Restoring tropical forests as a mitigation measure of global climate change: a meta-analysis

Bachelors thesis
Milieu-Natuurwetenschappen (GEO3-2138)

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Abstract

Restoring tropical forests as a mitigation measure of climate change has been a widely accepted method. However, the areas in which afforestation is taking place might be misinterpreted. These areas are identified as suitable for afforestation as they are assumed to be secondary products of agriculture. However, most of these areas are ancient grassy biomes that store significant amounts of carbon dioxide. Therefore, this research aims to provide an insight in the efficiency of restoring tropical forests in tropical grassy biomes. Via a meta-analysis the differences between carbon storage in restored tropical forests and tropical grassy biomes have shown to be insignificant. Yet, assuming that restored forest will eventually reach a mature state, the differences in carbon storage between mature tropical forest and tropical grassy biomes found via meta-analysis are significant. Concluding, this research shows that mature forests can store more carbon than tropical grassy biomes while secondary tropical forests cannot.

Het herstellen van tropisch bos als verzachtende maatregel voor klimaatverandering is een algemeen aanvaarde methode. Echter, de gebieden waarin bebossing plaatsvindt, worden mogelijk onjuist geïnterpreteerd. Zij worden geïdentificeerd als secundair product van landbouw, terwijl zij in werkelijkheid oeroude tropische grasbiomen zijn die aanzienlijke hoeveelheden koolstofdioxide opslaan. Dit onderzoek zal daarom gefocust zijn op het creëren van inzichten omtrent de doeltreffendheid van het herstellen van tropisch bos in tropische grasbiomen. Uit de uitvoering van een meta-analyse blijkt dat er geen significant verschil is in koolstofopslag tussen secundair tropisch bos en tropische grasbiomen. Echter, aannemend dat secundair bos uiteindelijk een volgroeid stadium zal bereiken, blijkt er uit de meta-analyse dat het verschil in koolstofopslag tussen volgroeid tropisch bos en tropische grasbiomen wel significant is.
Er kan geconcludeerd worden dat volgroeid tropisch bos meer koolstof kan opslaan dan tropische grasbiomen, terwijl secundair tropisch bos dat niet kan.

Table of contents

1. Introduction

Climate change has been a widely discussed topic, since researchers have found that this change has been developing rapidly. Even though the Earth has experienced changes in climate before, as can be seen in historical data, during the past century it has been influenced by anthropogenic causes (Miller & Spoolman, 2012).
Different processes are contributing to this change. One of these processes is the increased anthropogenic emission of carbon dioxide (CO_2), mainly due to burning fossil fuels. This affects the atmospheric concentrations of gasses (Miller & Spoolman, 2012). In addition, people change the land surface, for example by burning forests in the process of clearing land for agricultural use (Cubasch et al., 2013). Not only does this add more CO_2 to the atmosphere, it also changes the vegetation type and by that the amount of CO_2 that can be taken up by the vegetation (Cubasch et al., 2013). Especially in tropical regions, deforestation has been expanding due to an increase in food demand (DeFries & Rosenzweig, 2010). This changes the vegetation type and therefore the carbon stocks in above and below ground biomass. Recent estimates of CO_2 emissions from deforestation and forest degradation in tropical regions indicate ≈1.2 Pg C/y (4.8 Pg CO_2/y) for 1997–2006 (12% of all anthropogenic CO_2 emissions) (DeFries & Rosenzweig, 2010). Due to the projected food demand in the future, these emissions will increase even more (DeFries & Rosenzweig, 2010).
Meanwhile, restoring degraded tropical areas has become a widely accepted mitigation measure of climate change (Thorsell & Sigaty, 1997). However, depending on the type of trees and the amount of species with which cleared tropical forests are being reforested, the effects on the biodiversity of the reforested area are only moderately positive (Kanowski, Catterall, & Wardell-Johnson, 2005). This means that the biodiversity of a restored area increases only slightly when afforestation has taken place and can't compare to the diversity of an old-growth tropical forest (Kanowski et al., 2005). As research has pointed out that a more diverse tropical forest can store more CO_2 (Poorter et al., 2015), this would mean that a reforested area would not be able to store the same amount of CO_2 as a natural tropical forest. A case study by Wheeler et al. (2016) on restoring a tropical forest in Uganda shows that after 18 years of active restoration, a degraded tropical forest has only 12% of the above ground biomass that an old-growth forest has. This above ground biomass consists for 80% of grasses and contains a significantly lower biodiversity (Wheeler, Omeja, Chapman, Glipin, Tumwesigye, & Lewis, 2016).
Another problem arises when reforesting tropical savannahs and grasslands, which cover approximately 20% of the globe (Parr, Lehmann, Bond, Hoffmann, & Andersen, 2014). These tropical grassy biomes (TGBs) have been identified by the World Resources Institute as suitable areas for reforestation as they are assumed to be secondary product of deforestation and degradation (Bond, 2016; Minnemeyer et al., 2014). However, these lands are mostly ancient tropical grasslands and savannahs which are highly biodiverse and provide a special habitat and ecosystem services for approximately 500 million people who live in these areas (Bond, 2016). They also store about 15% of the carbon on Earth, which makes them important factors in the carbon and energy cycles (Parr et al., 2014).
To contribute to the already existing knowledge about reforestation, this thesis will focus on the efficiency of secondary tropical forest growth in TGBs as a mitigation measure of climate change. This research aims to answer the question '***Is restoring tropical forests in tropical grassy biomes an efficient mitigation measure of climate change?***'.

It is hypothesized that this question will lead to the following: secondary tropical forests have less biomass (above and below ground) than tropical grassy biomes and can therefore store less carbon. However, in the long run, when secondary tropical forests reach climax state and turn into mature tropical forests, they gain biomass and consequently carbon storage capacity. Thus, when focusing only on carbon storage in biomass as a mitigation measure, converting TGBs to tropical forest is in the long run an efficient way of mitigating climate change. Nevertheless, precipitation rates must be taken into account for the comparison of TGBs and old-growth forest, as an area can only host tropical forests when precipitation rates are high enough (D'Onofrio, von Hardenberg & Baudena, 2018).
The structure of this thesis is as follows. First, an overview of the existing literature is given in order to provide a theoretical background. Then, this research proceeds to a meta-analysis to research the hypothesis. Therefore, three research questions will then be answered:

- How does secondary tropical forest compare to natural tropical forest in terms of biomass and carbon storage?
- How do secondary tropical forests compare to tropical grassy biomes in terms of biomass and carbon storage?
- How do natural tropical forests compare to tropical grassy biomes in terms of biomass and carbon storage?

Herein 'tropical forest' and 'TGB' refer to tropical biomes that are natural and/or old-growth. These biomes have reached a mature state. 'Secondary tropical forest' refers to an either anthropogenic or naturally restored tropical forest. Thus, both active and passive restoration of tropical forests will be referred to as 'secondary forest'. Assuming that secondary forest will eventually reach a mature state, a comparison of biomass and carbon storage between natural tropical forest and TGBs will also be made. This will be done for TGBs with a precipitation rate of >1200 mm/yr as TGBs with <1200 mm/yr can't host a mature forest (D'Onofrio et al., 2018).

2 Theoretical framework

This chapter provides an overview of the existing literature about tropical forests and tropical grassy biomes. In the first paragraph a description of the interaction between tropical forests and the climate is given. In the second paragraph the same is effectuated for tropical grassy biomes.

