Soil degradation caused by Brazilian Amazon Forest deforestation and local soil carbon storage

LWS 548 Major project

Faculty of Land and Food Systems

The University of British Columbia

Xinyang Wang

94290756

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Executive summary:

The Brazil Amazon Forest is considered an important carbon sink, yet the region continuously suffers from deforestation. Since a huge amount of soil carbon is released into the air as rainforests disappear, solutions are urgently needed considering the growing concern of climate change. This report reviewed different studies about deforestation in the Brazil Amazon Forest and associated land management impact on soil carbon storage. It was found that cropland and pastureland are the land types that lost the most soil carbon among all common land uses due to their unsustainable land management and lack of incentive policies to promote intensification practices. On the other hand, secondary forests are shown to have the ability to restore carbon into the soil, then these forests are recommended to replace other land uses. This paper aims to help local governments formulate reasonable incentive policies, give scientists future research directions, and help farmers to manage land more sustainably without compromising their interests to prevent soil carbon loss. Several mitigation solutions are suggested to prevent soil carbon loss caused by improper land management and expansion, long-term effort and commitment are necessary to reach this goal.

Introduction:

Deforestation is a global issue leading to an increase in carbon dioxide emissions and, at the same time, lowering the carbon sequestration rate. This may be considered an emergency for the global society to realize the impact of deforestation and find alternative ways to rebalance the carbon cycle. According to the measurement of NOAA (2022), the level of carbon dioxide reached 420.99 ppm in the atmosphere in 2022, which is more than 50% higher than the pre-industrial levels. Most of the increased amount is from human activities. For example, the global constructor sector contributed 5.7 gigatons of carbon dioxide in 2009 (Huang et al., 2018). The global concern about climate change, lead the Paris Agreement in 2015 to suggest that the goal of the century is to limit the global warming level to 2 °C above the preindustrial level, and in addition several alter solutions to climate change have been suggested in recent years (UNFCCC, 2015). However, the public regarding global range usually lacks the details of the factors causing climate change, and this could lead to uninformed decisions about climate change (Sheppard, 2012).

Scientific studies have shown that soil stores more carbon than the atmosphere (Schimel et al., 1995). Forest vegetation and other plants, through the photosynthesis process, absorb carbon dioxide and fix it into organic matter. But much of the fixed carbon is released back into the atmosphere through plant respiration and the organic matter decomposition process. As long-lived plants, trees can store more carbon and keep them in the form of organic matter for a long time. Trees also have root systems that penetrate deeper into the soil, which allows organic matter, such as dead roots, to store carbon under anaerobic and moist conditions. These conditions in deep soil allow organic matter to be decomposed at much slower rates and prevent being burned, which helps keep carbon from being released into the atmosphere (Toochi, 2018). However, after the industrial revolution, large amounts of forests were logged or disappeared due to climate change; this leads to a large scale of soil degradation and negatively impact local soil carbon storage. In the end, most of the lost carbon is released into the atmosphere.

Although the development of agriculture has made a large increase in the number of crops grown, its ability to store carbon is relatively limited compared to forests (Damian et al., 2021). Yes, carbon can be stored in the soil by planting crops, but the shallow root systems typically found in crops make the effectiveness of storage limited. Unlike deep-rooted and long-lived trees, which can store carbon for a longer time and more effectively, carbon fixed by crops is usually centralized at the surface of the ground. This makes them more susceptible to decomposition or burning, which result in the release of the fixed carbon back into the atmosphere (Toochi, 2018). Furthermore, the primary purpose of cropping products is for consumption. Crops are grown and harvested to provide food or raw materials for markets and for industrial purposes. As a result, much of the fixed carbon that has been stored in the crops will be released back into the atmosphere quickly. Once the crops are ready to be harvested and processed, the fixed carbon is released through processes of respiration, decay, or combustion.

Therefore, studying how and how much deforestation could impact soil carbon storage is essential. In this report, the Brazilian Amazon Forest was selected as a focus to assess the impact of deforestation on soil carbon storage. Thus analysis can lead to examines what alternative solutions could be suggested to restore soil carbon. By looking at the case studies, this provides approaches to managing our land resources and carbon output more scientifically and sustainably.

Study location:

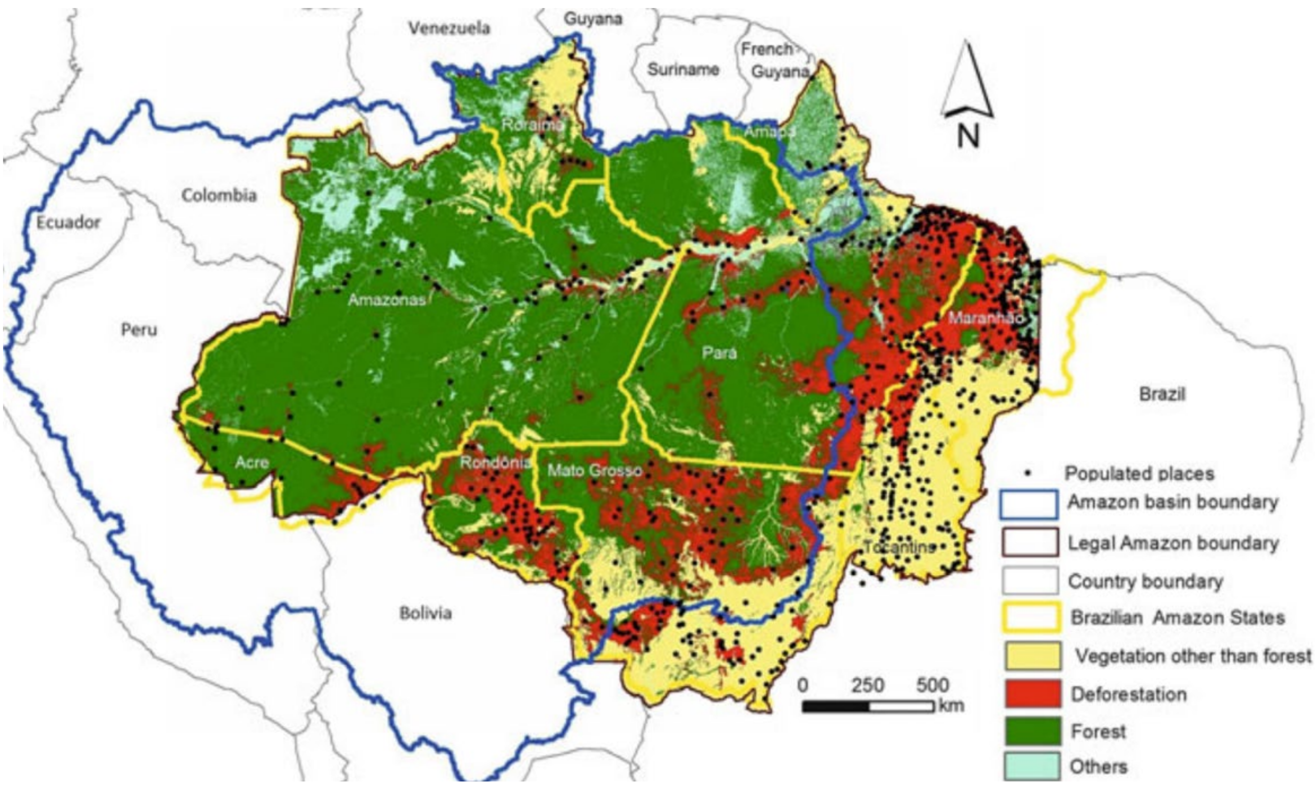


Figure 1: The map pf Brazilian Amazon forests and its land division (Ometto et al., 2016).

