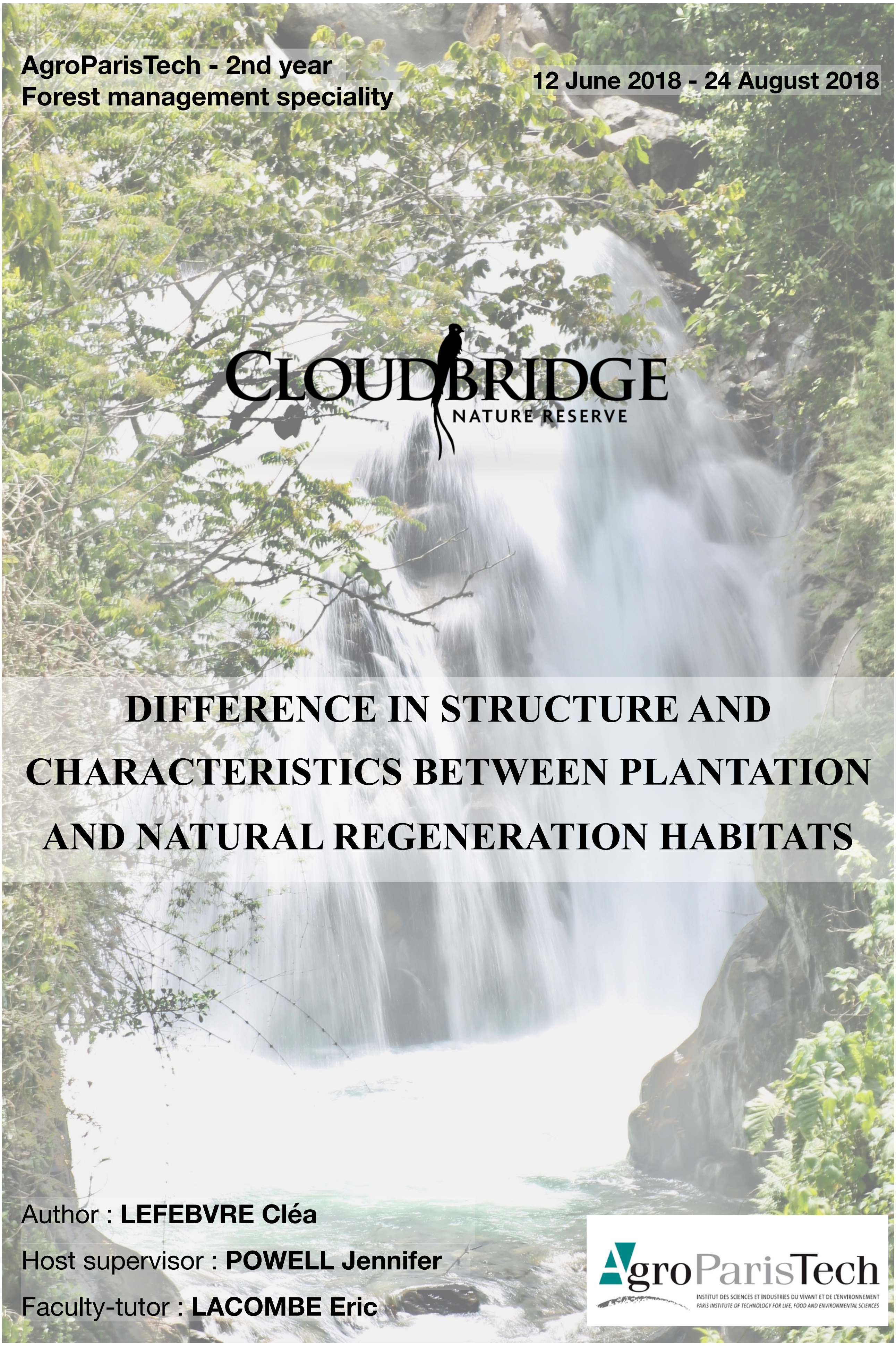

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CLOUDBRIDGE NATURE RESERVE

DIFFERENCE IN STRUCTURE AND CHARACTERISTICS BETWEEN PLANTATION AND NATURAL REGENERATION HABITATS

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Abstract :

The main goal in Cloudbridge is reforestation. There are a few places where it is possible to see the old agricultural activity, which have no trees, only open pasture. One reforestation method in the reserve is plantation, but some places are left without human activity, and the reforestation is only due to natural regeneration.

