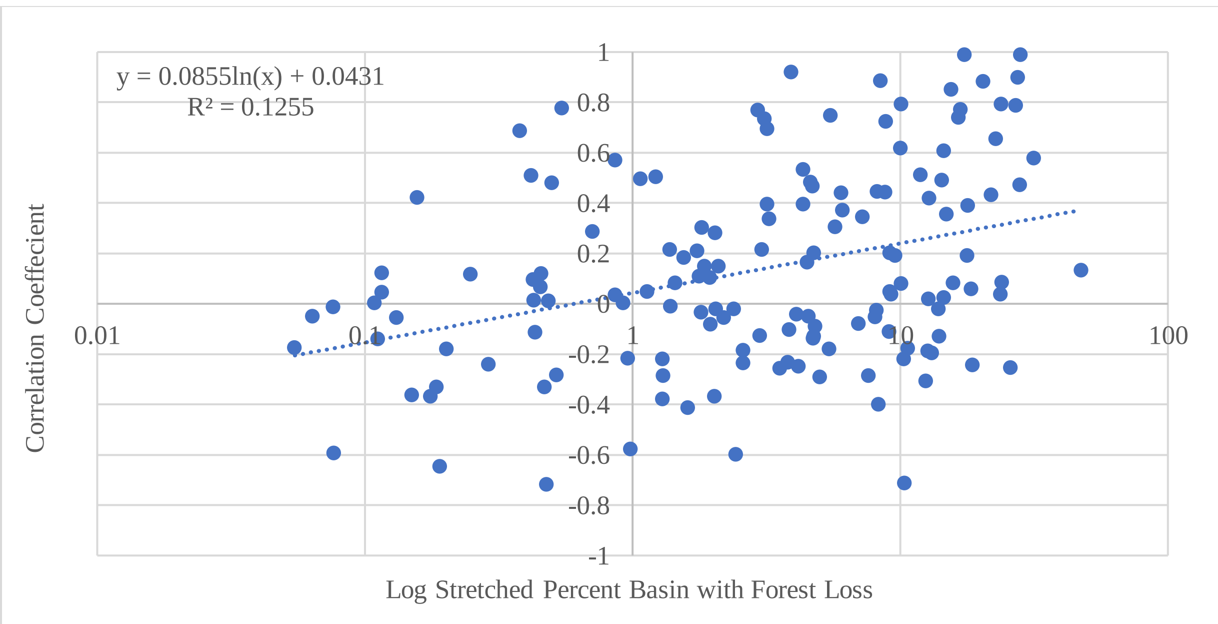


Figure 18. Minor Tributary Basin Spatial Correlations vs. Percentage of sub-basin forest loss

Similar results are observed in Figure 19. Sub basins with a large long-term[3] average deforestation signal are shown to have a strong, positive spatial correlation (**Fig. 19A**). Similarly, sub-basins with a large total deforestation signal have a strong, positive spatial correlation (**Fig. 19B**). Both these relationships are significant at the 95% confidence level (both p values are < 0.00001).

Grouping deforestation amounts into three categories (less than 5% deforested, between 5 and 10 percent deforested, and greater than 10% deforested), I observe significant differences in the average spatial correlations of these groups. Heavily deforested sub basins (>10% deforested), had a greater average correlation than sub basins with medium (between 5 and 10%) or little (<5%) deforestation **(Table 5, Table 6)**.

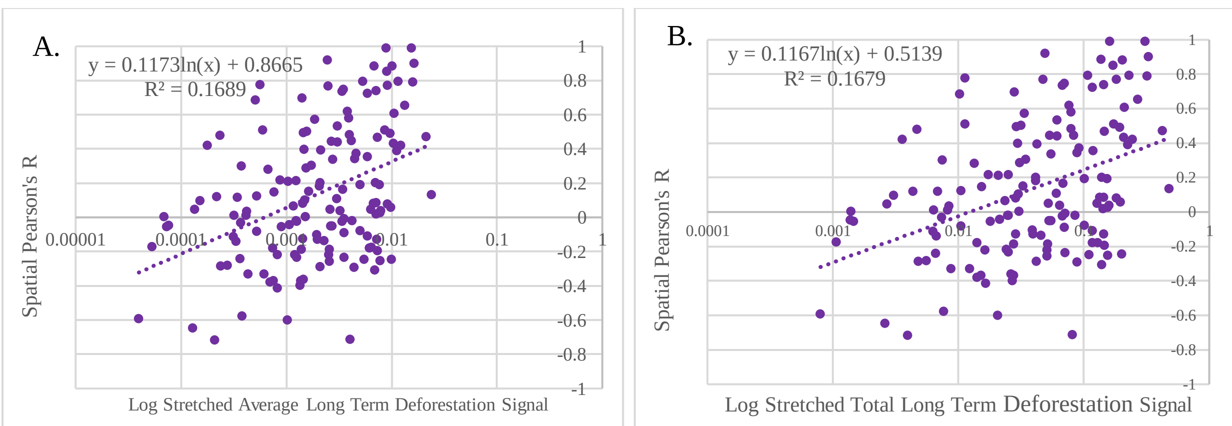


Figure 19. BL4 Deforestation-TSS Spatial Correlations (Pearson's R) vs. Log Stretched Average Long Term Deforestation Signal **(A.)**, BL4 Deforestation-TSS Spatial Correlations (Pearson's R) vs. Log Stretched Total Long Term Deforestation Signal **(B.)**.

Table 5. Summary Statistics for BL4 Correlations (grouped by deforestation)

Percent Deforested	*Basins within Group*	*Average Correlation*	*Std.Dev*
Less than 5%	85	0.04	0.34
Between 5-10%	21	0.17	0.34
Greater than 10%	40	0.30	0.42

[3] Over the 2001-2020 period

Table 6. ANOVA Results for BL4 Correlations. * Indicates a significant correlation

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.92	2	0.96	6.78	0.001*	3.05
Within Groups	20.29	143	0.14			
Total	22.21	145				

Observing only *significant* spatial correlations with long term deforestation averages, two distinct groups are shown in Figure 20; in this plot, positive correlations are shown in green, and negative correlations are shown in red. Within the positive correlation group, I identify a significant increase in correlation strength as the long-term average deforestation signal increases ($p < 0.001$). Simultaneously, negative spatial correlations, are significantly weakened as the deforestation signal increases ($p = 0.043$).

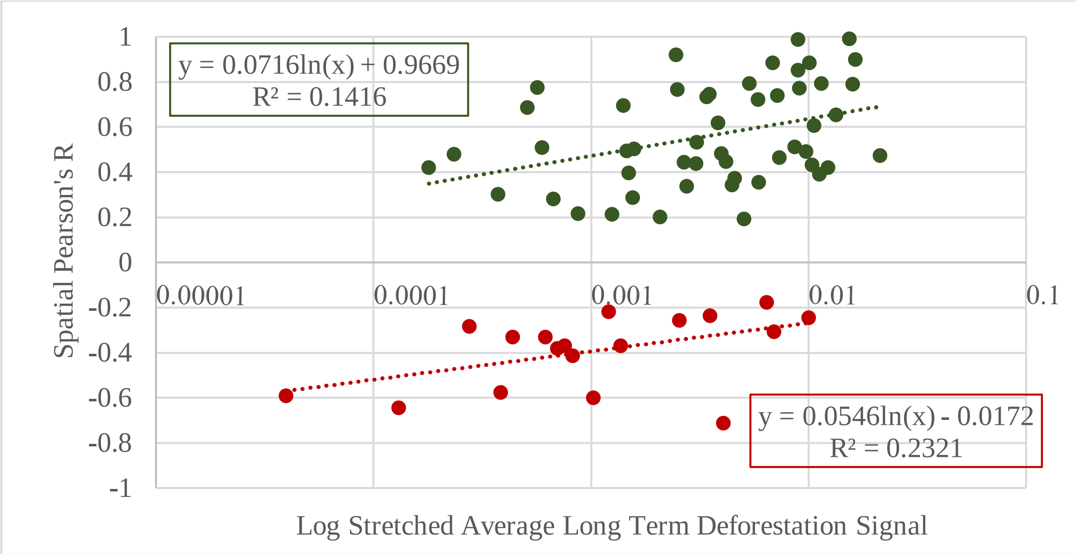


Figure 20. BL4 Significant Deforestation-TSS Spatial Correlations (Pearson's R) vs. Log Stretched Average Long Term Deforestation Signal. Green points indicate basins with positive spatial correlations. Red points indicate basins with negative spatial correlation

CHAPTER 4

DISCUSSION

Throughout the Amazon River Basin, temporal correlations vary greatly in strength and polarity between major, minor, and sub-basins. Generally, basin wide TSS trends follow that of deforestation apart from 2016 and 2017 (**Fig. 14**). From late-2015 to mid-2016, positive anomalies in fire occurrences[4] were observed in the Brazilian Amazon (Silva Junior et al., 2019). Simultaneously, the Amazon experienced extreme drought conditions brought on by a combination of overall regional warming and weather pattern changes driven by the 2015/2016 El Niño Southern Oscillation (ENSO) (Jiménez-Muñoz et al., 2016). Although these fires occurred during the wet season, the severe drought caused by the ENSO may have reduced the sediment transport capacity in the Amazon, thereby limiting the observable TSS response in later years