2.1 Tropical forest

Tropical forests contain approximately 25% of all terrestrial carbon and sequester a lot of carbon, which makes them either carbon neutral or carbon sinks (Bonan, 2008). There are multiple factors that explain the sequestration of carbon in tropical forests: above ground biomass (AGB), below ground biomass (BGB), species richness and forest structures (figure 1).

Tropical forests are highly biodiverse. They only cover 2% of the Earths' land surface but contain at least half of the Earths' species (Miller & Spoolman, 2012). As a consequence, tropical forests have a lot of biomass and can thus capture a lot of CO_2 (Miller & Spoolman, 2012). This is due to two effects: with higher biodiversity niche complementarity increases; there are more species that inhabit different niches and thus more of the available resources can get accessed (Poorter et al., 2015). This is due to the fact that interspecific resource use leads to more efficient use of limiting resources (Fargione et al., 2007).

Furthermore, the chances of having highly productive species in the ecosystem and species that alternate productivity every other year increase with more biodiversity (Poorter et al., 2015). These two effects of biodiversity mean that species rich areas have more biomass and with that a higher net primary productivity (NPP) (Poorter et al., 2015; Zhang et al., 2012). NPP is defined as the rate of capturing CO_2 and using it for photosynthetic activity minus the rate of CO_2 emitted by plants respiration. Therefore, species richness indirectly contributes to the sequestration of CO_2 (figure 1).

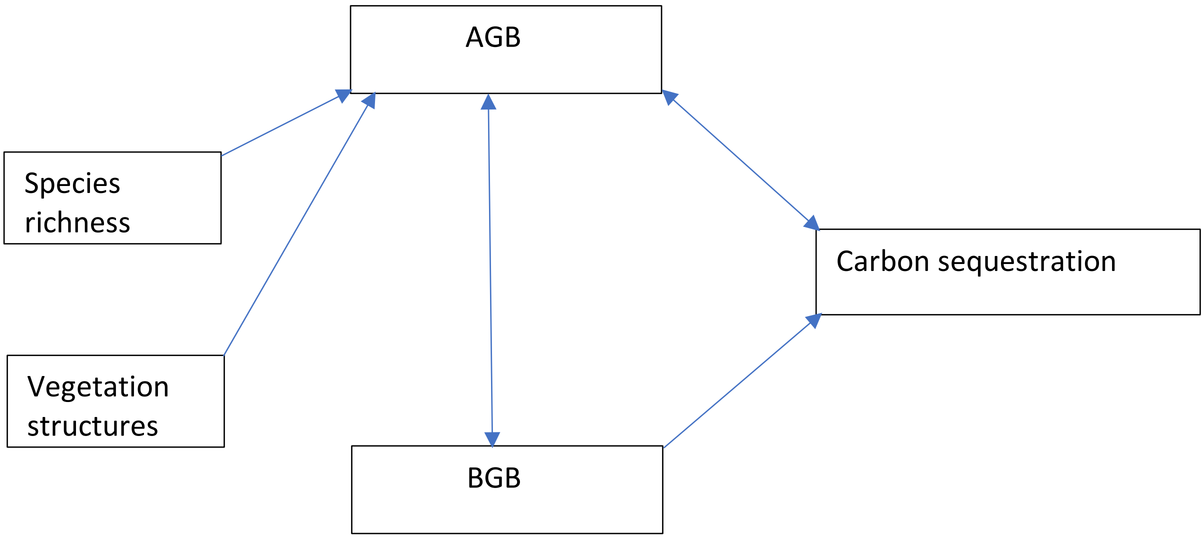

Figure 1: carbon sequestration in tropical forest ecosystems: species richness and forest structures positively influence the amount of above ground biomass (AGB). Above ground biomass and below ground biomass (BGB) influence each other positively and together they have a positive influence on carbon sequestration

Not only biodiversity increases the AGB. This is also influenced by vegetation structures e.g. leaf layering, leaf area index, stem diameter and vegetation density (Poorter et al., 2015). For example, the leaf area index in tropical forests is 5-14 m^2/m^2. As the leaf is the part of the plant in which photosynthesis is being conducted, a bigger leaf area index has a positive influence on the NPP and biomass carbon stocks (Smithson et al., 2008).
Another factor is below ground biomass (BGB). BGB influences the soil fertility and the sequestration of soil carbon. Estimates show that the global amount of carbon in soils is 2500 GtC of which 1550 GtC is soil organic carbon. This amount is 3.3 times the amount of atmospheric carbon and 4.5 times the amount of biotic carbon, which makes land use changes of high impact on total terrestrial carbon stocks (Hounkpatin, Op de Hipt, Bossa, Welp, & Amelung, 2018). BGB and AGB also influence each other; more AGB means more litterfal and thus more litter input in the ground. This creates higher soil fertility and availability of nutrients, which influences AGB positively. This in turn increases BGB. BGB also influences carbon sequestration directly; sequestration of CO_2 in soil organic matter absorbs CO_2 into the soil (Smithson et al., 2008).
Due to human-generated increases in CO_2 emissions, tropical forests can increase their photosynthetic activities. This means that higher amounts of atmospheric CO_2 could lead to more carbon sequestration, which leads to higher rates of photosynthesis and thus more plant growth. More plant growth leads to more carbon sequestration and thus the plant-CO_2 feedback is negative. Therefore, atmospheric CO_2 could decrease due to increased photosynthetic activity (Bonan, 2008). This process is shown in figure 2.

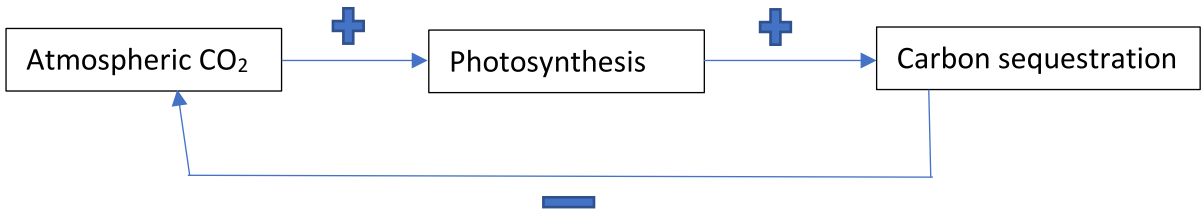

Figure 2: plant-CO2 feedback

Terrestrial carbon storage could increase due to climate change: as an additional amount of CO_2 is emitted to the atmosphere by anthropogenic sources, NPP could increase with 12-76% (Bonan, 2008). Half of the annual NPP occurs in the tropics, where most of this productivity can be found in tropical forests (Melillo et al., 1993). This estimation has been made through the modeling of doubled CO_2 concentrations. The chosen baseline CO_2 concentration was 312,5 p.p.m.v. (Melillo et al., 1993). More recent research states that the amount of carbon stored in tropical forests could even be as high as 70% of all forest storage (Urbazaev et al., 2018). According to Saugier et al. (2001), tropical forests have an above ground NPP of 1400 $g/m^2/yr$ and a below ground NPP of 1100 $g/m^2/yr$. In total this means sequestration of 21.9 Pg C per year via NPP (Smithson et al., 2008). Limitations of NPP increase in tropical forests are not set by nitrogen, as in other types of forests, but could be limited by other nutrients such as phosphorous (Melillo et al., 1993). This means that carbon sequestration in tropical forests could cease to increase at a certain point due to a lack of nutrients. Another limiting factor on the sequestration of CO_2 in tropical forests is change in soil organic matter due to higher temperatures or the increase or decrease of precipitation. A change in the amount of soil organic matter could negatively influence the nutrient-holding capacity of soils and damage the forests (Smithson et al., 2008).