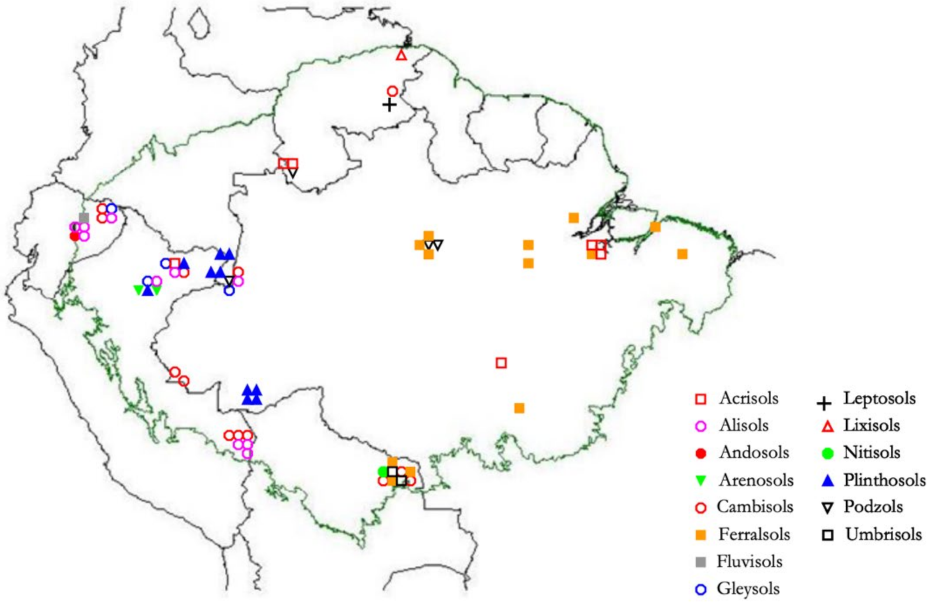


Fig. 1. Distribution of identified soil types across Amazonia.

Figure 2: The map of distribution of identified soil types across Brazilian Amazon Forests (Quesada et al., 2010).

This study focuses on the Brazilian Amazon rainforest, which makes up about 40% of the tropical forest in the whole world (Grace et al., 1995). However, the forest has experienced the fastest speed of deforestation in the world, which has reached almost 2 million hectares per year (Carvalho et al., 2001). The rapid decrease of the forest is due to many reasons, including increasing population, industrial logging, mining, wildfires, cattle ranching, and agriculture (Goodman, 1990; Laurance, 1998).

According to Instituto Nacional de Pesquisas Espaciais (INPE) in 2013, approximately 18.8% of the Brazilian Amazon's natural vegetation (mainly tropical rainforest) had been changed to different land uses by 2013. About 60% of this conversion took place between 1990 and 2010 (INPE 2011). The land use change of deforested areas in the Brazilian Amazon was followed in 2010: pasture accounted for 45.8%, pasture where the regeneration of woody vegetation occupied 8.2%, secondary woody vegetation covered 22.3%, and cropland represented 5.4% (INPE 2011).

In the Brazilian Amazon forests, very diverse soil types exist. Soils such as Cambisols tend to be found in the western and southern areas with a lower pedogenetic level (Figure 2). On the other hand, more weathered soils are found in the central and eastern areas of Amazonia, such as Ferralsols and Acrisols (Figure 2). In these soils, carbon exists in both light and heavy fractions of the soil. The light fraction is low density and is decayed organic matter that is ready to be decomposed by organic matters, while the heavy fraction is humic substances associated with minerals, which is high density and more stable (Six et al., 1998; Aanderud et al., 2010). Depending on soil types, the percentages and distribution of soil carbon among different fractions and depths could be different.

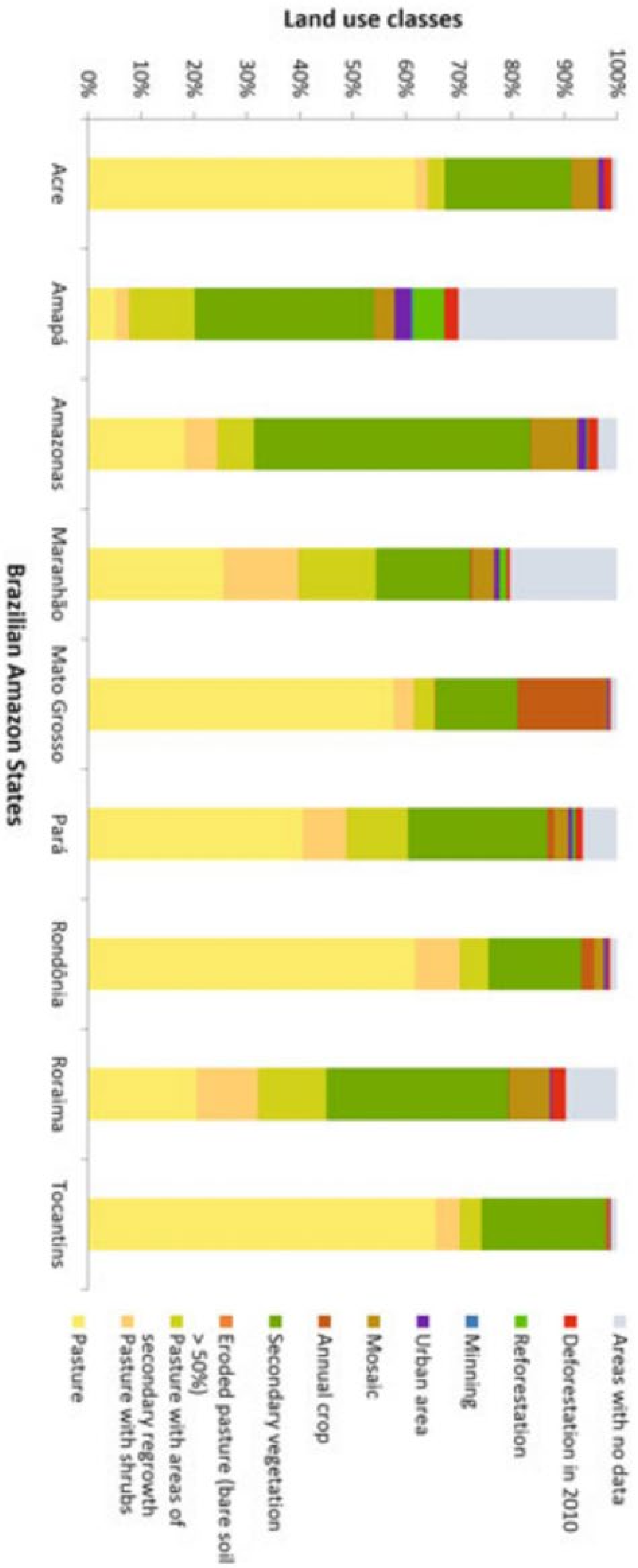

Land use classes
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Acre
Amapá
Amazonas
Maranhão
Mato Grosso
Pará
Rondônia
Roraima
Tocantins
Brazilian Amazon States
Areas with no data
Deforestation in 2010
Reforestation
Minning
Urban area
Mosaic
Annual crop
Secondary vegetation
Eroded pasture (bare soil > 50%)
Pasture with areas of secondary regrowth
Pasture with shrubs
Pasture

Figure 3: Percentage of land use types per state in deforested places of Brazilian Amazon, data in 2010 (INPE 2011; Ometto et al., 2016).

Objectives:

The objectives of the study was a focus on the changing of carbon storage in the Brazilian Amazon forest and relate this to the changes in land use. Through the case study, the project aims to answer the following questions:

- How does the deforestation process impact soil carbon storage and with soil depth?
- How do different land uses impact soil carbon storage after deforestation?
- What land management can be locally recommended to restore the soil carbon at depth in the soil?