In previous studies, stronger relationships between deforestation and sediment are observed within smaller river basins compared to larger river basins. For example, in New Zealand's Waipoa River System, which encompasses an area of 1,987 km^2, Kettner et al. (2007) observed a sixfold increase in suspended sediment discharge at the river outlet due to deforestation. In Wisconsin's North Fish Creek (drainage area of 122 km^2), deforestation and human settlement was observed to increase sediment to 4-6 times pre-settlement rates. (Fitzpatrick & Knox, 2000). In larger catchments however, the influence of deforestation on

[4] Fire is the primary method of forest clearing in the Amazon.

sediment appears to decrease as more variability is introduced into the relationship. Within Spain's Ebro River basin (85,530 km^2), long term anthropogenic land use was revealed to increase sediment by 35%, from 30.5 Mt $yr.^{-1}$ to 47.2 Mt $yr.^{-1}$ over a 4000-year period (Xing et al., 2014). In the Magdalena River Basin (273,459 km^2), Restrepo et al. (2015) observed a 9% increase in sediment load attributable to deforestation. Transport processes, such as deposition and dilution of the deforestation-sourced sediment[5], are magnified at larger basin scales. The increased occurrence of these processes allows for large basins to have a greater buffering capacity, and therefore produce a small sediment delivery ratio[6] (Walling, 1983, Walling 1999).

Following this logic, it would be assumed that within a very large river basin like the Amazon (6,300,000 km^2) and even its smaller tributaries, the relationship between deforestation and sediment would be extremely weak. However, the results show that 26% of the temporal (yearly) variability in sediment is attributed to deforestation (**Fig. 14A**). Though the relationship between deforestation and TSS appears to be somewhat weak, for a basin as large as the Amazon, this observation of 26% is considerable. It is important to note that these prior studies used to compare deforestation's influence on sediment examined relationships at the river outlet. However, because studies examining basin-wide sediment dynamics are limited, these were used as a reference point.

Examining the distribution of temporal correlation[7] strengths (Pearson's R), smaller basins were observed to have a wider distribution compared to larger basins which tended to have a narrower range (**Fig. 21A, B, C**). For example, within major tributary basins, all

[5] Due to water influx from other streams
[6] Ratio of sediment yield to gross erosion
[7] Correlation between the basin averaged TSS and deforestation signal for each year.

significant temporal correlations were positive with R values ranging from 0.44 to 0.63 (**Fig. 16A**; **Fig. 21A**). This range increases to 0.44 to 0.77 within minor tributary basins (**Fig. 16B**; **Fig. 21B**) and -0.64 to 0.95 within sub-basins (**Fig. 16C**; **Fig. 21C**). Although negative correlations are observed within the sub basin scale, stronger correlations are also present. I suspect this to be the result of some statistical bias when averaging large amounts of data. Larger basins have a greater number of reaches within them, therefore, when aggregated (averaged) they are more likely to reflect a value closer to the basin wide mean. Smaller basins, however, have a smaller number of reaches within them and may be better suited for use in deforestation-TSS studies as they are more likely to reflect local relationships. For example, the sub basin, Tapajós 912, had the strongest temporal correlation out of all sub-basins (BL5, R = 0.95); this sub basin contains only 7 reaches. At the larger scale (BL3), 97 reaches fell within the main Tapajós basin, however no significant temporal correlations were observed at this level (R=0.06). Similar observations are noted when examining spatial correlations (**Fig. 17**). At large scales, significant correlations are found throughout the basin (**Fig. 17A**), however the strength of these correlations increase at smaller scales (**Fig. 17B, Fig. 17C**).

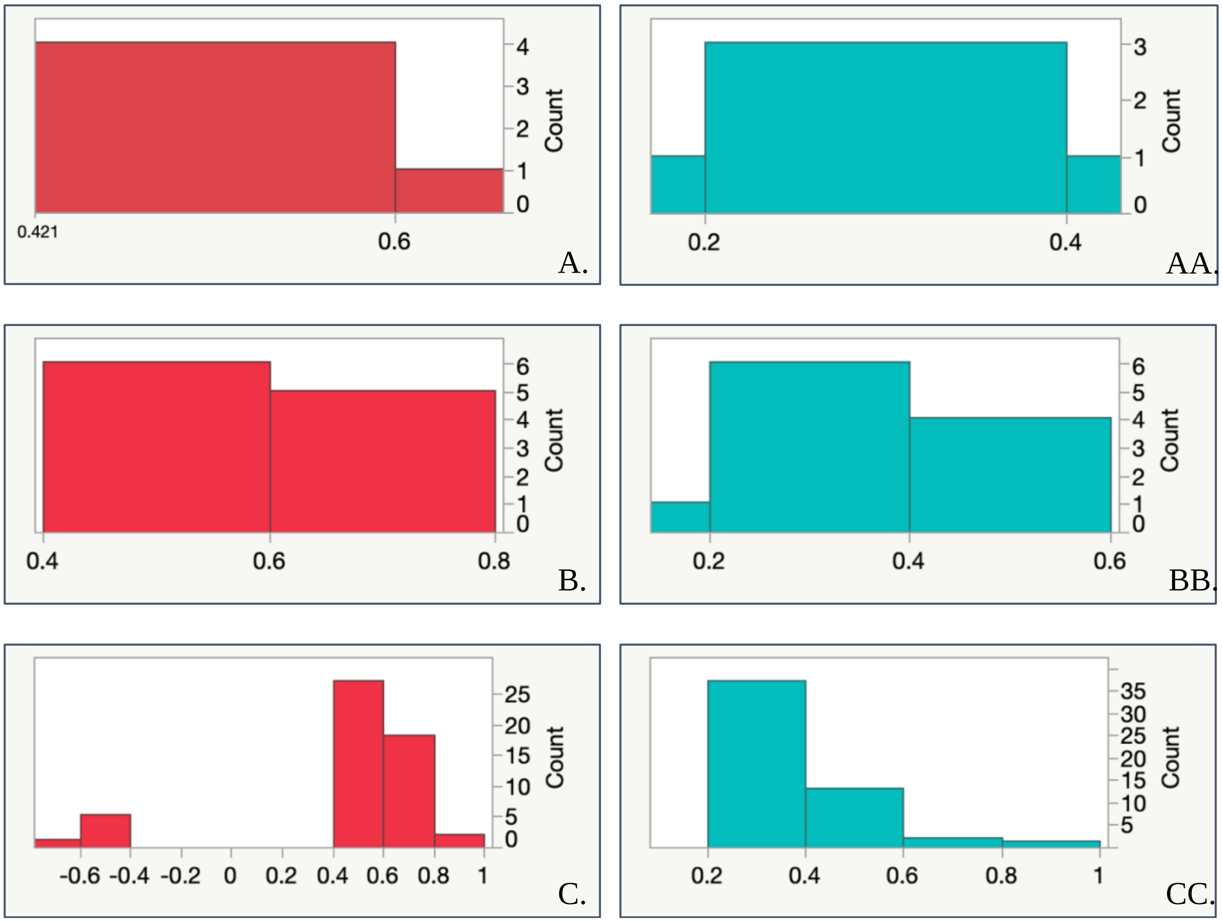


Figure 21. Histograms of Significant temporal R and R2 values for Major (**A and AA**), Minor (**B and BB**), and Sub-basins (**C and CC**).

Though this may be due in part to a biasing effect, I believe that these differences may also be used to explain an observed "proximal" effect of deforestation. When aggregating over large areas, streams affected by small amounts of deforestation and large amounts of deforestation are grouped together, thereby "canceling" each other out and weakening the correlation. However, over smaller areas, deforestations effects are stronger, yielding stronger correlations.

Strong, positive spatial correlations between deforestation and TSS are predominantly observed in southeastern sub-basins where deforestation rates are high (**Fig. 17B**). As expected, deforestation's influence on TSS increases in strength as a greater percentage of each basin is deforested ($p = 0.0001$; **Fig. 18**). Weak spatial correlations found throughout the north- and south-central basins may be partly attributed to limited amounts of deforestation occurring within these areas (**Fig. 5**). Over the 2001-2020 period and in decades prior, deforestation has been heavily concentrated in the southeast and northern region of the Amazon River Basin (**Fig. 5**). Potentially, increasing TSS trends observed within these regions (**Fig. 13**) were the result of significant deforestation during this time as strong, positive spatial correlations are also observed within these regions (**Fig. 17)**. Given this, it is suspected that a large amount of deforestation must occur over a long period of time to produce a significant effect on sediment (**Fig. 19**). As deforestation has only recently begun to spread into the north and south-central basins, the long-term impact of deforestation may not have had enough time to "accumulate", thereby limiting sediment response.

In the Northern region of the basin significant increases in sediment concentration were observed (**Fig. 13**), however it is unlikely that these increases can be attributed to deforestation. Rather, these increases may be more strongly tied to mining within the region. Illegal mining in the Amazon largely occurs in the western region of the basin near the Andes and in northern regions of Brazil near Venezuela. Although only 9% of deforestation in the Brazilian Amazon has been tied to mining activities (Sonter et al., 2017), these activities produce a greater amount of sediment compared to cattle ranching and soy cultivation due to excavation processes.