2.2 Tropical grassy biome

Another ecosystem that could mitigate the effects of increased CO_2 emissions is a tropical grassy biome (TGB). TGBs are all tropical savannahs and grasslands and cover approximately 20% of the land surface. They store approximately 15% of all carbon, which accounts for 30% of the terrestrial carbon (Parr et al., 2014).

These TGBs persist due to different processes compared to tropical forests. For example: litter in tropical forests decomposes quickly, while litter in TGBs decomposes slowly (Bond & Parr, 2010). This is one of the reasons that TGBs can persist without converting to forests. Litter from dried out grasses in dry seasons is highly flammable and will be cleared by fire. After a fire has burned out, C_4 grasses, of which TGBs mainly consist, are the first types of plants to grow back. These are grasses that transport CO_2 to localized cells during photosynthetic activities, which makes them highly tolerant to high temperatures, low precipitation rates and/or low CO_2 concentrations (Parr et al., 2014). Furthermore, these C_4 grasses don't reach a plateau of CO_2 uptake as happens in other plant species. Instead, the rate of photosynthesis increases with increases in solar radiation intensity (Smithson et al., 2008).

Fire is the main contributor to the positive feedback loop (grass-fire feedback) that enables TGB existence (Zaloumis, & Bond, 2016). This positive feedback loop has been shown in figure 3.

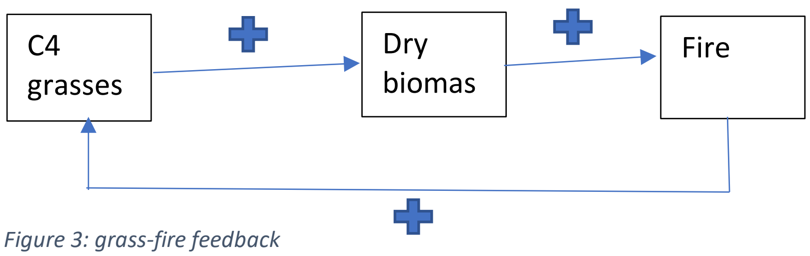

Figure 3: grass-fire feedback

This fire regime enables TGBs existence in areas with high precipitation rates (>1200 mm/yr) that can either host TGBs and tropical forests (D'Onofrio et al., 2018). As tree cover increases with increased precipitation rates, the opposite is also true; tree cover decreases with decreased precipitation rates (D'Onofrio et al., 2018). As rainfall decreases to less than 1200 mm/yr, trees do no longer grow and thus TGBs in these areas do not depend on the grass-fire feedback loop. When precipitation decreases to less than 630 mm/yr TGBs become water limited (D'onofrio et al., 2018).

Diversity in TGBs is to date poorly understood. However, in some areas, like the Cerrado and Campo biomes of Brazil, biodiversity has been researched and found to be very high. These two biomes are especially rich in flora species, with 6000 and 3000-4000 plant species respectively (Bond & Parr, 2010). TGBs contain many endemic species and, compared to tropical forests, have distinct species with little overlap with these forests. Therefore, tropical forests and TGBs both contribute to the diversity of tropical areas (Bond & Parr, 2010).

In a case study on old growth grasslands in South Africa, it became clear that there is a difference between old growth grasslands and secondary grasslands: old growth grasslands were two to four times as biodiverse as secondary grasslands (Zaloumis, & Bond, 2016). Furthermore, old growth grasslands have much more below ground biomass (BGB) than secondary grasslands; 31 Mg/ha and 2 Mg/ha respectively (Zaloumis, & Bond, 2016). As many plant species found in grasslands and savannahs have a lot of BGB, they have large underground storage organs (USOs) that enable them to survive fires (Bond, 2016). These USOs also enable them to allocate carbon into soil organic matter and the roots, which accounts for 80% of carbon in TGBs (Hall, 1998). Due to the extent of ancient TGBs, this creates a large underground carbon pool. Land use changes of TGBs can lead to carbon losses to the atmosphere due to oxidation and erosion (Hall, 1998). In theory, the increase of tree cover and subsequently the above and below ground biomass could lead to an increase in CO_2 storage in TGBs. However, this could also lead to changes such as a change in the grass-fire feedback and possible emissions of CO_2 due to changes in USO (Hall, 1998).

3 Methods

The methods that are used for this research are described in this chapter. Paragraph 1 gives an overview of the way in which data are collected. Paragraph 2 provides an explanation of the equations used for the conversion of the selected data and the statistical tests used to find significance of differences between the three types of biomes. Lastly, paragraph 3 gives the hypotheses that are tested.

3.1 Data selection

The data analysis has been done via meta-analysis.
First, relevant literature has been searched by the keywords ‘tropical grassy biome’, ‘restored tropical forest’, ‘secondary tropical forest’ and ‘tropical forest’. Secondary selection of literature has been done by adding the keywords ‘carbon’, ‘AGB’, ‘BGB’, ‘carbon stocks’ and ‘biomass’ to these results. These keywords are chosen as they are the most researched areas relevant to this research. ‘NPP’ and ‘NEP’ are excluded because they did not produce as much relevant data. Especially on tropical grassy biomes these key words did not produce much relevant literature and so the data on these key words for tropical forests could not be compared to TGBs. Therefore, this information proved to be irrelevant for this research. Thus, biomass and carbon storage are chosen as measures of efficiency in terms of climate change mitigation. Furthermore, it is assumed that secondary forests eventually turn into mature forests and therefore a comparison between mature forests and TGBs is also made.
Based on the amount of results that this search produced, synonyms for each of the keywords were used. Especially the search for literature on tropical grassy biomes did not provide much data, which favored the use of synonyms. For example, ‘tropical savanna’ or ‘tropical grassland’ instead of ‘tropical grassy biome’ and ‘reforested’, ‘afforestation’ or ‘regrowth’ instead of ‘secondary’.
The search has been conducted on various search engines, such as Web of Science, ScienceDirect, Scopus and Google Scholar. Furthermore, the ‘snowball’ method was applied to find literature based on references and related results that came up during the literature search. These references and related results have been reviewed and checked on suitability for this analysis.
For secondary tropical forests the criteria of age have been included as well. The scope was set from 10-100 years old as the researched secondary forests in the literature cases were also in this age category. As a result, 23 articles were selected as most relevant. More relevant articles were available, but due to the time framework these were not included. The same was true for mature tropical forests of which 19 relevant articles were selected. The criterium that was used to identify forest in a literature case as a mature forest, was checking for mentions of natural, unmanaged, old-growth, ancient or mature forest.
For tropical grassy biomes only 11 articles were selected as the literature search was exhaustive. This is probably due to the fact that not much research has been done on these types of biomes yet. These 11 articles have even been further narrowed down to 5 articles, as only high rainfall areas (>1200 mm/yr) can host tropical grassy biomes as well as tropical forests (D’Onofrio et al., 2018). Case numbers 3, 7 and 10 provided data of TGBs in low rainfall areas, while case numbers 1, 5 and 11 were left out as they didn’t provide any data on precipitation patterns. Thus, only case numbers 2, 4, 6, 8 and 9 remained.