Methods:

To solve the objective questions ,a systematic review was the main method in this project. This include published research and government documents. By comparing the soil carbon content between undisturbed forests, deforested areas, and different land use types, this project provided answers to the first two goals of the objectives. Then, based on the global study of soil carbon management, the project provided suggestions from experts on how to restore the soil carbon storage, especially at depth.

Needed data and information:

- Different land uses on the deforested area.

- Average soil carbon content for each land use.
- Average soil carbon stock of undisturbed forest.
- Usual practices to restore carbon storage in deep soil.

Context

Theme 1: How does the deforestation process impact soil carbon storage and with soil depth?

Forest act as a carbon sink; it continuously absorbs carbon dioxide in the atmosphere and fixes carbon into organic matter. In 1995, Grace et al. published research to calculate the carbon dioxide uptake by tropical rainforests in Southwest Amazonia. The measurement lasted for 55 days, including both dry and wet seasons, from 1992 to 1993 (Grace et al., 1995). According to this study at Reserva Jaru, Rondonia, Brazil, the carbon fixation rate in the undisturbed forest was higher than the loss of carbon through respiration, and a process-based model was used to estimate the carbon absorbed through the year (Grace et al., 1995). By using the climatological data from the observation tower, the model estimated that 8.5 ± 2.0 mol $*m^{-2}*year^{-1}$ of carbon would accumulate in the area of the rainforest from July 1992 until June 1993 (Grace et al., 1995). The Model analysis is shown in Figure 4; the model also estimated the carbon accumulation with different solar irradiance and temperature, considering the climate in 1992 was 0.5 °C cooler and had 4% less solar irradiance (Figure 4). Another research in central Amazon gives a similar result (Fan et al., 1990). The study of Grace et al. shows that if all the tropical rain forests in the Amazon Basin had the same carbon accumulation rate, this would fix 45 * 10^{12} mol of carbon per year (1995). Partially of the fixed carbon is stored in different layers of soil in several forms, including fallen leaves, dead roots, and animal manures. Some of the surface carbon will leach into deeper soils throughout times. However, after the deforestation process, bared soil begins to lose the carbon fixation input, while respiration and decomposition processes will continuously release soil carbon back into the atmosphere.

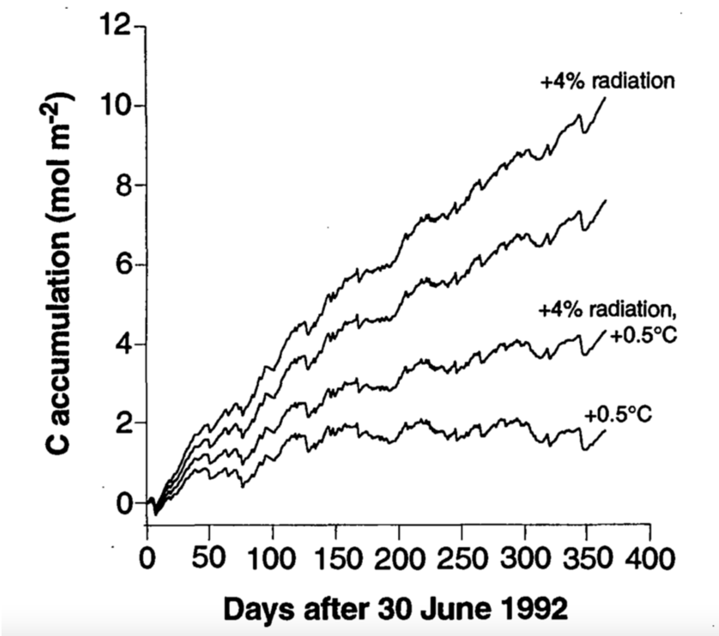


Figure 4: Model analysis over the entire year, starting from June 30, 1992. The modified climatological data are also used to estimate the impact of rising temperature and radiation (Grace et al., 1995).

In the research by Marques et al. in 2017, carbon stability is mentioned as an essential factor related to soil carbon storage (Fearnside, 2010). The physical structure of Amazonian soils beneath forests can promote carbon storage, preventing its loss into the atmosphere (Marques et al., 2017). The findings indicate a prevalence of small pores, which can slow down the movement of carbon and prevent decomposers' access to soil organic matter, leading to substrates being kept within aggregates (Ekschmitt et al., 2005). Due to small pores, limited diameters, and association with clay surfaces contribute to carbon retention, resulting in slower movement through soil layers (Marques et al., 2012). Conversely, larger pores allow the movement of carbon and allow carbon to migrate across different soil layers (Marques et al., 2017). After deforestation occurs, carbon stability will be affected, leading the carbon cycle into a new equilibrium (Fearnside, 2010). As a result, deforestation will directly impact the carbon stocks in the labile fraction, which makes up the largest part of the soil surface (Marques et al., 2017). The soil carbons in the free light fraction is easily decomposed and released as carbon dioxide, especially in tropical areas with high temperatures, high precipitation, and high biological activities (Mielniczuk et al., 2003). According to the study and figures by Marques et al. (2017), about 26% to 90% of soil carbon is in the free light fraction of the soil, and this carbon is very sensitive to changing conditions. An example is shown in Figure 5; the sample soil is located in the valley bottoms and considered Spodosol, which is a soil type that is usually ashy grey, acidic, and with a strongly leached surface layer and sandy texture underlying layer (Britannia, 2016). This sample has its carbon stock in the free light fraction (FLF) far exceeds other parts of the soil. Factors such as improper land management, climate change, and deforestation can release large amounts of carbon in the free light fraction back into the atmosphere, making the soil under the origin Amazon Forest lose its function as a carbon sink (Soares, 2007). In conclusion, this result suggests that the soil under tropical rainforests needs to be preserved; changes in land use and forest cover could greatly reduce the carbon stocks due to the potential carbon emissions of the labile fraction (Marques et al., 2017).

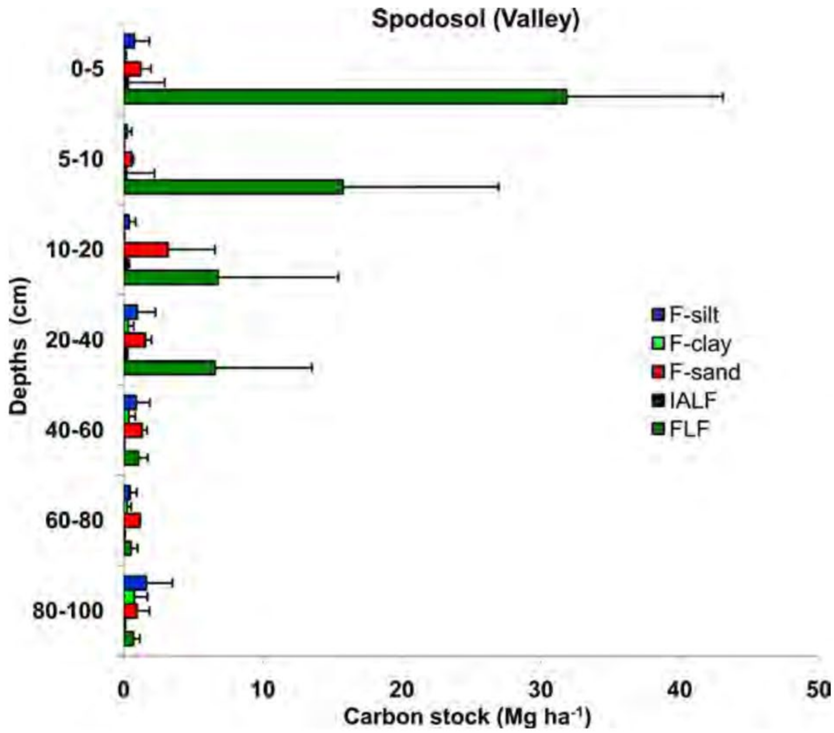


Figure 5: Average soil carbon content in both light and heavy fractions in the valley bottoms. The respective standard deviation is shown by the horizontal lines (Marques et al., 2017).