It is of interest to know which of the two reforestation methods is most effective. My study was focused on the comparison of the forest structure in these different habitats, using the primary forest as a reference. I collected my data during my first nine weeks, namely DBH (diameter at breast height), height, canopy closure, crown class, wood density, and the number of trees in each plot. Aboveground biomass and carbon storage were also calculated. To finish, I looked for a significant difference in the structure between the plantation area and the natural regeneration area to propose the most effective method to achieve the aim. Significant differences between the plantation and the natural regeneration habitats were found for diameter, volume, canopy closure, and carbon storage, while the heights and the wood density were not significantly different. However, it remains difficult to propose a most effective method given the young age of these habitats compared to primary forest.

Résumé :

L'un des objectifs principaux de la réserve de Cloudbridge est la reforestation. Il reste de nombreuses zones où l'ancienne activité agricole est encore visible, traduite par des zones dénudées d'arbres. Une méthode de reforestation dans la réserve est la plantation de diverses essences mais il y a également des espaces qui sont laissés sans intervention et où la régénération se fait naturellement.

Il est donc intéressant de savoir si leur méthode de plantation est plus intéressante et plus utile que de laisser la nature suivre son cours et se régénérer naturellement. Mon étude était alors de comparer l'état de la forêt dans ces différentes zones avec la forêt primaire prise comme référence pour l'objectif recherché. J'ai alors collecté des données durant mes premières semaines de stage à savoir relevés de diamètre, de hauteur, de canopée, de classe de dominance des arbres, de densité et du nombre d'arbre présent dans chacune des placettes.

J'ai ensuite analysé statistiquement mes données afin de chercher des différences notables entre les zones de plantation et de régénération naturelle dans le but de pouvoir proposer la meilleure des solutions pour atteindre l'objectif fixé. Les différences observables entre les zones de plantation et de régénération naturelle concernent les diamètres, le volume, la fermeture de la canopée et le stockage de carbone. Tandis que les hauteurs et la densité ne sont pas significatives. Il reste cependant difficile de proposer une méthode de reforestation préférable au vu du jeune âge de ces forêts par rapport à la forêt primaire.

Introduction :

Although forest habitat represents a large share of the world's surface, deforestation problems are increasing, with many billions of hectares disappearing each year, particularly in Africa and South America. Forests are an essentiel ecosystem which face many threats (climate change, erosion, air quality, etc.), so it is necessary to conserve existing forests and reforest areas victim to mass deforestation. The Cloudbridge reserve defends as best she possibly can these values, conservation and reforestation. To this end, the reserve really relies on the help of volonteers and researchers, who come for variable amounts time, to reforest the empty areas. In view of both reforestation methods used at the reserve, it would be helpful to know which method is the most effective to reach the aim, namely the old growth structure, or if there is no significant difference between the two.