Though it is observed that deforestation has a long-term effect on sediment response (Fitzpatrick & Knox, 2000; Ochiai et al., 2015), attempts to directly quantify the amount of time that deforestation had a discernable influence on sediment as well as the rate of decreasing influence were proven unsuccessful. As forest loss and TSS is measured at an annual timestep in this study, the cumulative effects of deforestation may have been lost through temporal and spatial aggregations. Potentially, this effect may only be identified in data at a finer temporal (e.g., seasonal, monthly) and spatial resolution (e.g., reach level) compared to the courser data used in this analysis.

For deforestation to significantly influence sediment regimes, there must be a large amount of deforestation present within/upstream of the basin. Even when TSS within the basin is decreasing due to external factors, significant correlations can still be identified given that deforestation is still large. For example, the Iriri and the Coari Grande minor tributary basins were both identified as having significant decreasing sediment trends over the 2001-2020 period, however the Iriri had a significant, positive spatial correlation while the Coari Grande had a negative correlation. What differentiates these basins is the amount of deforestation influencing sediment dynamics. Comparing the twenty-year average and total deforestation signal, as well as the percent of each basin deforested, the Iriri is subjected to more deforestation than the Coari Grande (**Table 7**). Potentially, because deforestation has a very strong influence on the Iriri's sediment dynamics, TSS decreases at a lesser rate allowing the basin to maintain a positive correlation.

Table 7. Iriri and Coari Grande Minor Tributary Basin Comparison Chart

	Minor Tributary Basin	
	Iriri	Coari Grande
Spatial TSS-Deforestation Correlation	Positive	Negative
TSS trend (slope)	-0.116	-1.009
Percent Basin Deforested	6.1%	0.52%
Avg. Deforestation Signal 2001-2020	0.004	0.0002
Sum Deforestation Signal 2001-2020	0.091	0.005

Unusually, at the minor and sub basin observation scales, significant negative correlations were observed in both the temporal and spatial analysis (**Fig.16, Fig. 17**). Potentially, these basins may not have enough deforestation to influence sediment regimes; rather, other agents such as damming, flooding, or changes in discharge may have a dominating effect on sediment dynamics. Or, these negatively trending basins may be experiencing a natural decline in sediment and require a significant amount of deforestation sourced sediment to alter its trend (**Table 7**). Another possibility is that these basins may have a larger buffering capacity due to variations in basin topology (vegetation, additional streams, etc.). These basins will, therefore, require a greater amount of deforestation to alter sediment levels. As a basin is exposed to more deforestation, the buffering capacity is more likely to be exceeded. The effects of these impediments (damming) and processes (flooding, buffering ability) are difficult to account for on a broad, basin wide analysis. The presence of these negative correlations requires further investigations into the complex factors that influence local sediment dynamics.

Within this study, deforestation-sediment relationships were examined through major tributary basins, minor tributary basins, and sub-basins. As relationships were examined at finer scales, shifts in significance and correlations are observed throughout the basin. Scaling and aggregations (Openshaw, 1983) as well as the resolution of data (Peter et al., 2020) directly affects the analyses results. Therefore, it is important to examine relationships at multiple scales to gain a more accurate understanding of deforestation-sediment dynamics. One example of variations occurring within different basin scales is observed within the Minor Amazon tribs Jutai (BL3). Over the twenty-year period, the basin had a significant positive temporal correlation between deforestation and sediment. However, when examining relationships within its sub-basins, we observe both regions with and without significant correlations (**Fig. 22**). I suspect that during the study period, deforestation within this basin predominantly occurred within its significantly trending sub-basins. Potentially, these correlations were strong enough to allow for it to appear that the correlation was present throughout the entire basin rather than in the sub basins where they truly existed.

Within the spatial analysis, Minor Amazon tribs Jutai had significant correlations within major and minor tributary basins however, at the sub-basin scale no sub basins were shown to have a significant correlation (**Fig. 23**). The lack of significant correlations at finer scales does not necessarily signify a lack of correlation overall, rather it may mean that the spatial relationship within this basin exists in a more general sense than at finer spatial scales.

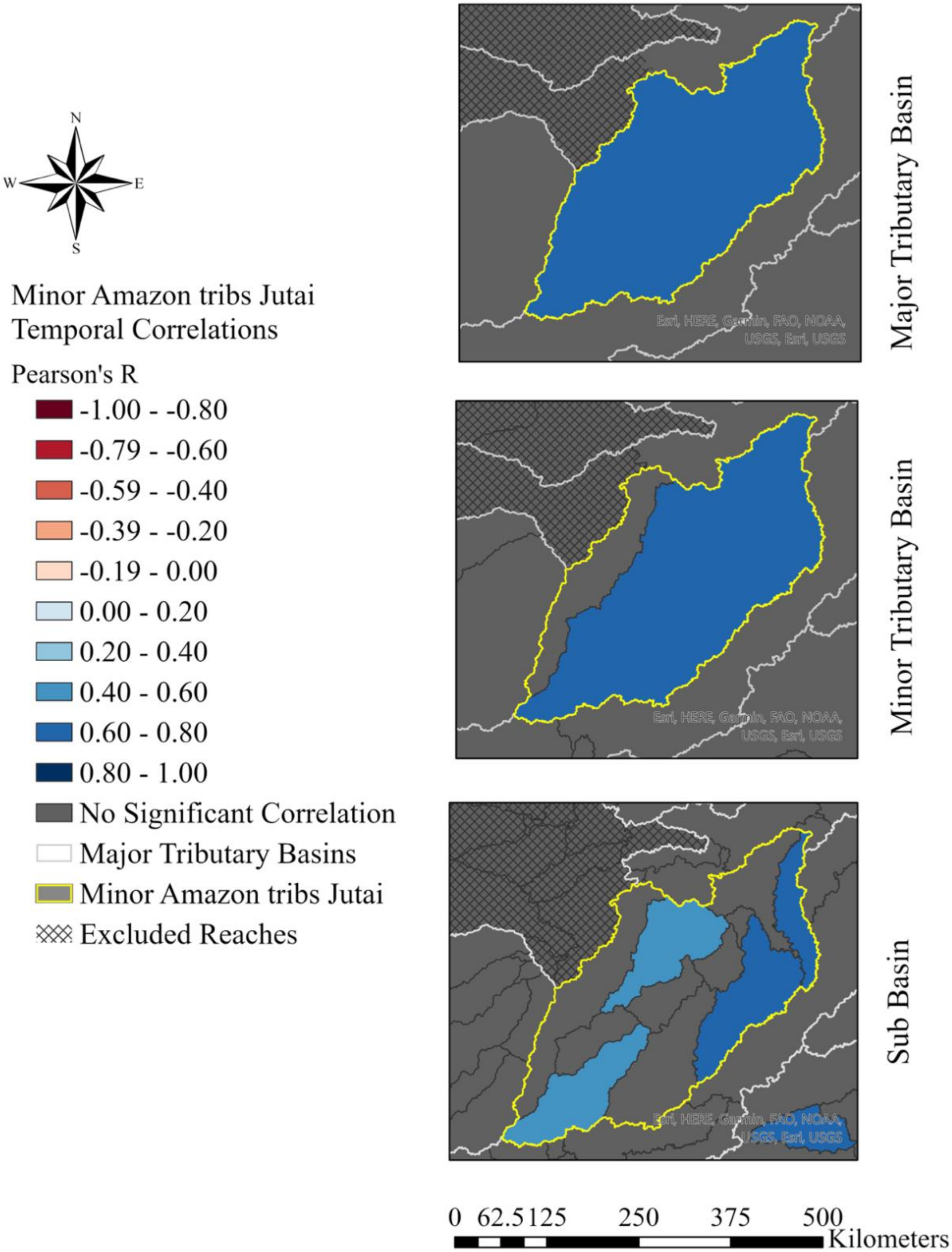


Figure 22. Temporal TSS-Sediment Correlations within the Minor Amazon tribs Jutai, 2001-2020