On the other hand, soil carbon in the deeper layers is also important and could be influenced after changing land management and plant covers. As soil depth increases, carbon stocks in free light fractions continuously decrease, while soil carbon is more present in heavier fractions than in labile fractions (Marques et al., 2017). In three different locations of Marques et al.'s study, the carbon in heavy fractions under 40 cm accounts for 66% to 80% of total carbon on the plateau, 56% to 74% on the slope, and 0.5% to 2.5% in the valley (2017). This part of the carbon stocks will also be released back into the atmosphere as carbon dioxide or methane, but the release rate is much slower due to the hypoxic, moist, and stable environment (Marques et al., 2017). Eventhough the carbon in heavier fractions made up a smaller proportion of soil carbon contents, it was still a significant carbon sink (figure 5). Furthermore, depending on soil types, the carbon content in labile fractions could also make contribution a high percentage at depth. For example, Marques et al. (2017) found that carbon content in free light fractions makes up around 40% of soil carbon in-depth among the valley samples (Figure 6). In 2008, Nepstad et al. estimated that about 55% of the Amazon forests would disappear due to burning, logging, and other reasons; the loss of such forest cover will emit 15 to 26 Pg of C into the air before 2030.

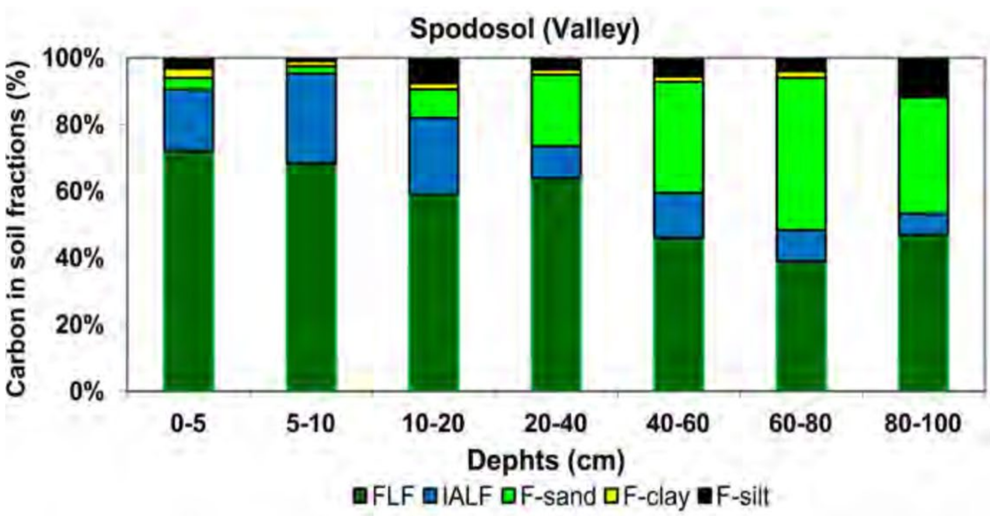


Figure 6: Central Amazonia forest soil carbon contents in different soil fractions in valley bottom (Marques et al., 2017).

Theme 2: How do different land uses impact soil carbon storage after deforestation?

Damian et al. in 2021 published their research to contrast soil carbon storage in undisturbed Amazon forests with different land uses, this include logged and burnt forests, secondary forests in different stages of growth, pasture, and cropland. The study took place in 2010, by collecting soil samples in 356 transects and calculating the response ratio of soil carbon stocks after transformation from undisturbed forests to different land uses (Damian et al., 2021). Two regions were selected in the study, including Paragominas and Santarém, Pará state, eastern Brazilian Amazon (Damian et al., 2021). The two regions are impacted mainly by human activities, and the study collected carbon stock data from 1990 to 2010 (Damian et al., 2021). The result of the study is shown in Figure 7, it shows the response ratio of each sample in two regions, and the red line represents the response ratio for undisturbed forests (Damian et al., 2021). Most samples have a lower soil carbon stock than the undisturbed forest. For example, the transformation of the Amazon Forest into logged and burned forest decreases soil carbon in both regions; 64% of transactions have response ratios lower than 1, meaning that the samples have less soil carbon storage compared with undisturbed forest (Figure 7a; Figure 7b). In all land uses, cropland and pasture lost the most soil carbon with 86% and 74% of response ratio smaller than 1, which is the highest (Figure 7i; Figure 7j; Figure 7k; Figure 7m). The result of the response ratio shows that different land uses have different impacts on soil carbon storage, while changes to cropland and pasture from forests caused the most soil carbon losses (Damian et al., 2021).

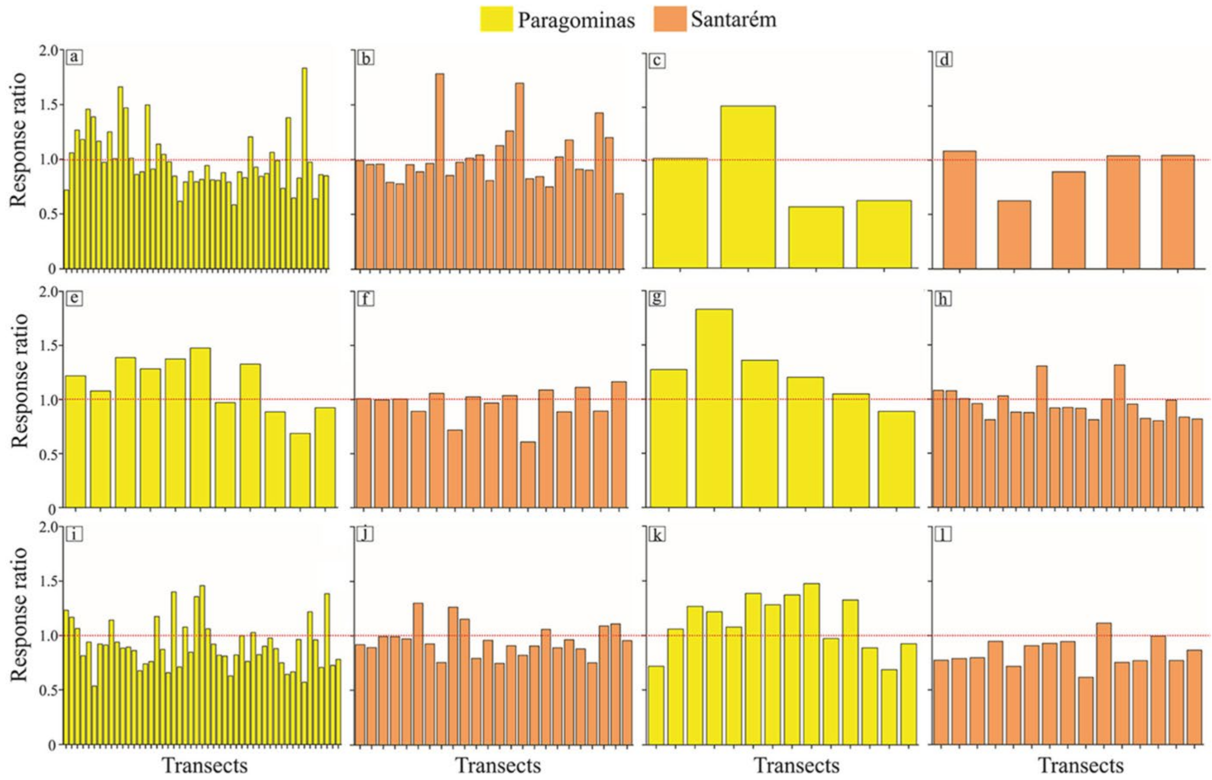


Figure 7: Response ratios of soil carbon content in six different land uses, include: Logged and burnt forest (a and b); young secondary forest (c and d); intermediate secondary forest (e and f); old secondary forest (g and h); pasture (I and j); and cropland (k and l). The horizontal line shows the response ratio for undisturbed forest (Damian et al., 2021).