3.2 Data analysis

The analysis of the selected data has been conducted as follows.
Three tables have been created in which the numerical data from the selected literature has been written down. These tables look as follows:

Table 1: data table as used in this research

AGB/BGB	Carbon stocks	Reference

For all three types of biomes (grassy, forest and secondary forest) data from the selected literature have been provided in different tables. These three tables can be found in the appendix (table 4, 5 and 6). Three similar tables have been provided in which the data are converted to the same metrics and the data are rounded off to two significant numbers, as the selected data are averages from data in the literature cases and thus not precise (table 1, 2 and 3).

The following steps will be taken to convert the data of natural and secondary forest:

1. Per reference a mean of the given data will be taken
2. When AGB is given, BGB will be calculated via the following equation (Wang et al., 2014):
$$BGB = AGB * 0.23$$
When BGB is given, AGB will be calculated via the following equation:
$$AGB = {}^{BGB}\!/_{0.23}$$
3. AGB and BGB will be added up to get the total biomass
4. From the total biomass, total carbon stocks can be calculated via the following equation (Ekoungoulou et al., 2015; Feldpausch et al., 2004):
$$Carbon\ stock = total\ biomass * 0.47$$

The root : shoot ratio (0.23) that is used to convert AGB to BGB is a widely used rule of thumb in literature, such as in Wang et al. (2014). The carbon : biomass ratio is a semi-randomly chosen value from different researches, such as those by Ekoungoulou et al. (2015) and Feldpausch et al. (2004). It has been chosen based on the used ratios in the literature cases; they were mainly in between 0.46 and 0.50 and so the ratio used for this research has been chosen as a value in between these two values.
The steps of converting data of tropical grassy biomes are similar, but use a different root : shoot ratio: 6.0 (Wang et al., 2014). This makes sense as TGBs have large underground storage organs (see chapter 2.2).
To analyze the data, a statistical test has been conducted. Three variables have been created: 'total carbon stocks', 'total biomass' and a grouping variable. This third variable groups the first two into three groups: secondary tropical forest (group 1), TGB (group 2) and natural tropical forest (group 3). Before the analysis could start, these three groups had to

be tested on normality. Because the data showed no normal distribution and the amount of cases tested was small (<25), a Mann-Whitney U Test was performed to check for differences between the data of the three groups. The outcomes of this test can be found in the appendix (figure 9, 10 and 11).
Lastly, a check for correlation between carbon stock data and precipitation rates for TGBs has been done. This can be found in the appendix as the outcomes are not relevant for answering the research question but are however relevant for further research.

3.3 Statistics

The following hypotheses were tested:

1. H_0 = the biomass and carbon stocks of secondary tropical forest doesn't differ from the biomass and carbon stocks of natural tropical forest.
   H_1 = the biomass and carbon stocks of secondary tropical forest differs from the biomass and carbon stocks of natural tropical forest.
2. H_0 = the biomass and carbon stocks of secondary tropical forest doesn't differ from the biomass and carbon stocks of tropical grassy biomes.
   H_1 = the biomass and carbon stocks of secondary tropical forest differs from the biomass and carbon stocks of tropical grassy biomes.
3. H_0 = the biomass and carbon stocks of natural tropical forest doesn't differ from the biomass and carbon stocks of tropical grassy biomes.
   H_1 = the biomass and carbon stocks of natural tropical forest differs from the biomass and carbon stocks of tropical grassy biomes.

These hypotheses were tested via a Mann-Whitney U Test. When the significance was $p<0.05$ the null-hypothesis was rejected, while when $p>0.05$ the null-hypothesis could not be rejected.
Furthermore, precipitation rates were plotted against carbon stocks of TGBs to check for trends and correlation.

4 Results

In this paragraph the results of the meta-analysis are given. Paragraph 1 provides the data tables for the three types of biomes. Paragraph 2 gives the means of the selected data per biome and the distribution of the data. Paragraph 3 provides the results of the Mann-Whitney U Test.

4.1 Data tables

From the data selection, three tables with results were created: one for secondary tropical forest, one for tropical grassy biomes and one for natural tropical forest. These tables can be found in the appendix (table number 4, 5 and 6). Three similar tables with data converted to comparable data are provided below. Furthermore, the data have been rounded off to three significant figures as they are already approximations and thus not precise.

Table 2: Data on secondary tropical forest (10-100 years).

Case number	Mean total Biomass (Mg/ha)	Mean total Carbon Stocks (Mg C/ha)	Converted based on data from:
1	190	90	Aide et al., 2000
2	30	15	Álvarez-Yépiz et al., 2008
3	155 Mg/ha	75	Alves et al., 1997
4	55	25	Anderson-Teixeira et al., 2016
5	150	70	Chazdon et al., 2016
6	115	55	Drake et al., 2002
7	360	170	Ekoungoulou et al., 2015
8	160	75	Feldpausch et al., 2004
9	100	180	Fonseca et al., 2011
10	50	25	Gradstein et al., 2007
11	345	155	Hector et al., 2011
12	340	160	Hughes et al., 1999
13	110	50	IPCC, 2003
14	260	125	Moore et al., 2018
15	585	275	Ngo et al., 2013
16	30	15	Omeja et al., 2011
17	270	130	Shimamoto et al., 2014
18	285	135	Sierra et al., 2007
19	100	45	Sierra et al., 2012
20	185	85	Steininger, 2000
21	65	30	Toledo et al., 2018

22	80	35	Vaglio Laurin et al., 2014
23	225	105	Wang et al., 2017

Table 3: Data on tropical grassy biomes

Case number	Mean total Biomass (Mg/ha)	Mean total Carbon Stocks (Mg C/ha)	Converted based on data from:
1	275	130	Baccini et al., 2008
2	435	205	Chen et al., 2003
3	1	0	Djagbletey et al., 2018
4	15	5	Fidelis et al., 2013
5	280	135	IPCC Working Group I, 2001
6	35	15	Martinez-Sanchez & Cabrales, 2012
7	295	140	Michelsen et al., 2004
8	185	90	Moore et al., 2018
9	45	20	Oliveras et al., 2014
10	2	1	Piao et al., 2007
11	5	2	Singh & Yadava, 1974

Table 4: Data on natural tropical forest

Case number	Mean total Biomass (Mg/ha)	Mean total Carbon Stocks (Mg C/ha)	Converted based on data from:
1	275	130	Alves et al., 2010
2	285	135	Anderson-Teixeira et al., 2016
3	245	115	Asner et al., 2010
4	205	95	Asner & Mascaro, 2014
5	220	105	Baccini et al., 2008
6	220	105	Brown et al., 1991
7	510	240	Brown & Lugo, 1992
8	320	150	Brown, 1997
9	365	170	Chave et al., 2004
10	415	195	DeFries et al., 2002
11	195	95	Drake et al., 2002
12	135	65	Gibbs & Brown, 2007a
13	210	100	Gibbs & Brown, 2007b
14	275	130	Gradstein et al., 2007
15	230	105	IPCC, 2003

16	355	165	IPCC, 2006
17	255	120	Olsen et al., 1983
18	565	265	Sierra et al., 2007
19	195	90	Vaglio Laurin et al., 2016

4.2 Mean carbon storage and distribution

The calculated means of the three types of biomes show an increase in carbon storage from tropical grassy biomes to secondary tropical forests and thirdly natural tropical forest. The largest difference is therefore found between TGBs and natural tropical forests. The smallest difference can be found between TGBs and secondary tropical forests. For TGBs only the five relevant literature cases have been included as comparing data of the other six cases to secondary tropical forest and mature tropical forest is not relevant. However, this increases the error found in the data of TGBs and therefore the uncertainty of the data.