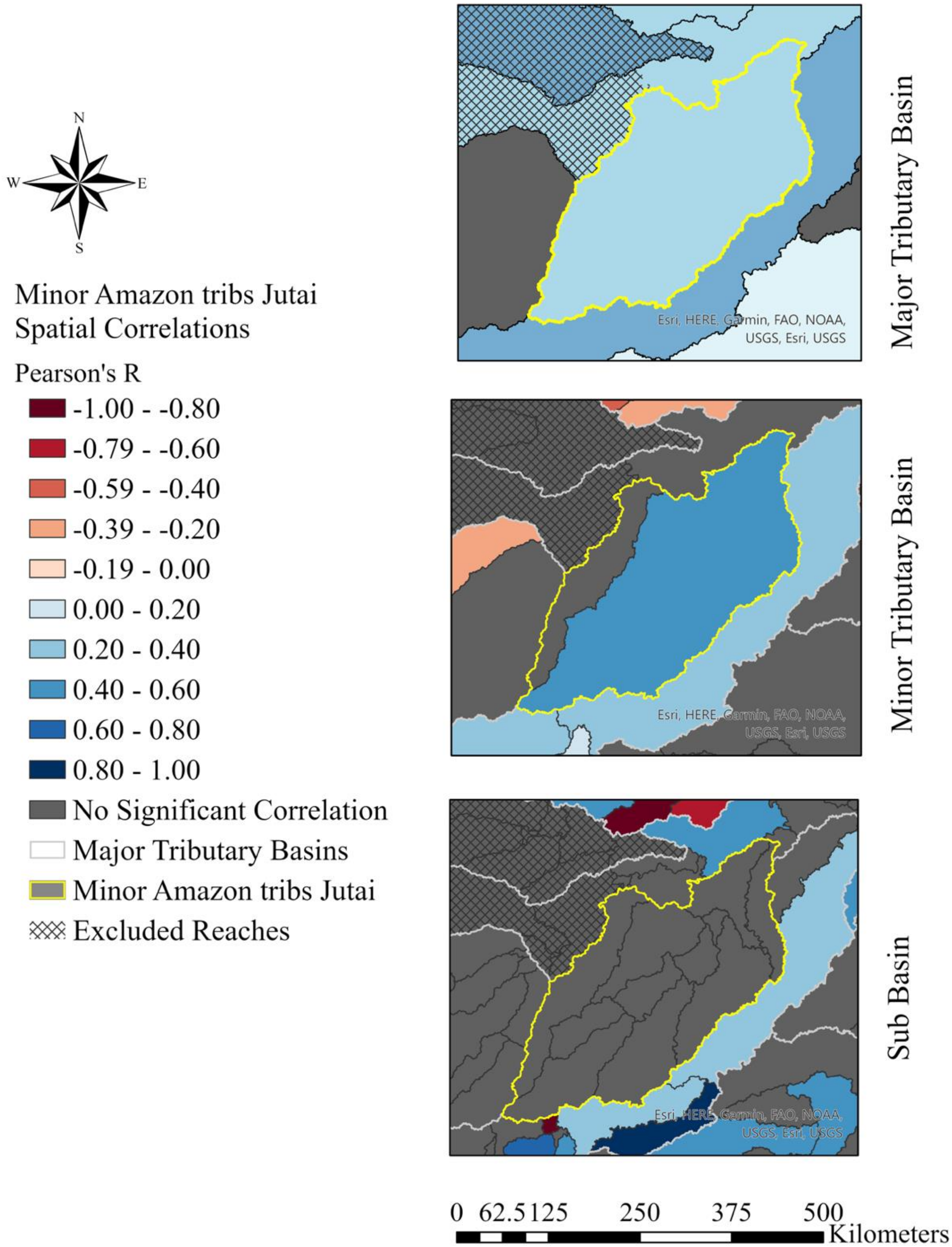


Figure 23. Spatial TSS-Sediment Correlations within the Minor Amazon tribs Jutai, 2001-2020

One puzzling observation from this study is the limited number of significant spatial and temporal correlations observed within the Madeira River Basin. From 2001 to 2020 the Madeira River Basin experienced roughly 39,189km^2 of forest loss (almost 70% of which was identified to be attributed to deforestation). This river basin was the second most deforested river basin in terms of area (behind the Xingu River Basin) and third most deforested in terms of percent forest loss. Therefore, it would be expected that strong correlations would be observed at most scales like the Xingu. Potentially, the lack of significant correlations may be due to the construction of the Santo Antônio and Jirau mega dams along the Madeira River beginning in 2008 (**Fig. 24**). The Santo Antônio and Jirau dams are run-of-river dams, meaning that the flow of water downstream of the dam is the same as the flow upstream. Instead of impounding water, pipes or canals are used to pass water through power generation turbines before returning it back to the main river channel. Most run-of-river dams do not create a reservoir, though some may create a small water storage known as a pondage. The Jirau and Santo Antônio dams, however, were constructed so that after flooding, a reservoir develops and is kept at bank full stage through the entire year (Almeida et al., 2019). The result is the creation of a reservoir similar to one that would be created by a traditional impoundment dam allowing for sediment to be trapped upstream of the dam (**Fig. 24**).

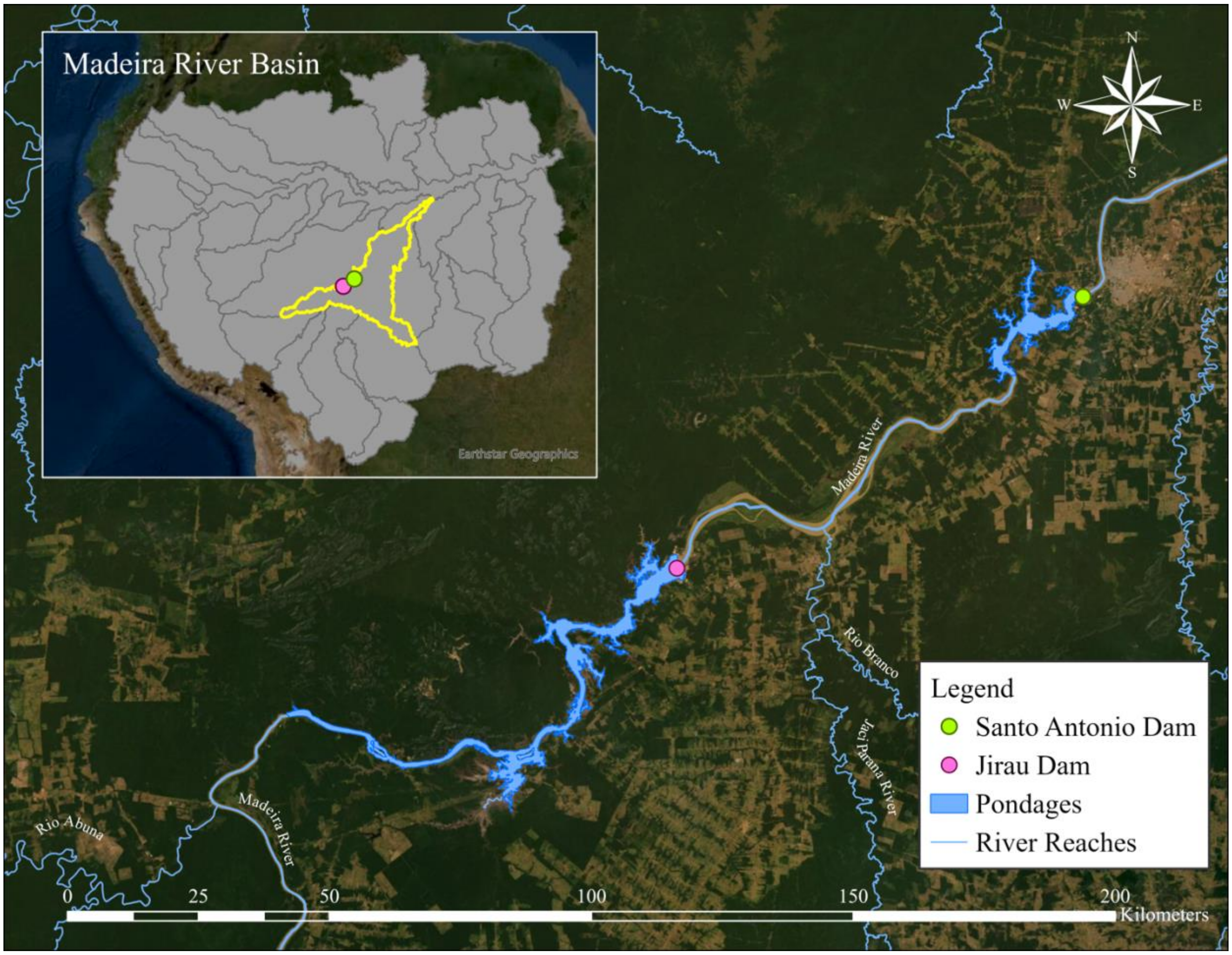


Figure 24. Madeira River Basin and Santo Antônio and Jirau Dams and pondages

As the Madeira River is the second Andean tributary of the Amazon River Basin (Guyot et al., 1995), carrying up to 50% of the Amazon's sediment load (Ayes Rivera et al., 2021), the creation of such impoundments may have severe implications for downstream sediment supply and transport. Measuring the extent to which these dams affect sediment trapping, however, is complex as previous observations have shown that the Madeira River Basin is currently experiencing a natural decline in sediment. Although Latrubesse et al. (2017) determined that the Madeira's mean surface suspended sediment concentration decreased by 20% because of the Santo Antônio and Jirau dams, Ayes Rivera et al. (2019) observed that the Madeira River Basin is experiencing an overall decline in fine suspended sediments (FSC) both upstream (36%

decline) and downstream (30% decline) of these complexes during the peak months of sediment load (December-March). Expanding upon the time period used by Ayes Rivers et al. (2019), a similar decline is also observed in dry season TSS data when comparing 2001-2008 to 2009-2020 (**Fig. 25**). These confounding results between sediment decline attributed to dam construction and sediment decline due to other factors indicate that damming introduces a unique set of complexities to sediment studies and that caution must be taken when examining dammed rivers.