Damian et al. (2021) also conducted a descriptive statistical analysis of soil carbon storage (Table 1). The result showed that the soil carbon storage in undisturbed forests exceeded most of the other land uses in Paragominas and Santarém (Table 1). In both sites, undisturbed forest samples had the highest mean value, equal to 64.38 Mg ha^{-1} and 57.61 Mg ha^{-1} (Table 1). In Paragominas' samples, the lowest mean value is 44.74

Mg ha^{-1}, which belongs to cropland samples; on the other hand, the young secondary forest and pasture samples from Santarém had the lowest carbon stock, which equals 44.29 Mg ha^{-1} and 48.48 Mg ha^{-1} (Table 1). The coefficient of variation (CV) analysis revealed interesting results among different land uses in the two study sites (Table 1). On average, the CV exhibited a value of 18 ± 9%, indicating moderate variability (Damian et al., 2021). However, some land uses showed significantly higher CV values (Table 1). For example, the young secondary forest and pasture areas had CV ranges of 31 to 63% in Paragominas and 24 to 36% in Santarém (Table 1). These results suggest that some land uses have more significant soil carbon content heterogeneity than other land uses studied (Table 1). The higher CV values in these areas reflected variations in plant cover, land management, or other factors influencing soil carbon stability and storage. The observed variability highlights the significance of land use differences in affecting soil carbon storage. Overall, the transformation from Amazon Forests to other land used type lead to a mean carbon storage decrease of 7%, which is about 4.10 Mg ha^{-1} (Damian et al., 2021).

Table 1: Statistical analysis of soil carbon content (Mg ha^{-1}) in the soil in Paragominas and Santarém.

Site	N^a	Land use	Minimum	Mean	Maximum	CV (%)^b
Paragominas	46	UF	41.51	64.38	66.22	10.23
		LB	40.81	59.09	83.90	18.16
	4	UF	41.51	53.31	65.11	25.56
		SY	26.04	51.01	98.40	63.38
	11	UF	32.53	51.52	66.22	32.35
		SI	40.34	56.70	90.19	29.99
	6	UF	32.53	52.18	66.22	29.38
		SO	44.09	63.70	79.37	21.73
	49	UF	32.53	49.10	66.22	28.21
		PA	20.41	44.74	81.56	35.99
	14	UF	41.51	64.38	66.22	10.23
		CP	40.81	59.09	83.90	18.16
Santarém	46	UF	37.67	52.94	58.89	16.38
		LB	24.16	52.62	104.90	35.24
	5	UF	37.67	50.10	58.89	20.99
		SY	27.11	44.29	63.80	30.74
	15	UF	37.77	54.28	58.89	13.52
		SI	25.35	52.42	68.45	23.18
	21	UF	52.17	57.61	58.89	4.69
		SO	42.23	55.09	77.24	15.09
	24	UF	37.67	52.52	58.89	15.80
		PA	27.41	48.48	67.89	24.19
	15	UF	52.17	57.55	58.89	4.83
		CP	32.17	48.74	65.57	16.73

N: number of transects; CV: coefficient of variation; UF: primary undisturbed forest; LB: logged and burnt forest; SY: young secondary forest; SI: intermediate secondary forest; SO: old secondary forest; PA: pasture; CP: cropland (Damian et al., 2021).

The research by Damian et al. (2021) estimated changes in soil carbon stocks from 1990 to 2010, which were caused by land use changes, including the transformation to secondary forest, cropland, and pasture. The result is shown in Table 2. During this period, land-use change in sites Paragominas and Santarém had a total decrease of 1.51 Tg C $year^{-1}$ (Table 2). In Paragominas, land for pasture lost soil carbon ranging from 0.33 to 0.67 Tg C $year^{-1}$, while cropland has carbon losses ranging from 0.01 to 0.33 Tg C $year^{-1}$ (Table 2). In Santarém, pasture and cropland lost soil carbon ranging from 0.58 to 0.92 Tg C $year^{-1}$, and 0.07 to 0.09 Tg C $year^{-1}$ (Table 2). These results demonstrate the significant carbon losses related to land use change in Paragominas and Santarém over the studied period (Table 2). Furthermore, the uncertainty in these results shows the complexity and variability inherent in measuring soil carbon storage associated with land use change. In conclusion, these findings demonstrate the importance of considering the carbon storage change impacted by land use change in order to understand climate change and promote a more sustainable land management practice.

Table 2: Estimated changes of soil carbon stocks (Tg C/year) in different land uses of Paragominas and Santarém, ranging from 1990 to 2010

Site	Land use	Area (km^2)	C change (Tg)	Mean C flux (Tg C $year^{-1}$)	Mean C rate (Mg C ha^{-1} $year^{-1}$)	Uncertainty (± %)
Paragominas	SF	358.23	2.33±0.92	0.12±0.05	0.16±0.06	39.53
	PA	2145.70	−10.07 ±3.48	−0.50±0.17	−0.12±0.04	34.53
	CP	59.70	−0.32±0.10	−0.02±0.01	−0.13±0.04	30.28
	Total	2563.63	−8.06±2.28	−0.40±0.11	0.14±0.04	28.30
Santarém	SF	983.75	−5.23±0.88	−0.26±0.04	−0.13±0.02	16.82
	PA	3478.34	−15.54 ±3.93	−0.78±0.20	−0.11±0.03	25.26
	CP	324.61	−1.52±0.26	−0.08±0.01	−0.12±0.02	17.27
	Total	4786.70	−22.29 ±4.03	−1.11±0.20	−0.12±0.02	18.09

Positive values shows an increase of soil carbon stocks, negative values a decrease of soil carbon stocks. SF: secondary forest; PA: pasture; CP: cropland (Damian et al., 2021).

Theme 3: What land management can be locally recommended to restore the soil carbon at depth in the soil?

1. Establish Secondary Forest

More sustainable land management is necessary to restore the soil carbon at depth in the Brazil Amazon Forest. Many different types of research worldwide have provided suggestions about land uses to mitigate soil carbon loss and reach more sustainable management. In the study mentioned previously, Damian et al.'s study (2021) found that the intermediate and old secondary forest in Paragominas have an average of 10% (5.18 Mg ha^{-1}) and 22% (11.53 Mg ha^{-1}) soil carbon increase compared to the undisturbed forest (Table 1). In Table 2, the research compared soil carbon stock in different land use categories; the only exception is the secondary forests in Paragominas. This category of land use has an input of soil carbon that ranges from 0.07 to 0.17 Tg C $year^{-1}$ and with an average uncertainty of ± 39.53% Tg C $year^{-1}$ (Table 2). According to this result, the authors suggested establishing a secondary forest to increase soil C (Damian et al., 2021). This conclusion agrees with the study of Blécourt et al. in 2013; who found a positive relationship between soil carbon concentration and basal tree area in old secondary forests, which means more biomass is produced and input of carbon into deeper soil depths through root residues. Carvalho et al. (2019) also suggest that the secondary tropical vegetation has a high value in increasing biodiversity, improving ecosystem services, and becoming a potential carbon sink; therefore, it is ideal to replace pasture and cropland.

The involvement of organizations and governments is considered very important to regenerate the Amazon rainforest. In 2017, a forest restoration movement appeared that involved organizations including the Brazilian Ministry of Environment (MMA), the World Bank, the Global Environment Facility (GEF), the Brazilian Fund for Biodiversity (FUNBIO), Conservation International (CI-Brasil), and the socioenvironmental initiative adopted by Rock in Rio, and Amazonia Live (The World Bank Group, 2017). The movement planned to recover 30000 hectares of forest by 2023, which is about 73 million trees (The World Bank Group, 2017). In 2020, Amazon Live posted an update, claiming that about 3.6 million trees were planted during the four years of the movement, and the organization did not post any updates in 2023 (Amazonia Live - Rock in Rio, 2020). Such types of movement could help regenerate the lost forest and mitigate the soil carbon loss; however, the current status of the Amazon live movements is warning us that society, governments, and different organizations need to make huge efforts to achieve the goal.