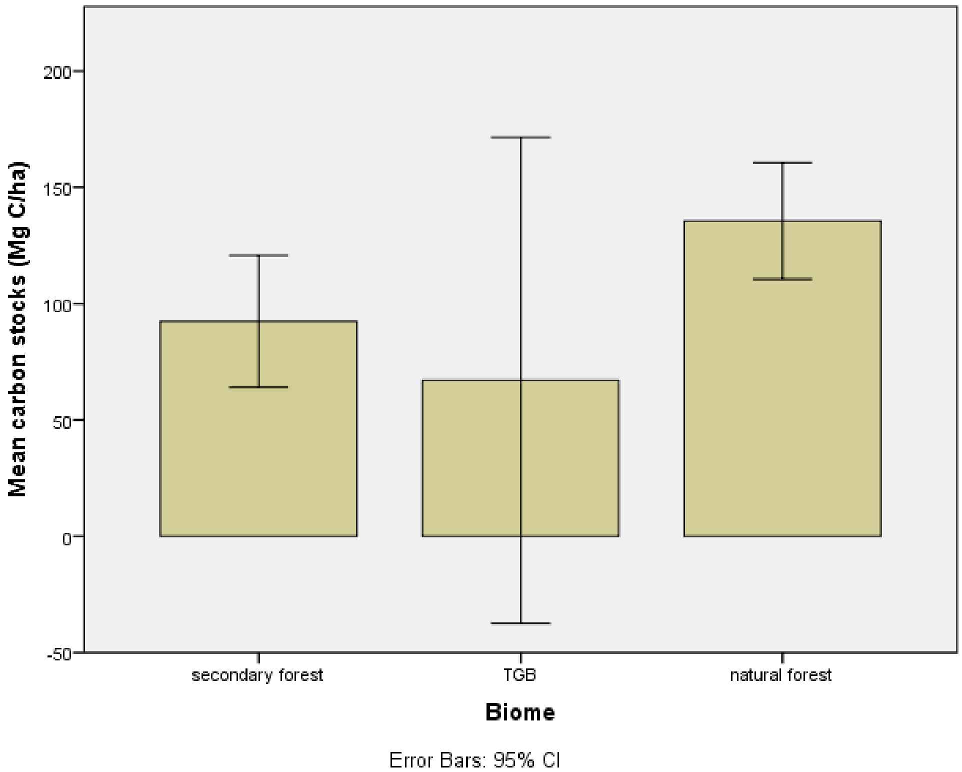

Figure 4: Mean carbon storage of three biomes: tropical grassy biome (TGB), secondary tropical forest (STF) and mature tropical forest (TF). Errors calculated with a 95% confidence interval

Boxplots of the data show that the data is not normally distributed. This can be concluded from a comparison of lengths of the upper and lower whisker for all three types of biomes. Upper whiskers show to be more extreme for the three biomes, which indicates that the data is not normally distributed as the largest data points are further away from the median than the lowest data points.

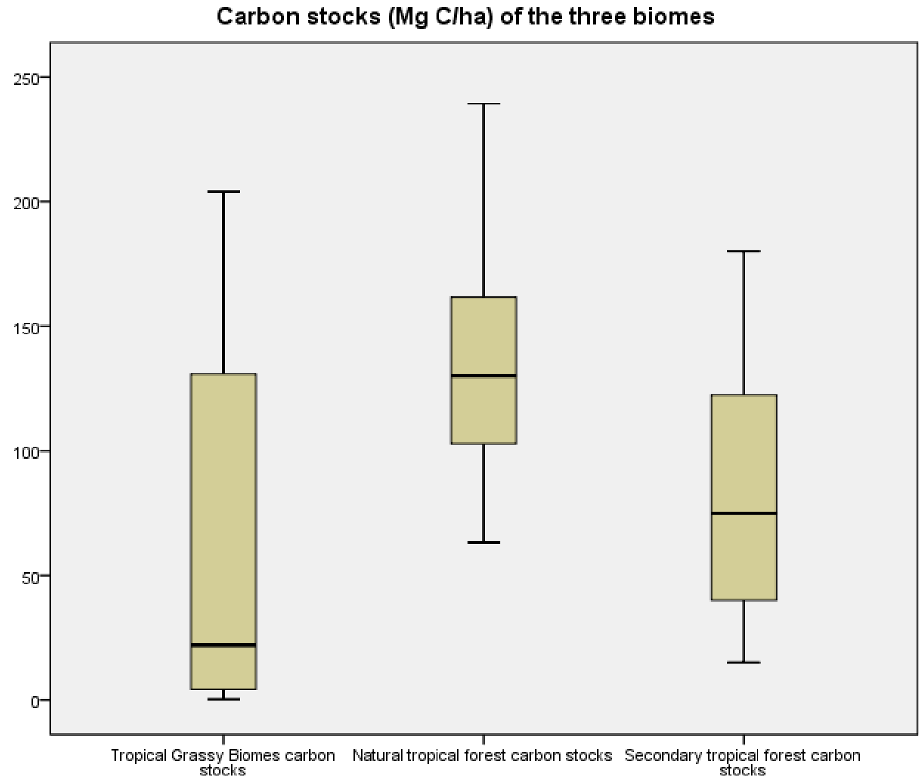

Figure 5: boxplot representing median, upper- and lower quartiles, minimum and maximum for carbon stocks of TGBs, natural tropical forests and secondary tropical forests. Upper whiskers show to be more extreme than lower whiskers, which indicates no normal distribution fort he three types of biomes

4.3 Significance

4.3.1 Comparison of secondary tropical forest and mature tropical forest

The Mann-Whitney U Test for group 1 and 2 showed probability values for total biomass and carbon stocks of 0.005 and 0.017 respectively. This means that the difference found between the two groups is statistically significant and thus we can reject the null-hypothesis. The conclusion can be drawn that the mean carbon stock of mature tropical forests is significantly higher than the mean carbon stock of secondary tropical forest (see chapter 4.2).

4.3.2 Comparison of secondary tropical forest and TGB

The test of group 1 and group 3 showed that the mean ranks for both biomass and carbon stocks of group 1 were higher than group 3, meaning that overall secondary forest has a higher total biomass, and therefore carbon stocks as well, than TGBs. This effect is found to be statistically insignificant as the p values for biomass and carbon stocks are 0.280 and 0.254 respectively. Therefore, the null-hypothesis cannot be rejected and thus there is no significant difference between the two groups.

4.3.3 Comparison of mature tropical forest and TGB.

When testing group 2 and 3, the Mann-Whitney U Test showed a statistically significant difference between the biomass and carbon stocks of the two groups (tropical grassy biomes and mature tropical forest) with a p-value of 0.036 for biomass and 0.039 for carbon stocks. Therefore, the null-hypothesis was rejected. This means that the mean carbon stocks of mature tropical forest are significantly higher than mean carbon stocks of tropical grassy biomes.