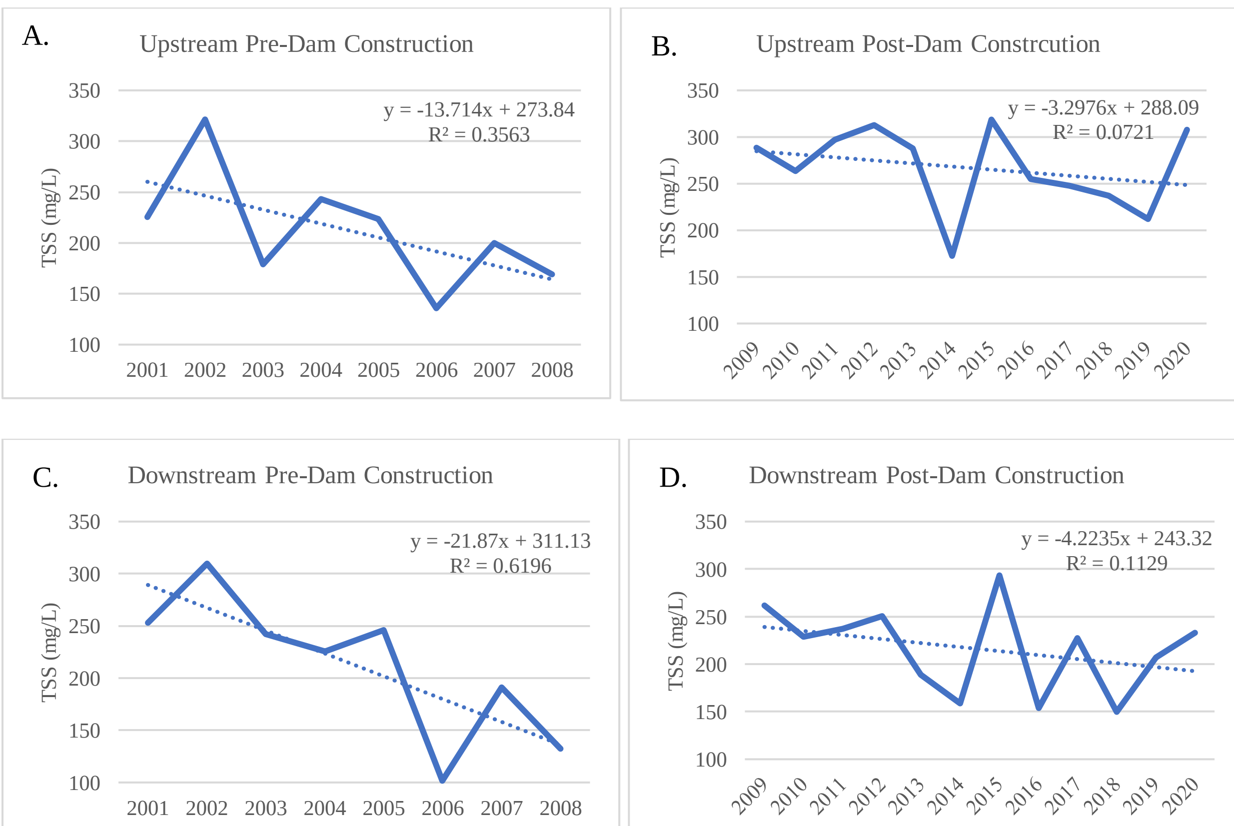


Figure 25. TSS Trends Upstream and Downstream of the dam complex reservoirs before and after dam construction.

It is well documented that land use has a direct effect on erosional and infiltration rates (Sun et al., 2018; Marie Mireille et al., 2019), effectively contributing to sediment production and mobility. During the study period, land use within deforested areas may have shifted from cattle pastures to soybean plantations, potentially affecting the observed deforestation-TSS relationship. International agreements aimed to reduce Amazonian deforestation rates, like Brazil's Soy Moratorium (SoyM) (2006), were successful in preventing new deforestation from occurring due to soy cultivation (Gibbs et al., 2015). Instead of clearing new land, soy production was contained within already cleared land. Although these agreements greatly reduced deforestation rates associated with soy cultivation, this caused land use intensification within preexisting pastures as land use shifted from "extensive" use (e.g., cattle ranching) to "intensive" use (e.g., soybean cultivation). Potentially, the amount of erosion caused by soybean cultivation may be greater than what is produced by cattle ranching; soil tilling, overgrazing, and land management practices can dramatically affect the erosional rate as well as soil infiltration rate. One study conducted in the Brazilian State of Mato Grosso observed more than a 50% reduction in soil infiltrability four years after pastures were converted to soybean fields (Neill et al., 2013). Further, economic pressures to produce more goods on smaller land parcels may further intensify land use, leading to increased land degradation. Between 1985-2006, Brazil's national average total farm productivity (TFP) increased at a rate of 2.55% a year (Rada et al., 2012). Whether or not TFP was allowed to increase at an environmentally sustainable rate remains uncertain, however with increased land use, there is the potential for increased erosion. Information on post-deforestation land use is not included in this study as I examine only the effects of forest loss on sediment dynamics. Further studies may be required to quantify soil erosion produced from different land use categories.

CHAPTER 5

CONCLUSIONS

Since the 1960s, deforestation has significantly altered the Amazon River Basin's landscape and fluvial systems, resulting in widespread changes to sediment dynamics throughout much of the basin. Overall, I observed that deforestation during the 2001-2020 period explains 26% of the (increasing) yearly variability observed in TSS. For a basin as large as the Amazon, a relationship of this magnitude is considerable, as previous works have only observed a figure of that scale in small and medium size basins. These results have significant implications for the effects of deforestation on hydrologic systems; if deforestation continues expanding into the Amazon, greater increases in sediment concentration are expected. Though this study examines only the effect of forest cover removal on sediment dynamics, increases in land-use intensity from soybean cultivation, cattle ranching, and urbanization following deforestation, may further drive changes in sediment dynamics well after the land has cleared.

It is suspected that the extent of deforestation's influence is strongly dependent on the amount of deforestation occurring within the basin (**Hypothesis 2**). In the central and northwestern regions and protected areas of the basin where deforestation is limited, deforestation-TSS relationships are weak or non-existent. In these more pristine areas, deforestation is not a key sediment producer, rather other agents such as hillslope, damming, and discharge may play a stronger role in sediment dynamics. For deforestation to significantly influence sediment regimes in large river basins, I strongly believe there must be a significant amount of deforestation present within the basin, potentially over a long period of time. The strongest deforestation-TSS relationships were observed in the eastern region of the basin, which has been subject to widespread deforestation beginning in the 1960s. Simultaneously, increases in TSS during the 2001-2020 period were also observed in this region. Potentially, deforestation may have had a large impact on sediment dynamics in this region (**Hypothesis 1**).

As expected, small sub-basins in the Amazon were more reactive to deforestation than larger basins (**Hypothesis 3**), however the reasoning behind this observation may not be fully attributed to the reduced buffering capacity of these smaller basins. The methods used to quantify deforestation take into consideration deforestation that has occurred upstream of the basin. Although deforestation occurring within a sub basin carries a larger “weight” than deforestation that has occurred upstream, these upstream influences may overpower local deforestation if they are very large and if deforestation within the basin is limited. Whether the presence of stronger correlations is observed due to the reduced buffering capacity of smaller basins, the “proximal” effect of deforestation, or some combination of the two remains uncertain. However, by applying multiple scales to this analysis, varying spatial patterns of correlation strength and polarity were revealed between the major tributary (BL3), minor tributary (BL4), and subbasins (BL5). Although some significant negative correlations were observed within the Amazon, particularly at smaller basin scales, it is not to be interpreted that deforestation in these regions decreases sediment production. Rather, case-by-case investigations of damming or the presence other impediments of sediment transport, should be conducted to understand the specific complexities identified by such results. Further, future investigations should continue to examine deforestation-sediment dynamics at multiple scales and should consider the scale at which these relationships exist.

Despite local and global efforts to reduce deforestation in the Amazon, the rate of forest loss has risen since 2012 due to increased global demand for beef, soy, and timber products. As deforestation expands further into the basin, severe consequences are to be expected for the Amazon's indigenous peoples, freshwater availability, biodiversity, and infrastructure. Given the immense importance of the Amazon River Basin, as well as other forested landscapes to the global carbon cycle, biodiversity, and fluvial geomorphology, it is important to continue examining the effects of anthropogenic activities on river systems. By quantifying and characterizing deforestation-TSS relationships within a large scale, tropical hydrologic system, this research advances our understanding of anthropogenic impacts on the Earth system allowing us to plan for (and potentially offset) future changes to the environment.