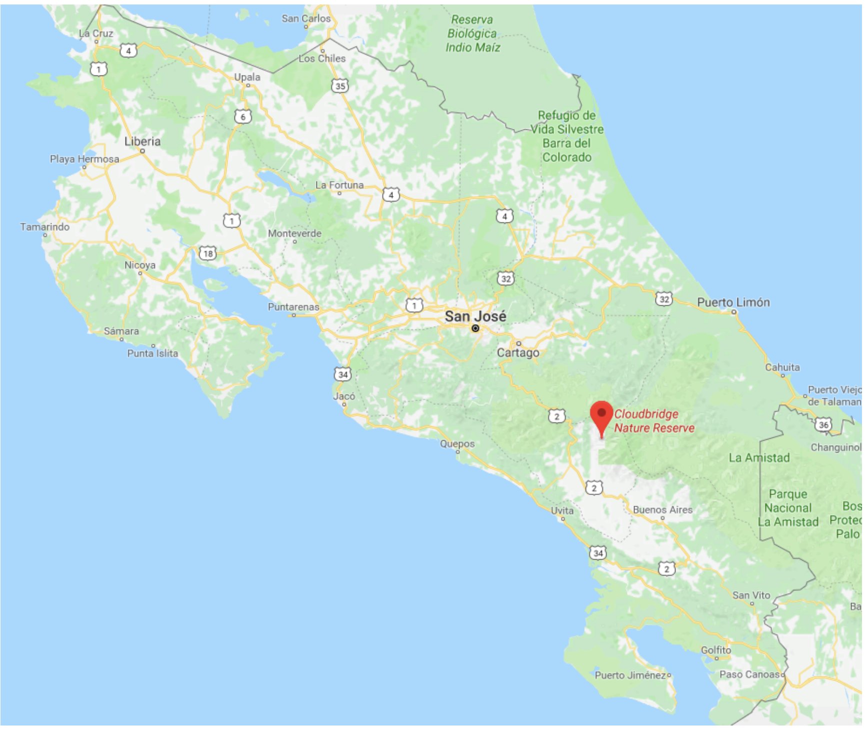
The goal of my project was to address this problem by comparing the structure of the forest in planting and natural regrowth areas of the same age. The richness of the Cloudbridge reserve is that it has three different successional habitats in a close space, so forests grow in a relatively similar atmosphere. However, they may exist other differences, namely on the nature of the soil, but that is beyond my study.

A/ General information about Cloudbridge Nature Reserve

1. Reserve location

Cloudbridge is a private nature reserve located in the San Gerardo de Rivas valley, 2km from the village, in the Talamanca mountains of Costa Rica. The reserve lies between 1550 and 2600 meters above sea level and includes 280 hectares of forest. The forest is a cloud forest in which clouds condense providing moisture necessary for the health of the trees. The forest is very dependent on moisture brought by the clouds and not only on the rain (which is abundant in the months of May to November). The percentage of humidity is close to 100% (Samauma o Bresil, 2018). The reserve is located between two reserves, Chirripó National Park (recognized as an UNESCO world heritage site), and the Talamanca Reserve.

<u>Figure 1 :</u> Geographic location of Cloudridge Nature Reserve



The reserve was created in 2002 by Geneviève Giddy and her husband, Ian Giddy. At that time, 255 hectares of the reserve was either pasture or cropland. Costa Rica suffered a strong wave of deforestation after 1970 because farmers received grants to burn forests to convert land to pasture to provide the country meat (Community carbon tress, 2018). Now the consequences of deforestation are well known, which is why in recent years, Costa Rica has pledged to reforest the most ancient forest areas. Currently there are 161 national parks in Costa Rica, thus placing the country 5th in the world in environment protection (Imagenes Tropicale, 2002).