5 Discussion

The data show that there is a significant difference in biomass and carbon stocks between mature tropical forest and secondary tropical forest as well as tropical grassy biomes. However, between secondary tropical forest and tropical grassy biomes no significant difference could be discovered. This could be due to the fact that for TGBs little literature cases could be included. Another factor that adds limitations to the results is that the time scale for secondary forest is reasonably large. It accounts for the first 100 years of forest succession, even though a forest of 10 years old has different vegetation cover than a forest of 100 years old. The fact that the scale covers the first 100 years of succession indicates that reforesting in TGBs might be a bad managing practice, as in this research no significant difference in carbon storage could be found between TGBs and secondary tropical forest. It is crucial to begin implicating climate change mitigation measures before 2030, as delaying mitigation could decrease the amount of options to keep the temperature change below 2°C relative to pre-industrial levels (Edenhofer et al., 2014).

Furthermore, some important factors have not been taken into account as otherwise data selection would become too small. One of these is the fact that TGB is a collective noun and accounts for all tropical grassy biomes, such as savannas and grasslands. This means that there can be large vegetation differences between these biomes, as some are more grassy and others consist more of woody vegetation. This influences the storage of carbon.

Another factor that hasn't been accounted for, but which could influence the data is the usage of different types of models to obtain data. In the selected literature cases different models and measuring equipment were used to gain information on e.g. biomass, such as LiDaR and other remote sensing methods. Moreover, different diameters at breast height (DBH) were used; some researches used ≥ 10 cm, while others also measured at DBH ≥ 5 cm or DBH ≥ 1 cm and some only measured for large trees with DBH ≥ 30 cm. Furthermore, once biomass data was obtained, different ratios for converting this data to carbon stock data were used in the literature. In this thesis a semi-randomly chosen average is used. This could account for small differences in the outcomes for carbon stocks compared to data from other literature cases.

Furthermore, tropical forests and TGBs are both highly biodiverse. However, they consist of a different type of vegetation; tropical forests have more canopy layer, while TGBs have more grasses and forbs (Osborne et al., 2018). When afforestation is taking place in TGBs, biodiversity is lost due to the loss of grasses and forbs (figure 8) (Osborne et al., 2018). As explained in the theoretical framework, tropical forests that are more diverse can store more carbon. Thus, afforestation in TGBs could induce a loss of carbon storage. As this topic hasn't been researched enough it is not included in this research.

The last important factor that hasn't been taken into account in this research is that when actively restoring tropical forests in TGBs, CO_2 might be emitted because of erosion of the soil. Since this topic hasn't been researched yet, it could only be partly taken into account by estimating the below ground biomass.

All of these factors haven't been taken into account, since they would limit the available literature and data selection to the point where not enough data could have been found for the meta-analysis. Further research could therefore focus on each of these left out factors, to provide for a more integrated insight of the restoration of tropical forests as a mitigation measure of climate change.

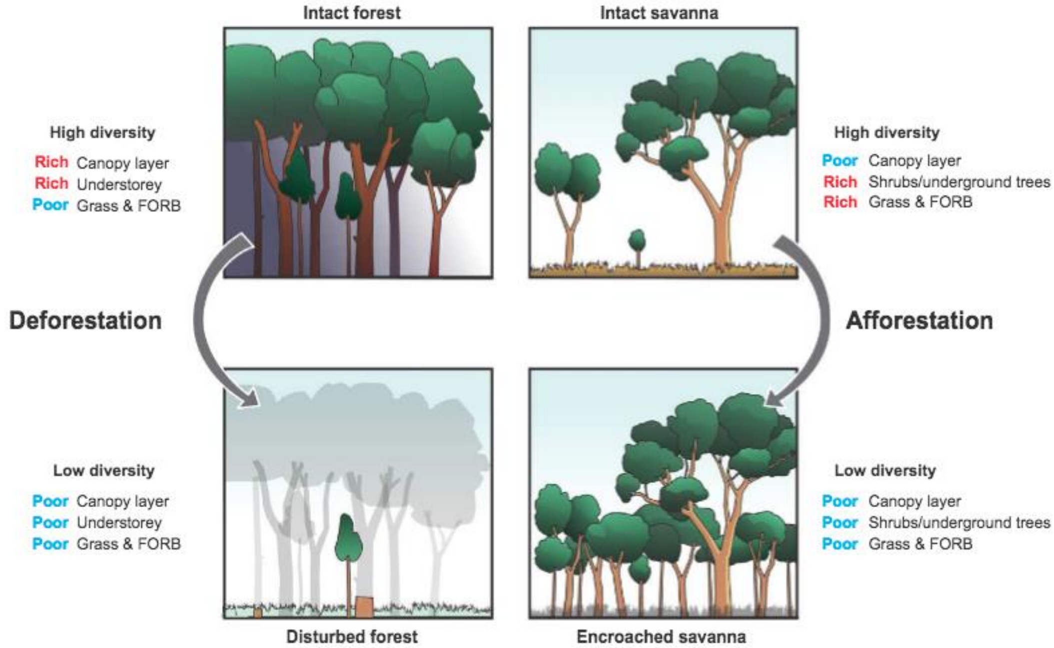

Figure 6: degradation of tropical forests and tropical savannas leads to a loss of biodiversity (Osborne et al., 2018)

6 Conclusion

This past century climate change has been accelerated by anthropogenic forces. One of the contributors to climate change is land use change. Especially in the tropics this is a problem, as many people depend on the ecosystem services of tropical forests as well as tropical grassy biomes. As converting tropical forests to e.g. agricultural lands leads to a loss of biodiversity, the capacity of these areas to store CO_2 is lost as well. In order to gain back the CO_2 holding capacity of tropical forests, attempts at restoration have been made. However, the World Resources Institute might have misidentified areas suitable for restoration. Tropical grassy biomes have been assumed to be secondary products of agriculture, while in fact most of them are ancient and store a lot of carbon. It is hypothesized that converting these lands to tropical secondary forest would increase the carbon storing capacity. This hypothesis has been found partly true: there is no significant difference between the carbon storage in tropical grassy biomes and secondary forests. However, a significant difference between the mean carbon storage of mature tropical forest and tropical grassy biomes has been found. Therefore, the answer to the research questions '*Is restoring tropical forests in tropical grassy biomes an efficient mitigation measure of climate change?'* cannot be a simple yes or no. The answer is more elaborate: in the first stages of restoration (10-100 years) carbon storing capacity of tropical forests is similar to that of tropical grassy biomes, while once matured a tropical forest can store more carbon than a TGB. Therefore, it can be concluded that restoring tropical forest in tropical grassy biomes is not an efficient way of mitigation climate change as these tropical forests will only begin storing more carbon than TGBs after 100 years.