REFERENCES

Ahmed, J., Constantine, J. A., & Dunne, T. (2019). The role of sediment supply in the adjustment of channel sinuosity across the Amazon Basin. In Geology (Vol. 47, Issue 9, pp. 807–810). Geological Society of America. https://doi.org/10.1130/g46319.1

Alewell, C., Borrelli, P., Meusburger, K., & Panagos, P. (2019). Using the USLE: Chances, challenges and limitations of soil erosion modelling. In International Soil and Water Conservation Research (Vol. 7, Issue 3, pp. 203–225). Elsevier BV. https://doi.org/10.1016/j.iswcr.2019.05.004

Allen, G. H., & Pavelsky, T. M. (2018). Global extent of rivers and streams. *Science*, 361(6402), 585–588. https://doi.org/10.1126/science.aat0636

Almeida, R. M., Hamilton, S. K., Rosi, E. J., Arantes, J. D., Jr., Barros, N., Boemer, G., Gripp, A., Huszar, V. L. M., Junger, P. C., Lima, M., Pacheco, F., Carvalho, D., Reisinger, A. J., Silva, L. H. S., & Roland, F. (2019). Limnological effects of a large Amazonian run-of-river dam on the main river and drowned tributary valleys. In Scientific Reports (Vol. 9, Issue 1). Springer Science and Business Media LLC. https://doi.org/10.1038/s41598-019-53060-1

Altenau, E. H., Pavelsky, T. M., Durand, M. T., Yang, X., Frasson, R. P. D. M., & Bendezu, L. (2021). *SWOT River Database (SWORD) (Version v1) [Data set]*. Zenodo.

Arima, E. Y., Richards, P., Walker, R., & Caldas, M. M. (2011). Statistical confirmation of indirect land use change in the Brazilian Amazon. In Environmental Research Letters (Vol. 6, Issue 2, p. 024010). IOP Publishing. https://doi.org/10.1088/1748-9326/6/2/024010

Ayes Rivera, I., Molina-Carpio, J., Espinoza, J. C., Gutierrez-Cori, O., Cerón, W. L., Frappart, F., Armijos Cardenas, E., Espinoza-Villar, R., Ayala, J. M., & Filizola, N. (2021). The Role of the Rainfall Variability in the Decline of the Surface Suspended Sediment in the Upper Madeira Basin (2003–2017). In Frontiers in Water (Vol. 3). Frontiers Media SA. https://doi.org/10.3389/frwa.2021.738527

Ayes Rivera, I., Armijos Cardenas, E., Espinoza-Villar, R., Espinoza, J., Molina-Carpio, J., Ayala, J., Gutierrez-Cori, O., Martinez, J.-M., & Filizola, N. (2019). Decline of Fine Suspended Sediments in the Madeira River Basin (2003–2017). In Water (Vol. 11, Issue 3, p. 514). MDPI AG. https://doi.org/10.3390/w11030514

Baker, J. C. A., Garcia-Carreras, L., Buermann, W., Castilho de Souza, D., Marsham, J. H., Kubota, P. Y., Gloor, M., Coelho, C. A. S., & Spracklen, D. V. (2021). Robust Amazon precipitation projections in climate models that capture realistic land–atmosphere interactions. In Environmental Research Letters (Vol. 16, Issue 7, p. 074002). IOP Publishing. https://doi.org/10.1088/1748-9326/abfb2e

Barthem, Ronaldo & Marques, M & Charvet, Patricia & Montag, Luciano. (2005). Amazon River Basin: I – characterization and environmental impacts due to deforestation.

Bathiany, Sebastian, et al. "Combined biogeophysical and biogeochemical effects of large-scale forest cover changes in the MPI earth system model." Biogeosciences 7.5 (2010): 1383-1399.

Brasil. Lei n. 12.651, de 25 de maio de 2012. Diário Oficial da República Federativa do Brasil , Brasília, DF (2012 May 28) [cited 2022 April. 24]. Available from: http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2012/lei/l12651.htm

Brasil. Lei n. 4.771, de 15 de setembro de 1965. Diário Oficial da República Federativa do Brasil , Brasília, DF (1965 setembro 16) [cited 2022 April. 24]. Available from: https://www2.camara.leg.br/legin/fed/lei/1960-1969/lei-4771-15-setembro-1965-369026-publicacaooriginal-1-pl.html

Bringhurst, K., Jordan, P. The impact on nutrient cycles from tropical forest to pasture conversion in Costa Rica. *Sustain. Water Resour. Manag.* **1,** 3–13 (2015). https://doi.org/10.1007/s40899-015-0003-x

Browder, J. (1988). Public policy and deforestation in the Brazilian Amazon. In Repetto, R., and Gillis, M. (eds.), Public Policies and the Misuse of Forest Resources. World Resources Institute and Cambridge University Press, Washington, D.C.

Brancalion, P. H. S., Garcia, L. C., Loyola, R., Rodrigues, R. R., Pillar, V. D., & Lewinsohn, T. M. (2016). A critical analysis of the Native Vegetation Protection Law of Brazil (2012): updates and ongoing initiatives. In Natureza & Conservação (Vol. 14, pp. 1–15). Elsevier BV. https://doi.org/10.1016/j.ncon.2016.03.003

Butler, R. A. (2021, November 22). *Deforestation in the Amazon*. Mongabay. Retrieved April 3, 2022, from https://rainforests.mongabay.com/amazon/amazon_destruction.html

Callède, J., Cochonneau, G., Alves, F., Guyot, J. L., Guimarães, V., & De Oliveira, E. (2010). Les apports en eau de l'Amazone à l'Océan Atlantique. *Revue des sciences de l'eau/Journal of Water Science, 23*(3), 247-273.

Coe, M. T., Costa, M. H., & Soares-Filho, B. S. (2009). The influence of historical and potential future deforestation on the stream flow of the Amazon River – Land surface processes and atmospheric feedbacks. Journal of Hydrology, 369(1–2), 165–174. https://doi.org/10.1016/j.jhydrol.2009.02.043

Coe, M. T., Latrubesse, E. M., Ferreira, M. E., & Amsler, M. L. (2011). The effects of deforestation and climate variability on the streamflow of the Araguaia River, Brazil. Biogeochemistry, 105(1-3), 119–131. doi:10.1007/s10533-011-9582-2

Costa, M. H., Botta, A., & Cardille, J. A. (2003). Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. Journal of Hydrology, 283(1–4), 206–217. https://doi.org/10.1016/s0022-1694(03)00267-1

Crochemore, L., Isberg, K., Pimentel, R., Pineda, L., Hasan, A., & Arheimer, B. (2019). Lessons learnt from checking the quality of openly accessible river flow data worldwide. In Hydrological Sciences Journal (Vol. 65, Issue 5, pp. 699–711). Informa UK Limited. https://doi.org/10.1080/02626667.2019.1659509

D'Almeida, C., Vörösmarty, C. J., Hurtt, G. C., Marengo, J. A., Dingman, S. L., & Keim, B. D. (2007). The effects of deforestation on the hydrological cycle in Amazonia: a review on scale and resolution. International Journal of Climatology: A Journal of the Royal Meteorological Society, 27(5), 633-647.

Dearing, J.A. & Jones, R.T. (2003). *Coupling temporal and spatial dimensions of global sediment flux through lake and marine sediment records., 39(1-2), 0–168.* doi:10.1016/s0921-8181(03)00022-5

da Cruz, D.C., Benayas, J.M.R., Ferreira, G.C. et al. An overview of forest loss and restoration in the Brazilian Amazon. New Forests (2020). https://doi.org/10.1007/s11056-020-09777-3

Ellison, J. C. (1999). *Impacts of Sediment Burial on Mangroves. Marine Pollution Bulletin, 37(8-12), 420–426.* doi:10.1016/s0025-326x(98)00122-2

Ellwanger, J. H., Kulmann-Leal, B., Kaminski, V. L., Valverde-Villegas, J. A. C. Q. U. E. L. I. N. E., VEIGA, A. B. G., Spilki, F. R., ... & Chies, J. A. B. (2020). Beyond diversity loss and climate change: Impacts of Amazon deforestation on infectious diseases and public health. In Anais da Academia Brasileira de Ciências (Vol. 92, Issue 1). FapUNIFESP (SciELO). https://doi.org/10.1590/0001-3765202020191375

Exbrayat, JF., Liu, Y.Y. & Williams, M. Impact of deforestation and climate on the Amazon Basin’s above-ground biomass during 1993–2012. *Sci Rep* **7,** 15615 (2017). https://doi.org/10.1038/s41598-017-15788-6

Fitzpatrick, F. A., & Knox, J. C. (2000). Spatial and temporal sensitivity of hydrogeomorphic responceand recovery to deforestation, Agriculture, and floods. In Physical Geography (Vol. 21, Issue 2, pp. 89–108). Informa UK Limited. https://doi.org/10.1080/02723646.2000.10642701

Foley, J. A., Asner, G. P., Costa, M. H., Coe, M. T., DeFries, R., Gibbs, H. K., … Snyder, P. (2007). *Amazonia revealed: forest degradation and loss of ecosystem goods and services in the Amaz*on Basin. Frontiers in Ecology and the Environment, 5(1), 25–32. doi:10.1890/1540-9295(2007)5[25:arfdal]2.0.co;2

Gibbs, H. K., Rausch, L., Munger, J., Schelly, I., Morton, D. C., Noojipady, P., Soares-Filho, B., Barreto, P., Micol, L., & Walker, N. F. (2015). Brazil's Soy Moratorium. In Science (Vol. 347, Issue 6220, pp. 377–378). American Association for the Advancement of Science (AAAS). https://doi.org/10.1126/science.aaa0181

Grecchi, R. C., Beuchle, R., Shimabukuro, Y. E., Aragão, L. E. O. C., Arai, E., Simonetti, D., & Achard, F. (2017). *An integrated remote sensing and GIS approach for monitoring areas affected by selective logging: A case study in northern Mato Grosso, Brazilian Amazon. International Journal of Applied Earth Observation and Geoinformation, 61, 70–80.* doi:10.1016/j.jag.2017.05.001

Guyot, J.L., Quintanilla, J., Cortes, J., Filizola Jr, N. (1995). The dissolved and sediment yields from the Andes of Bolivia to the Madeira River in the Brazilian Amazon. Bulletin - Institut Francais d'Etudes Andines. 24. 415-423.fjirau

Hansen, M. C., P. V. Potapov, R. Moore, M. Hancher, S. A. Turubanova, A. Tyukavina, D. Thau, S. V. Stehman, S. J. Goetz, T. R. Loveland, A. Kommareddy, A. Egorov, L. Chini, C. O. Justice, and J. R. G. Townshend. 2013. "High-Resolution Global Maps of 21st-Century Forest Cover Change." Science 342 (15 November): 850–53. Data available on-line from: http://earthenginepartners.appspot.com/science-2013-global-forest.