2. Stop Expansion of Agricultural Lands

The article by DeFries and Rosenzweig (2010) focuses on another aspect of achieving sustainable land use. The authors' mentioned that expanding agricultural land is one of the main reasons for deforestation in the tropical region (DeFries & Rosenzweig, 2010). In the past 40 years, about 30% of crop production increase in developing countries was the result of the expansion of agricultural land (Food and Agriculture Organization, 2002). The authors' used various sources of data to compare the contributions of the deforestation process to soil carbon emissions and crop production increase from 2000 to 2005 (Table 3). The Table shows that the deforestation of tropical forests caused only a 4.3% increase in agricultural land in tropical countries of Latin America, which is also the highest increase compared with Africa and Asia (DeFries & Rosenzweig, 2010). On the other hand, the loss of tropical forests in Latin America is responsible for 53% of total carbon emissions in the region (DeFries & Rosenzweig, 2010). The result concluded that deforestation could lead to a huge amount of soil carbon loss while having little contribution to agricultural area expansion (DeFries & Rosenzweig, 2010). Therefore, intensification that increases crop yield per area should become the major metric to improve food production and prevent food insecurity. Food and Agriculture Organization (FAO) predict that over 80% of future crop production increase is the result of intensification, instead of expanding the agricultural area (2002). Notably, in tropical areas with low crop yield, intensification is the key element to ensuring food security and lowering the demand for agricultural expansion (Schmidhuber & Tubiello, 2007; DeFries & Rosenzweig, 2010). Considering the increasing urbanization and international trade, large-scale commercial agriculture will likely become the major driver for future deforestation (DeFries et al., 2010). The increase in large-scale commercial agriculture gives incentive policies a great chance to stimulate new productions on land that was already cleared or with low carbon stocks (DeFries & Rosenzweig, 2010). Some international policies also apply to this situation, such as adding soil carbon fixation credits of local cropping areas in the carbon market, stimulation for projects that prevent forest loss and raise cropping yield, and guidance for involvement in international markets (DeFries & Rosenzweig, 2010). On the other hand, these policies have little impact on farmers that control small-scale agricultures since shift of locations are difficult for them; therefore, other choices that include stimulating conservation tillage, intercropping, and composting are more feasible (DeFries & Rosenzweig, 2010). Among all solutions, intercropping could be one of the major solutions to mitigate soil carbon loss in small-scale cropping areas, as it allows different crop species to grow in one area instead of a sole crop. According to the study by Cong et al. in 2015, rotational strip intercrop systems have 4% ± 1% higher soil carbon storage in the top 20 centimeters soil compared with ordinary single crop rotations. The two systems' differences can reach 184 ± 86 kg C ha^{-1} yr^{-1} (Cong et al., 2015). This result showed that the ability of soil carbon fixation of intercropping systems makes it an effective way to mitigate soil carbon loss from agriculture practices (Cong et al., 2015). During intercropping practices, crop species such as fruit trees have deeper root systems, thus allowing root litter to be transferred into deep soil layers and restoring carbon content in depth.

Table 3: Comparison of area gained for food production from deforestation and carbon losses from 2000 to 2005 (DeFries & Rosenzweig, 2010)

Table S2. Comparison of maximum land area gained for food production from deforestation (gross forest loss) and estimated carbon emissions for 2000–2005

	Change in gross forest area 2000–2005 from ref. 1, km^2		Agricultural area in 2000 based on ref. 2, km^2*		Estimated deforestation emissions (2000–2005), Pg CO_2†		CO_2 emissions excluding organic sources from ref. 3 (2000–2005), Pg
	Dry tropical forest	Humid tropical forest	Crop area	Pasture area	Dry forest	Humid forest	
Tropical Latin America	53,959	159,427	1,187,396	3,797,626	0.98	7.52	7.44
Tropical Africa	94,088	14,494	1,820,616	6,470,506	1.00	0.52	3.70
Tropical Asia	8,766	72,194	2,928,100	187,070	0.21	6.43‡	14.73
Total tropics	156,813	246,115	5,936,113	10,455,202	2.20	14.47	25.87

3. Sustainable Practices on Pastureland

Finally, the unsustainable management of pastureland also leads to its lower response ratios compared with undisturbed forests (Figure 7i; Figure 7j). About half of the pasture area in Amazonia is already degraded or in some stage of degradation (Dias Filho, 2015). The situation is the result of overgrazing pressure and lack of sustainable management (Dias Filho, 2015). Stahl et al.'s study (2017) found that the pasture can partially recover the soil carbon content lost in the Amazon Forest, but this may take 24 years of sustainable management and implementation. These management practices include: preventing fires; controlling overgrazing; designing a rotation grazing plan; and also have a mix of both C4 and C3 plant species (Stahl et al., 2017). Many studies also suggest that intensification and diverse systems (e.g., integrated crop-livestock, and crop-forest-livestock systems) can increase pasture land's ability to restore soil carbon under this management; and the soil carbon storage can even exceed areas with forests (Grahmann et al., 2020; Silva et al., 2017; Vicente et al., 2019; Damian et al., 2021). Therefore, sustainable management and diverse systems are necessary to recover the soil carbon loss from deforestation. Thus local policies are important to stimulate individuals or companies to abandon their unsustainable management practices.

Summary and Conclusions:

This paper examined the impact of deforestation and subsequent land development on soil carbon storage. The disappearance of the Amazon Forest is destructive to the local soil carbon storage, and the subsequent different land use and management have caused different degrees of carbon loss. The literature review of different studies leads to the following conclusions:

1. Amazon Forests act as a carbon sink. Grace et al. published a study in 1995 that measured the carbon fixation and loss rates in the Amazon Forest. Carbon continuously accumulates in the undisturbed forest area, and some of them will be transferred into the soil through leaf and root litter (Grace et al., 1995). Deforestation impacts soil carbon storage by changes the soil's physical structure under forests that affects soil carbon stability, causing the carbon cycle to change into a different equilibrium and the releasing of huge amounts of carbon into the air (Marques et al., 2017). The majority of released carbon was stored in the labile fraction of soil, which stores most of the surface soil carbon (Marques et al., 2017).
2. Damian et al.'s study (2021) found that most of the land uses lead to soil carbon loss compared with undisturbed forests (Damian et al., 2021). Among all sites, cropland and pastureland have the highest carbon loss, and most of the sites have smaller response ratios than the undisturbed forests (Damian et al., 2021). Statistical analysis also suggests that land uses have different soil carbon stock variations (Damian et al., 2021). The result showed that these land uses and management are variable, but most have negative impacts on soil carbon storage and would be improved to mitigate their impact on soil carbon stock.
3. Secondary forests were found to have higher soil carbon storage than undisturbed forests; establishing secondary forests and replacing pasture and

cropland is a possible solution to recover soil carbon storage (Damian et al., 2021). DeFries and Rosenzweig (2010) strengthened a common conclusion that agricultural expansion in tropical areas would not solve food insecurity but leading to massive soil carbon loss. Intensification becomes the solution to increasing crop yield instead of removing forests for more cropland (DeFries & Rosenzweig, 2010). Local policies and more sustainable land management practices (e.g., intercropping) should be promoted in both large-scale commercial farms and individual farmers (DeFries & Rosenzweig, 2010). Finally, sustainable managements are necessary when managing pastureland, this could include building more diverse pasture systems, or practices such as preventing fires, controlling overgrazing, and designing a rotation grazing plan. Through sustainable management, it is possible for pasturelands to recover part of the lost carbon caused by deforestation (Stahl et al., 2017).