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8 Appendix

8.1 Data tables

Table 5: Data from selected literature on restored and secondary tropical forests

AGB/BGB	Carbon stocks	Reference
AGB: 165 mg/ha (35-40 yr) 220 mg/ha (70 yr)		Aide et al., 2000
AGB: 22.4 ± 2.4 Mg/ha		Álvarez-Yépiz et al., 2008
AGB: 63-141 t/ha (11 yr), 273-143 t/ha (18 yr)		Alves et al., 1997
	5.4 ± 3.2 Mg C/ha (<20 yr) 48 ± 11.6 Mg C/ha (20-100 yr)	Anderson-Teixeira et al., 2016
	21 Pg C on 2861519 km^2(1-60yr)	Chazdon et al., 2016
AGB: 78.5 – 147.7 Mg/ha		Drake et al., 2002
	AGB stocks: 135.976 t C/ha BGB stocks: 31.94 t C/ha	Ekoungoulou et al., 2015
AGB: 128.1 Mg/ha (12-14 yr)		Feldpausch et al., 2004
AGB: 174.5 ± 16.4 Mg/ha (10yr), 82.2 ± 47.9 Mg/ha (average 0-20yr)	Total stocks: 180.4 Mg C/ha (20yr)	Fonseca et al., 2011
AGB: 40.6±7.7 (18yr)		Gradstein et al., 2007
AGB: 272.1 Mg/ha	136 Mg C/ha	Hector et al., 2011
AGB: 278 Mg/ha (50 yr)	136 Mg C/ha (50yr)	Hughes et al., 1999
AGB: 30-150 t/ha		IPCC, 2003
	Varying over 3 plots: 142 ± 17 Mg C/ha, 127 ± 11 Mg C/ha, 101 ± 14 Mg C/ha	Moore et al., 2018
AGB: 122 Mg/ha (20yr)	Total stocks: 274.2 Mg C/ha. AGB stocks: 104.5 Mg C/ha	Ngo et al., 2013
AGB: 15,675 kg/ha 4560 kg/ha AGB: 165 mg/ha (35-40 yr) 220 mg/ha (70 yr)		Omeja et al., 2011
	Total stocks: varying from 0-60 Mg C/ha (10 yr), varying from 10-200 Mg C/ha (20 yr), 240 Mg C/ha (40 yr)	Shimamoto et al., 2014
	228.2 ± 13.1 Mg C/ha of which 9% AGB stocks and 5% BGB stocks	Sierra et al., 2007

	AGB stocks: appr. 50 Mg C/ha (20 yr), 100 Mg C/ha (40yr) BGB stocks: appr. 12 Mg C/ha (20 yr), 22 Mg C/ha (40 yr)	Sierra et al., 2012
AGB: 15.0 kg/m^2		Steininger, 2000
AGB: 0-104.7 t/ha		Toledo et al., 2018
AGB: 64.3 Mg/ha		Vaglio Laurin et al., 2014
AGB: 122 Mg/ha (20yr)	63.5 ± 10.1 Mg C/ha (20 yr) 149 ±18 Mg C/ha (52 yr)	Wang et al., 2017

Table 6: Data from selected literature on tropical grassy biomes

AGB/BGB	Carbon stocks	Reference
AGB grasslands: 1-7 Mg/ha **AGB savanna: 77.4 Mg/ha**		Baccini et al., 2008
	204 ± 53 ton C/ha with 84% below-ground and 16% above-ground	Chen et al., 2003
	AGB stock: 0.08-0.47 Mg C/ha BGB stock: 0.03-0.44 Mg C/ha	Djagbletey et al., 2018
	Total stocks: 621-716 g C/m^2	Fidelis et al., 2013
	AGB stock: 29 Mg C/ha BGB stock: 90-117 Mg C/ha	IPCC Working Group I, 2001
AGB: 4.5 -5.5 Mg/ha		Martinez-Sanchez & Cabrales, 2012
AGB: 30.1 ± 2.8 t/ha - 53.5 ± 5.2 t/ha		Michelsen et al., 2004
	AGB stock: 62 ± 8 Mg C/ha BGB stock: 26 ± 1 Mg C/ha	Moore et al., 2018
AGB 6.7 ± 0.2 Mg/ha	AGB stocks: 3.35 ± 0.1 Mg C/ha	Oliveras et al., 2014
	AGB stocks: 9.57 Tg C in $10.90*10^4$ km^2 12.35 Tg C in $10.90*10^4$ km^2	Piao et al., 2007
Total: 3,538 g/m^2		Singh & Yadava, 1974

Table 7: Data from selected literature on natural tropical forests

AGB/BGB	Carbon stocks	Reference
166.3 Mg/ha to 283.2 Mg/ha (different elevations		Alves et al., 2010
133.9+-50.8 Mg C/ha		Anderson-Teixeira et al., 2016
	AGB stocks: 85 to 100 Mg C/ha, 110 to 125 Mg C/ha, 65 to 80 Mg C/ha (different types of soil)	Asner et al., 2010
	AGB stocks: 105.5 – 33.5 Mg C/ha (moist to dry, Hawaii) 95.5 Mg C/ha (moist, Colombia)	Asner & Mascaro, 2014
AGB 238.1 Mg/ha, 216.3 Mg/ha, 85 Mg/ha, 169.6 Mg/ha (different plots)		Baccini et al., 2008
AGB 225-350 Mg/ha (moist) 55-82 Mg/ha (dry)		Brown et al., 1991
AGB 414 Mg/ha		Brown & Lugo, 1992
	Total stocks: 151 t C/ha (asia)	Brown, 1997
AGB 347 Mg/ha, 263 Mg/ha, 284 Mg/ha (different types of models)		Chave et al., 2004
	AGB stocks: 200, 140, 55 t C/ha (Latin-America) 250, 150 t C/ha (Asia)	DeFries et al., 2002
160.5 Mg/ha		Drake et al., 2002
	AGB stocks:17, 38, 99 t C/Mg (Africa)	Gibbs & Brown, 2007a
	Total stocks: 120, 12, 164 t C/Mg (asia)	Gibbs & Brown, 2007b
AGB: 55.8+-5.5/0,25ha		Gradstein et al., 2007
AGB: 70-300 tonnes d.m./ha (on different continents and different types of forest)		IPCC, 2003
	AGB stocks: 180 / 225 t C/ha (asia) 105 / 169 t C/ha (asia) 78 / 96 t C/ha (asia)	IPCC, 2006

	200, 152, 72 t C/ha (Africa) 193, 128, 26 t C/ha (Latin-America	
	Total stocks: 120 ton C/ha	Olsen et al., 1983
	Total stocks: 383.7 ± 55.5 Mg C ha of which 59% AGB stocks and 10% BGB stocks	Sierra et al., 2007
186 – 128 Mg/ha (different plots		Vaglio Laurin et al., 2016

8.2 Results Mann-Whitney U Test

Mann-Whitney Test

Ranks

	Group	N	Mean Rank	Sum of Ranks
Total Biomass	secondary forest	23	16,67	383,50
	natural forest	19	27,34	519,50
	Total	42		
carbon stocks	secondary forest	23	17,39	400,00
	natural forest	19	26,47	503,00
	Total	42		

Test Statistics[a]

	Total Biomass	carbon stocks
Mann-Whitney U	107,500	124,000
Wilcoxon W	383,500	400,000
Z	-2,806	-2,390
Asymp. Sig. (2-tailed)	,005	,017

a. Grouping Variable: Group

Figure 7: Mann-Whitney U Test of secondary tropical forest and natural tropical forest

Mann-Whitney Test

Ranks

	Group	N	Mean Rank	Sum of Ranks
Total Biomass	secondary forest	23	15,28	351,50
	TGB	5	10,90	54,50
	Total	28		
carbon stocks	secondary forest	23	15,33	352,50
	TGB	5	10,70	53,50
	Total	28		

Test Statistics[a]

	Total Biomass	carbon stocks
Mann-Whitney U	39,500	38,500
Wilcoxon W	54,500	53,500
Z	-1,080	-1,141
Asymp. Sig. (2-tailed)	,280	,254
Exact Sig. [2*(1-tailed Sig.)]	,290[b]	,264[b]

a. Grouping Variable: Group

b. Not corrected for ties.