Horton, A. J., Constantine, J. A., Hales, T. C., Goossens, B., Bruford, M. W., & Lazarus, E. D. (2017). Modification of river meandering by tropical deforestation. In Geology (Vol. 45, Issue 6, pp. 511–514). Geological Society of America. https://doi.org/10.1130/g38740.1

Hussain et al., (2019). pyMannKendall: a python package for non parametric Mann Kendall family of trend tests.. Journal of Open Source Software, 4(39), 1556, https://doi.org/10.21105/joss.01556

Hurwitz, Z. (2012). Dirty Business in Brazil: Rousseff Backslides on the Environment. In NACLA Report on the Americas (Vol. 45, Issue 1, pp. 17–22). Informa UK Limited. https://doi.org/10.1080/10714839.2012.11722107

Institut national des sciences de l'Univers. (2021). *HYdro-géochimie du Bassin Amazonien, SO-HYBAM.* [Data set]. Retrieved from https://hybam.obs-mip.fr/

Instituto Nacional de Pesquisas Espaciais. (2020). *Measurement of Deforestation by Remote Sensing, PRODES.* [Data set]. Retrieved from http://terrabrasilis.dpi.inpe.br/downloads/

Jiménez-Muñoz, J., Mattar, C., Barichivich, J. *et al.* Record-breaking warming and extreme drought in the Amazon rainforest during the course of El Niño 2015–2016. *Sci Rep* **6,** 33130 (2016). https://doi.org/10.1038/srep33130

Kettner, A. J., Gomez, B., & Syvitski, J. P. M. (2007). Modeling suspended sediment discharge from the Waipaoa River system, New Zealand: The last 3000 years. In Water Resources Research (Vol. 43, Issue 7). American Geophysical Union (AGU). https://doi.org/10.1029/2006wr005570

Kirby, K. R., Laurance, W. F., Albernaz, A. K., Schroth, G., Fearnside, P. M., Bergen, S., Venticinque, E. M., & da Costa, C. (2006). The future of deforestation in the Brazilian Amazon. In Futures (Vol. 38, Issue 4, pp. 432–453). Elsevier BV. https://doi.org/10.1016/j.futures.2005.07.011

Kjelland, M.E., Woodley, C.M., Swannack, T.M. et al. A review of the potential effects of suspended sediment on fishes: potential dredging-related physiological, behavioral, and transgenerational implications. Environ Syst Decis 35, 334–350 (2015). https://doi.org/10.1007/s10669-015-9557-2

Kooperman, G. J., Chen, Y., Hoffman, F. M., Koven, C. D., Lindsay, K., Pritchard, M. S., Swann, A. L. S., & Randerson, J. T. (2018). Forest response to rising CO2 drives zonally asymmetric rainfall change over tropical land. In Nature Climate Change (Vol. 8, Issue 5, pp. 434–440). Springer Science and Business Media LLC. https://doi.org/10.1038/s41558-018-0144-7

Latrubesse, E. M., Amsler, M. L., de Morais, R. P., & Aquino, S. (2009). The geomorphologic response of a large pristine alluvial river to tremendous deforestation in the South American tropics: The case of the Araguaia River. Geomorphology, 113(3-4), 239–252. doi:10.1016/j.geomorph.2009.03.014

Latrubesse, E. M., Arima, E. Y., Dunne, T., Park, E., Baker, V. R., d'Horta, F. M., Wight, C., Wittmann, F., Zuanon, J., Baker, P. A., Ribas, C. C., Norgaard, R. B., Filizola, N., Ansar, A., Flyvbjerg, B., & Stevaux, J. C. (2017). Damming the rivers of the Amazon basin. In Nature (Vol. 546, Issue 7658, pp. 363–369). Springer Science and Business Media LLC. https://doi.org/10.1038/nature22333

Laudares, H., & Gagliardi, P. H. (2020). Is Deforestation Spreading COVID-19 to the Indigenous Peoples?. Covid Econ Vetted Real Time Pap, 53, 33-71.

Lehner, B., & Grill, G., (2013). Global river hydrography and network routing: Baseline data and new approaches to study the world's large river systems. *Hydrological Processes*, 27(15), 2171–2186. https://doi.org/10.1002/hyp.9740

Lehner , B., C. Reidy Liermann, C. Revenga, C. Vörösmarty, B. Fekete, P. Crouzet, P. Döll, M. Endejan, K. Frenken, J. Magome, C. Nilsson, J.C. Robertson, R. Rodel, N. Sindorf, and D. Wisser (2011). High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. Frontiers in Ecology and the Environment 9 (9): 494-502.

Maeda, E. E., Formaggio, A. R., & Shimabukuro, Y. E. (2008). Impacts of Land Use and Land Cover Changes on Sediment Yield in a Brazilian Amazon Drainage Basin. In GIScience & Remote Sensing (Vol. 45, Issue 4, pp. 443–453). Informa UK Limited. https://doi.org/10.2747/1548-1603.45.4.443

Maina, J., de Moel, H., Zinke, J., Madin, J., McClanahan, T., & Vermaat, J. E. (2013). Human deforestation outweighs future climate change impacts of sedimentation on coral reefs. In Nature Communications (Vol. 4, Issue 1). Springer Science and Business Media LLC. https://doi.org/10.1038/ncomms2986

Marie Mireille, N., M. Mwangi, H., K. Mwangi, J., & Mwangi Gathenya, J. (2019). Analysis of Land Use Change and Its Impact on the Hydrology of Kakia and Esamburmbur Sub-Watersheds of Narok County, Kenya. In Hydrology (Vol. 6, Issue 4, p. 86). MDPI AG. https://doi.org/10.3390/hydrology6040086

Milliman, J. D., & Farnsworth, K. L. (2011). River discharge to the coastal ocean: a global synthesis. Cambridge University Press.

Milliman, J. D., Farnsworth, K. L., Jones, P. D., Xu, K. H., & Smith, L. C. (2008). Climatic and anthropogenic factors affecting river discharge to the global ocean, 1951–2000. *Global and planetary change*, *62*(3-4), 187-194. https://doi.org/10.1016/j.gloplacha.2008.03.001.

Moges, E., Demissie, Y., Larsen, L., & Yassin, F. (2020). Review: Sources of Hydrological Model Uncertainties and Advances in Their Analysis. In Water (Vol. 13, Issue 1, p. 28). MDPI AG. https://doi.org/10.3390/w13010028

Montanher, O. C., Novo, E. M. L. de M., & Souza Filho, E. E. de. (2018). Temporal trend of the suspended sediment transport of the Amazon River (1984–2016). In Hydrological Sciences Journal (Vol. 63, Issues 13–14, pp. 1901–1912). Informa UK Limited. https://doi.org/10.1080/02626667.2018.1546387

Moran, Emilio F. "Deforestation and land use in the Brazilian Amazon." Human Ecology 21.1 (1993): 1-21.

National Institute for Space Research (INPE). Earth observation general coordination, Monitoring Program of the Amazon and other biomes. Deforestation – Legal Amazon – Available at http://terrabrasilis.dpi.inpe.br/downloads/. Accessed: January 5, 2019

Neill, C., Coe, M. T., Riskin, S. H., Krusche, A. V., Elsenbeer, H., Macedo, M. N., McHorney, R., Lefebvre, P., Davidson, E. A., Scheffler, R., Figueira, A. M. e S., Porder, S., & Deegan, L. A. (2013). Watershed responses to Amazon soya bean cropland expansion and intensification. In Philosophical Transactions of the Royal Society B: Biological Sciences (Vol. 368, Issue 1619, p. 20120425). The Royal Society. https://doi.org/10.1098/rstb.2012.0425

Nobre, C. A., Sampaio, G., Borma, L. S., Castilla-Rubio, J. C., Silva, J. S., & Cardoso, M. (2016). Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. In Proceedings of the National Academy of Sciences (Vol. 113, Issue 39, pp. 10759–10768). Proceedings of the National Academy of Sciences. https://doi.org/10.1073/pnas.1605516113

Ochiai, S., Nagao, S., Yonebayashi, K., Fukuyama, T., Suzuki, T., Yamamoto, M., ... & Nakamura, K. (2015). Effect of deforestation on the transport of particulate organic matter inferred from the geochemical properties of reservoir sediments in the Noto Peninsula, Japan. *Geochemical Journal*, *49*(5), 513-522. https://doi.org/10.2343/geochemj.2.0379

Openshaw, S. (1981). The modifiable areal unit problem. *Quantitative geography: A British view*, 60-69.