In conclusion, most land practices after deforestation leads to soil carbon loss. More sustainable management mentioned in this report is needed to recover soil carbon on both surface and deeper in the soil. The involvement of local government and organizations is essential to stimulate the mitigation processes, and this will take a long time and huge effort.

Recommendation:

The project provides some and information to local and global governments and land managers regarding deforestation that can cause soil carbon loss and what could be done.

1. Secondary forest is a possible solution to replace other land uses to recover from the soil carbon loss of deforestation. Many ongoing movements and policies aim to increase secondary forest area; however, this needs continuous efforts and investment. Local governments should take responsibility, introduce incentive policies and collaborate more frequently with other organizations such as NGOs.
2. Cropland and pastureland should promote intensification, more sustainable land management, and slow down area expansion. Incentive policies are the key to preventing large-scale cropland and pastureland expansion, and possible sustainable management includes intercropping, conservation tillage, preventing fires, controlling overgrazing, and designing a rotation grazing plan.
3. This project limitation is that as it focused on regions of the Brazilian Amazon forest. Therefore, this project is limited by geography, soil types, local climate, the years of research. In future research, the study should focus on different soil types and their influence on soil carbon loss during deforestation; and climate as an impact during this process, which needs further detailed research. Finally, the water table is another factor affecting soil carbon stability. The relationship between deforestation, water table, and its influence on soil carbon stability should be studied since the transpiration process would reduced after deforestation.

References:

1. National Oceanic and Atmospheric Administration. (2022, June 3). *Carbon dioxide now more than 50% higher than pre-industrial levels*. National Oceanic and Atmospheric Administration. https://www.noaa.gov/news-release/carbon-dioxide-now-more-than-50-higher-than-pre-industrial-levels

2. Huang, L., Krigsvoll, G., Johansen, F., Liu, Y., & Zhang, X. (2018). Carbon emission of global construction sector. *Renewable and Sustainable Energy Reviews*, *81*, 1906-1916.

3. UNFCCC (2015). The Paris Agreement. United Nations Framework Convention on Climate Change. Retrieved from http://unfccc.int/paris_agreement/items/9485.php

4. Sheppard, S. R. J. (2012). Hot in my backyard: Seeing the impacts of climate change. *Visualizing climate change* (pp. 149-177). Routledge. https://doi.org/10.4324/9781849776882-14

5. Schimel, D. S. (1995). Terrestrial ecosystems and the carbon cycle. *Global change biology*, *1*(1), 77-91.

6. Toochi, E. C. (2018). Carbon sequestration: how much can forestry sequester CO2. *Forestry Research and Engineering: International Journal*, *2*(3), 148-150.

7. Damian, J. M., Durigan, M. R., Cherubin, M. R., Maia, S. M. F., Ogle, S. M., de Camargo, P. B., ... & Cerri, C. E. P. (2021). Deforestation and land use change mediate soil carbon changes in the eastern Brazilian Amazon. *Regional Environmental Change*, *21*(3), 64.

8. Grace, J., Lloyd, J., McIntyre, J., Miranda, A. C., Meir, P., Miranda, H. S., ... & Gash,

J. (1995). Carbon dioxide uptake by an undisturbed tropical rain forest in southwest Amazonia, 1992 to 1993. *Science*, *270*(5237), 778-780.

9. Carvalho, G., Cristina Barros, A., Moutinho, P., & Nepstad, D. (2001). Sensitive development could protect Amazonia instead of destroying it. *Nature*, *409*(6817), 131-131.

10. Goodman, D. E. (1990). Anthony Hall, eds. 1990. The Future of Amazonia: Destruction or Sustainable Development? New York: St.

11. Laurance, W. F. (1998). A crisis in the making: responses of Amazonian forests to land use and climate change. *Trends in Ecology & Evolution*, *13*(10), 411-415.

12. Ometto, J. P., Sousa-Neto, E. R., & Tejada, G. (2016). Land use, land cover and land use change in the Brazilian Amazon (1960–2013). *Interactions between biosphere, atmosphere and human land use in the amazon basin*, 369-383.

13. Instituto Nacional de Pesquisas Espaciais–INPE (2013) Amazon deforestation detection in real time (DETER). www.obt.inpe.br/deter.

14. Instituto Nacional de Pesquisas Espaciais–INPE/Empresa Brasileira de Pesquisa Agropecua´ria (EMBRAPA) (2011) TerraClass Project. www.inpe.br/cra/projetos_pesquisas/terraclass2010.php.

15. Quesada, C. A., Lloyd, J., Schwarz, M., Patiño, S., Baker, T. R., Czimczik, C., ... & Paiva, R. (2010). Variations in chemical and physical properties of Amazon forest soils in relation to their genesis. *Biogeosciences*, *7*(5), 1515-1541.

16. Six, J., Elliott, E. T., Paustian, K., & Doran, J. W. (1998). Aggregation and soil organic matter accumulation in cultivated and native grassland soils. *Soil Science*

Society of America Journal, *62*(5), 1367-1377.

17. Aanderud, Z. T., Richards, J. H., Svejcar, T., & James, J. J. (2010). A shift in seasonal rainfall reduces soil organic carbon storage in a cold desert. *Ecosystems*, *13*, 673-682.

Grace, J., Lloyd, J., McIntyre, J., Miranda, A. C., Meir, P., Miranda, H. S., ... & Gash, J. (1995). Carbon dioxide uptake by an undisturbed tropical rain forest in southwest Amazonia, 1992 to 1993. *Science*, *270*(5237), 778-780.

18. Fan, S. M., Wofsy, S. C., Bakwin, P. S., Jacob, D. J., & Fitzjarrald, D. R. (1990). Atmosphere-biosphere exchange of CO2 and O3 in the central Amazon forest. *Journal of Geophysical Research: Atmospheres*, *95*(D10), 16851-16864.

19. Marques, J. D. O., Luizão, F. J., Teixeira, W. G., Nogueira, E. M., Fearnside, P. M., & Sarrazin, M. (2017). Soil carbon stocks under amazonian forest: distribution in the soil fractions and vulnerability to emission.

20. Fearnside, P. M. (2010). Carbon Stock and Stability in Soils in the Brazilian Amazon. In W. G. Teixeira, D. C. Kern, B. C. Madari, H. N. Lima, & W. I. Woods, (Eds.), *The Dark Earth of the Amazon: Their Characterization and Use of this Knowledge in the Crea- tion of New Areas* (pp. 259-263). Manaus: Editora da Universidade Federal do Ama- zonas (EDUA) and Embrapa Amazônia Ocidental.

21. Ekschmitt, K., Liu, M., Vetter, S., Fox, O., & Wolters, V. (2005). Strategies used by soil biota to overcome soil organic matter stability—why is dead organic matter left over in the soil?. *Geoderma*, *128*(1-2), 167-176.

22. Marques, J. D. D. O., Luizão, F. J., Teixeira, W. G., & Ferreira, S. J. F. (2012). Variations of dissolved organic carbon and soil physical properties under different land

uses in Central Amazônia. *Volume 36, Número 2, Pags. 611-622*.

23. Mielniczuk, J., Bayer, C., Vezzani, F. M., Lovato, T., Fernandes, F. F., & Debarba, L. (2003). Soil and crop management and their relationship with carbon and soil nitrogen stocks. *Tópicos em Ciência do Solo; Curi, N., Marques, JJ, Guilherme, LRG, Lima, JM, Lopes, S., Alvarez, VVH, Eds*, 209-248.

24. Britannica, T. Editors of Encyclopaedia (2016, May 2). *Spodosol*. *Encyclopedia Britannica*. https://www.britannica.com/science/Spodosol

25. Soares, R. (2007). *Aggregation and Distribution of Organic Matter in Native Amazonian Soils of Central Amazonia* (107 p). Masters Dissertation in Geosciences, Niterói: Uni- versidade Federal Fluminense.