Figure 8: Mann-Whitney U Test of secondary tropical forest and tropical grassy biomes

Mann-Whitney Test

Ranks

	Group	N	Mean Rank	Sum of Ranks
Total Biomass	TGB	5	6,60	33,00
	natural forest	19	14,05	267,00
	Total	24		
carbon stocks	TGB	5	6,70	33,50
	natural forest	19	14,03	266,50
	Total	24		

Test Statistics[a]

	Total Biomass	carbon stocks
Mann-Whitney U	18,000	18,500
Wilcoxon W	33,000	33,500
Z	-2,098	-2,065
Asymp. Sig. (2-tailed)	,036	,039
Exact Sig. [2*(1-tailed Sig.)]	,036[b]	,036[b]

a. Grouping Variable: Group

b. Not corrected for ties.

Figure 9: Mann-Whitney U Test of natural tropical forest and tropical grassy biomes

8.3 Precipitation rates TGBs

As tree cover is dependent on precipitation rates (D'onofrio et al., 2018) and mean carbon stocks show the highest data for mature forest (most tree cover), carbon stock data is expected to increase as well with increasing precipitation. However, the data of TGBs in areas with high precipitation rates (>1200 mm/yr) show a slight negative correlation between precipitation and carbon stock data. Including all cases with both data for precipitation rates and carbon stocks a cubic trend can be spotted. This is not explainable with data from this research as the sample size is not large enough.

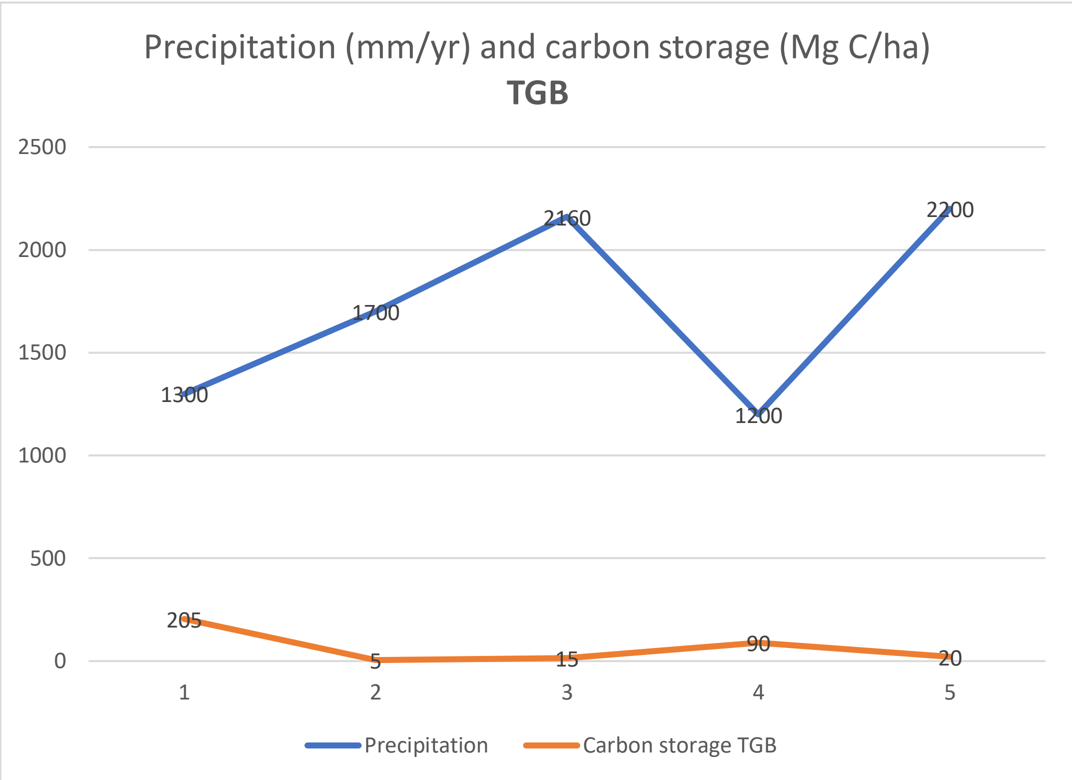

Figure 10: precipitation and carbon stocks in tropical grassy biomes with high rainfall rates (>1200 mm/yr). A slightly negative correlation can be spotted

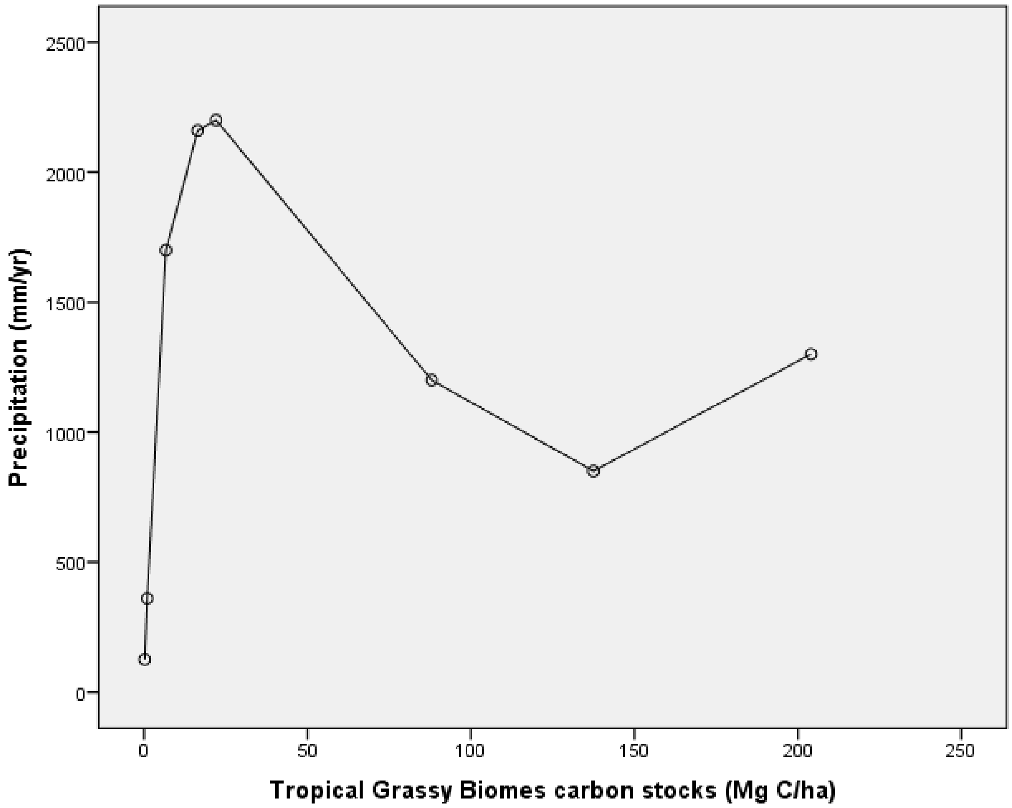

Figure 11: precipitation of both high and low rainfall rates plotted against carbon stocks of tropical grassy biomes. Data shows a cubic trend