Peter, B., Messina, J., Raney, A., Principe, R., Fan, P. (2021), "MSZSI: Multi-Scale Zonal Statistics [AgriClimate] Inventory", https://doi.org/10.7910/DVN/M4ZGXP, Harvard Dataverse, V3, UNF:6:IG+NJ3vv7hH2Ec5AHxE3lg== [fileUNF]

Peter, B. G., Messina, J. P., Carroll, J. W., Zhi, J., Chimonyo, V., Lin, S., & Snapp, S. S. (2020). Multi-Spatial Resolution Satellite and sUAS Imagery for Precision Agriculture on Smallholder Farms in Malawi. In Photogrammetric Engineering & Remote Sensing (Vol. 86, Issue 2, pp. 107–119). American Society for Photogrammetry and Remote Sensing. https://doi.org/10.14358/pers.86.2.107

Pereira, R. M., & Vila Nova de Souza, C. (n.d.). The Use of Information Technology in Environmental Management: The Case of PPCDAM. http://mesp.unb.br/images/eventofederalismo/trabalhos/PPCDAM-Paper_Final_Version.pdf

Rada, Nicholas and Valdes, Constanza, Policy, Technology, and Efficiency of Brazilian Agriculture (July 1, 2012). USDA-ERS Economic Research Report Number 137, Available at SSRN: https://ssrn.com/abstract=2112029 or http://dx.doi.org/10.2139/ssrn.2112029

Restrepo, J., Kettner, A., & Syvitski, J. (2015). Recent deforestation causes rapid increase in river sediment load in the Colombian Andes [Abstract]. *Anthropocene*, *10*, 13-28. doi:10.1016/j.ancene.2015.09.001

Richards, P. D., Walker, R. T., & Arima, E. Y. (2014). Spatially complex land change: The Indirect effect of Brazil's agricultural sector on land use in Amazonia. In Global Environmental Change (Vol. 29, pp. 1–9). Elsevier BV. https://doi.org/10.1016/j.gloenvcha.2014.06.011

Satyamurty, P., de Castro, A. A., Tota, J., da Silva Gularte, L. E., & Manzi, A. O. (2009). Rainfall trends in the Brazilian Amazon Basin in the past eight decades. In Theoretical and Applied Climatology (Vol. 99, Issues 1–2, pp. 139–148). Springer Science and Business Media LLC. https://doi.org/10.1007/s00704-009-0133-x

Shimada, M., Itoh, T., Motooka, T., Watanabe, M., Shiraishi, T., Thapa, R., & Lucas, R. (2014). New global forest/non-forest maps from ALOS PALSAR data (2007–2010). *Remote Sensing of environment*, *155*, 13-31. 10.1016/j.rse.2014.04.014

Silva Junior, C.H.L., Pessôa, A.C.M., Carvalho, N.S. et al. The Brazilian Amazon deforestation rate in 2020 is the greatest of the decade. Nat Ecol Evol 5, 144–145 (2021). https://doi.org/10.1038/s41559-020-01368-x

Silva Junior, C. H. L., Anderson, L. O., Silva, A. L., Almeida, C. T., Dalagnol, R., Pletsch, M. A. J. S., Penha, T. V., Paloschi, R. A., & Aragão, L. E. O. C. (2019). Fire Responses to the 2010 and 2015/2016 Amazonian Droughts. In Frontiers in Earth Science (Vol. 7). Frontiers Media SA. https://doi.org/10.3389/feart.2019.00097

Sonter, L.J., Herrera, D., Barrett, D.J. *et al.* Mining drives extensive deforestation in the Brazilian Amazon. *Nat Commun* **8,** 1013 (2017). https://doi.org/10.1038/s41467-017-00557-w

Staal, A., Fetzer, I., Wang-Erlandsson, L., Bosmans, J. H. C., Dekker, S. C., van Nes, E. H., Rockström, J., & Tuinenburg, O. A. (2020). Hysteresis of tropical forests in the 21st century. In Nature Communications (Vol. 11, Issue 1). Springer Science and Business Media LLC. https://doi.org/10.1038/s41467-020-18728-7

Sud, Y. C., Lau, W. K., Walker, G. K., Kim, J. H., Liston, G. E., & Sellers, P. J. (1996). Biogeophysical consequences of a tropical deforestation scenario: a GCM simulation study. Journal of Climate, 9(12), 3225-3247.

Sun, D., Yang, H., Guan, D., Yang, M., Wu, J., Yuan, F., Jin, C., Wang, A., & Zhang, Y. (2018). The effects of land use change on soil infiltration capacity in China: A meta-analysis. In Science of The Total Environment (Vol. 626, pp. 1394–1401). Elsevier BV. https://doi.org/10.1016/j.scitotenv.2018.01.104

Vale, P., Gibbs, H., Vale, R., Munger, J., Brandão, A., Christie, M., & Florence, E. (2019). Mapping the cattle industry in Brazil's most dynamic cattle-ranching state: Slaughterhouses in Mato Grosso, 1967-2016. PLOS ONE, 14(4), e0215286. doi:10.1371/journal.pone.0215286

Venticinque, E., Forsberg, B., Barthem, R., Petry, P., Hess, L., Mercado, A., Cañas, C., Montoya, M., Durigan, C., and Goulding, M.: An explicit GIS-based river basin framework for aquatic ecosystem conservation in the Amazon, Earth Syst. Sci. Data, 8, 651–661, https://doi.org/10.5194/essd-8-651-2016, 2016.

Vercruysse, K., Grabowski, R. C., & Rickson, R. J. (2017). Suspended sediment transport dynamics in rivers: Multi-scale drivers of temporal variation. In Earth-Science Reviews (Vol. 166, pp. 38–52). Elsevier BV. https://doi.org/10.1016/j.earscirev.2016.12.016

Vergopolan, N., & Fisher, J. B. (2016). The impact of deforestation on the hydrological cycle in Amazonia as observed from remote sensing. In International Journal of Remote Sensing (Vol. 37, Issue 22, pp. 5412–5430). Informa UK Limited. https://doi.org/10.1080/01431161.2016.1232874

Von Randow, C., Biermans, H., Guimberteau, M., Langerwisch, F., Garofolo, L., Poveda, G., Rammig, A., Von Randow, R., Rodriguez, D., Samprogna Mohor, G., Siqueira Júnior, J., Thonicke, K., Tomasella, J., Verbeeck, H. (2014). Report on the likely response of the Amazon basin hydrology and river discharge to land use and climate change. EU-AMAZALERT Delivery report 2.4. Grant agreement no:282664.

Water Resources National Agency (ANA); HidroWeb, Brazilian Water Resources Database. www.hidroweb.ana.gov.br

Walling D.E. (1999) Linking land use, erosion and sediment yields in river basins. In: Garnier J., Mouchel JM. (eds) Man and River Systems. Developments in Hydrobiology, vol 146. Springer, Dordrecht. https://doi.org/10.1007/978-94-017-2163-9_24

Walling, D. E. (1983). The sediment delivery problem. In Journal of Hydrology (Vol. 65, Issues 1–3, pp. 209–237). Elsevier BV. https://doi.org/10.1016/0022-1694(83)90217-2

Wood C., Schmink M. (1993). The military and the environment in the Brazilian Amazon. *Journal of Political & Military Sociology*, *21*(1), 81–105. http://www.jstor.org/stable/45293936

Wohl, E., Bledsoe, B. P., Jacobson, R. B., Poff, N. L., Rathburn, S. L., Walters, D. M., & Wilcox, A. C. (2015). The Natural Sediment Regime in Rivers: Broadening the Foundation for Ecosystem Management. In BioScience (Vol. 65, Issue 4, pp. 358–371). Oxford University Press (OUP). https://doi.org/10.1093/biosci/biv002

Xing, F., Kettner, A. J., Ashton, A., Giosan, L., Ibáñez, C., & Kaplan, J. O. (2014). Fluvial response to climate variations and anthropogenic perturbations for the Ebro River, Spain in the last 4000 years. In Science of The Total Environment (Vols. 473–474, pp. 20–31). Elsevier BV. https://doi.org/10.1016/j.scitotenv.2013.11.083

Yamazaki, D., Ikeshima, D., Sosa, J., Bates, P. D., Allen, G., & Pavelsky, T. (2019). MERIT Hydro: A high-resolution global hydrography map based on latest topography datasets. *Water Resources Research*, 55, 5053–5073. https://doi.org/10.1029/2019WR024873

Zhang, Z., Sheng, L., Yang, J., Chen, X.-A., Kong, L., & Wagan, B. (2015). Effects of Land Use and Slope Gradient on Soil Erosion in a Red Soil Hilly Watershed of Southern China. In Sustainability (Vol. 7, Issue 10, pp. 14309–14325). MDPI AG. https://doi.org/10.3390/su71014309