26. Nepstad, D. C., Stickler, C. M., Soares-Filho, B., & Merry, F. Interactions among Amazon land use, forests and climate. https://doi.org/10.1098/rstb.2007.0036

27. de Blécourt, M., Brumme, R., Xu, J., Corre, M. D., & Veldkamp, E. (2013). Soil carbon stocks decrease following conversion of secondary forests to rubber (Hevea brasiliensis) plantations. *PloS one*, *8*(7), e69357.

28. Carvalho, R., Adami, M., Amaral, S., Bezerra, F. G., & de Aguiar, A. P. D. (2019). Changes in secondary vegetation dynamics in a context of decreasing deforestation rates in Pará, Brazilian Amazon. *Applied Geography*, *106*, 40-49.

29. The World Bank Group. (2017, September 15). *Amazon rainforest to recover 30,000 hectares by 2023*. World Bank. https://www.worldbank.org/en/news/press-release/2017/09/15/brazil-initiative-recovers-forest-lands-amazon

30. Amazonia Live - Rock in Rio. (2020, September 8). *30.000 hectares de Floresta*

recuperada – amazonia live. Amazonia Live - Rock in Rio. https://amazonialive.com.br/73-milhoes-de-arvores-plantadas-e-em-projetos-de-restauro-florestal/

31. DeFries, R., & Rosenzweig, C. (2010). Toward a whole-landscape approach for sustainable land use in the tropics. *Proceedings of the National Academy of Sciences*, *107*(46), 19627-19632.

32. Food and Agriculture Organization. (2002) *World Agriculture: Towards 2015/2030*. https://www.fao.org/3/y3557e/y3557e.pdf

33. Schmidhuber, J., & Tubiello, F. N. (2007). Global food security under climate change. *Proceedings of the National Academy of Sciences*, *104*(50), 19703-19708.

34. DeFries, R. S., Rudel, T., Uriarte, M., & Hansen, M. (2010). Deforestation driven by urban population growth and agricultural trade in the twenty-first century. *Nature Geoscience*, *3*(3), 178-181.

35. Cong, W. F., Hoffland, E., Li, L., Six, J., Sun, J. H., Bao, X. G., ... & Van Der Werf, W. (2015). Intercropping enhances soil carbon and nitrogen. *Global change biology*, *21*(4), 1715-1726.

36. DIAS FILHO, M. B. (2015). Estratégias de recuperação de pastagens degradadas na Amazônia brasileira.

37. Stahl, C., Fontaine, S., Klumpp, K., Picon-Cochard, C., Grise, M. M., Dezécache, C., ... & Blanfort, V. (2017). Continuous soil carbon storage of old permanent pastures in Amazonia. *Global Change Biology*, *23*(8), 3382-3392.

38. Grahmann, K., Dellepiane, V. R., Terra, J. A., & Quincke, J. A. (2020). Long-term

observations in contrasting crop-pasture rotations over half a century: statistical analysis of chemical soil properties and implications for soil sampling frequency. *Agriculture, Ecosystems & Environment*, *287*, 106710.

39. de Oliveira Silva, R., Barioni, L. G., Hall, J. J., Moretti, A. C., Veloso, R. F., Alexander, P., ... & Moran, D. (2017). Sustainable intensification of Brazilian livestock production through optimized pasture restoration. *Agricultural systems*, *153*, 201-211.

40. Vicente, L. C., Gama-Rodrigues, E. F., Gama-Rodrigues, A. C., & Marciano, C. R. (2019). Organic carbon within soil aggregates under forestry systems and pasture in a southeast region of Brazil. *Catena*, *182*, 104139.

41. Damian, J. M., da Silva Matos, E., e Pedreira, B. C., de Faccio Carvalho, P. C., Premazzi, L. M., Williams, S., ... & Cerri, C. E. P. (2021). Predicting soil C changes after pasture intensification and diversification in Brazil. *Catena*, *202*, 105238.

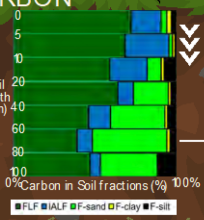
Appendix:

BRAZILIAN AMAZON FOREST DEFORESTATION & SOIL CARBON LOSS

The Brazilian Amazon Forest is a globally important carbon sink; however, continuous deforestation has resulted this ecological service. Therefore, it is necessary to explore the impact of deforestation and subsequent land uses on soil carbon storage, then restore the carbon storage.

FOREST LOSS & SOIL CARBON

- Deforestation changes the soil's physical structure under forests
  - Soil physical structure relate to soil carbon stability.[1]
  - Carbon in soil surface mostly present in light fraction of soil, deforestation leading to massive carbon release from this unstable form.[2]



Carbon storage in light fraction (FLF & IALF) continuously decrease.[2]

Carbon released slower when deeper in the soil due to lack of oxygen, higher moisture and more stable form of carbon (in heavy fraction of soil).[2]

SUBSEQUENT LAND USES & SOIL CARBON

- Damian et al. (2021) select two locations impacted most by human activities (Paragominas & Santarém). Most of the subsequent land uses lead to soil carbon loss.
  - Intermediate secondary forest & Old Secondary Forest have a higher average soil carbon stock than original forest.[3]
  - Among all sites, cropland and pastureland have the highest carbon loss.[3]
  - Land management could be improved to mitigate their impact on soil carbon stock.[3]

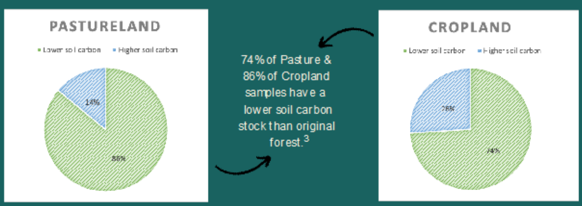


Figure: Comparison between soil carbon content in pastureland & cropland with the original Amazon tropical forest.[3]

CONCLUSION & RECOMMENDATIONS

- Secondary forests store more soil carbon storage than undisturbed forests.[3]
  - Establishing secondary forests to replace pasture & cropland.
- Agricultural expansion in tropical areas lead to massive soil carbon loss.[4]
  - Cropland & pastureland should promote intensification, more sustainable land management.
  - Suggested management includes intercropping, conservation tillage, controlling overgrazing, etc.
- Local policies and more sustainable land management practices (e.g., intercropping) should be promoted in both large-scale commercial farms and individual farmers.[4]

REFERENCES

1. Fearnside, P. M. (2010). Carbon Stock and Stability in Soils in the Brazilian Amazon. In W. G. Teixeira, D. C. Kern, B. C. Madari, H. N. Lima, & W. I. Woods, (Eds.), The Dark Earth of the Amazon: Their Characterization and Use of this Knowledge in the Crea- tion of New Areas (pp. 259-263). Manaus: Editora da Universidade Federal do Ama- zonas (EDUA) and Embrapa Amazônia Ocidental.
2. Marques, J. D. O., Luizão, F. J., Teixeira, W. G., Nogueira, E. M., Fearnside, P. M., & Sarrazin, M. (2017). Soil carbon stocks under amazonian forest: distribution in the soil fractions and vulnerability to emission.
3. Damian, J. M., da Silva Matos, E., e Pedreira, B. C., de Faccio Carvalho, P. C., Premazzi, L. M., Williams, S., ... & Cerri, C. E. P. (2021). Predicting soil C changes after pasture intensification and diversification in Brazil. Catena, 202, 105238.
4. DeFries, R., & Rosenzweig, C. (2010). Toward a whole-landscape approach for sustainable land use in the tropics. Proceedings of the National Academy of Sciences, 107(46), 19627-19632.