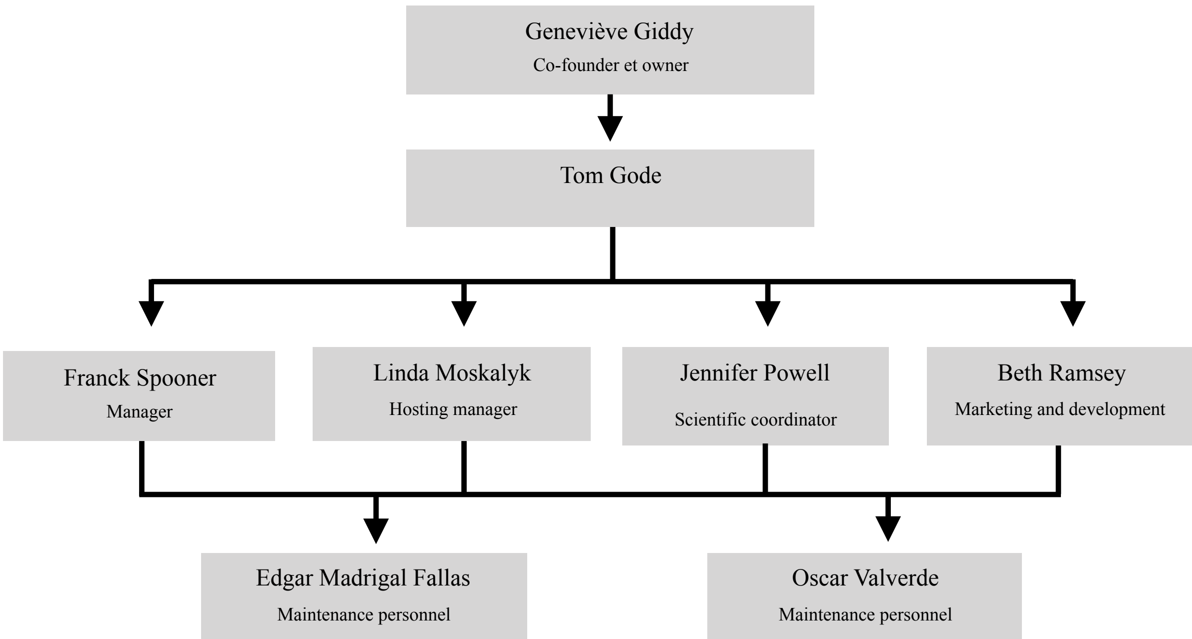
Faced with these deforestation issues, 255 hectares of un-forested land and 28 hectares of primary forest were bought to create Cloudbrigde Nature Reserve, which focuses on conservation, reforestation, and education. Thus, many researchers, volunteers and school groups come to help the project develop the best it can (CloudBridge, 2018).

2. Organisation of the reserve

Currently, Cloudbridge is run by a Board of Directors comprising the owner, Geneviève Giddy, and Tom Gode, who joined the project in 2005 and lives part of the year in the reserve. Cloudbridge is a private, non-profit reserve that depends on the donations of visitors.

In 2005, Tom Gode managed the reserve with only one employee, whereas today, eight people are part of the organisation and structure (figure 2):

Figure 2 : Organisation chart of the reserve



3. Activities present at the reserve

3.1 Research

Research is very active at Cloudbridge, which welcomes students from all around the world to carry out internships in all kinds of fields. Research allows the improvement of the education and reforestation activities. Research is very important because it improves the understanding of the functioning of the ecosystem by studying flora and fauna present on the site. As is well known, Costa Rica has a very diverse flora and fauna. Many species of birds, butterflies, mammals, insects and plants have already been identified in the reserve. However, much work still need to be done with regard to identifying tree species, since less than half of the species have been identified to date.

3.2 Education

Education about forest protection is developing more and more in the reserve. In fact, Cloudbridge very often welcomes school groups to participate in different projects, like tree planting. Education is one of the best ways to raise awareness of the importance of keeping these ecosystems healthy. A woman sometimes gives a talk to school groups on issues related to climate change in relation to the importance of conservation and reforestation of forests.

3.3 Reforestation

Reforestation has been the main activity since the beginning of the reserve. Since 2002, 50 000 trees have been planted to reforest the former pasture areas that had been cleared. A high mortality has been observed three years after the first plantations, and so it had been necessary to continue planting the following years. So, thanks to all of these past efforts, the landscape has already changed greatly, clearly visible in figure 3.

Figure 3 : Before and after the beginning of the reforestation work

However, all areas of the reserve have not been actively reforested, indeed some are left without human intervention so that natural regeneration can take its course. At present, planting is not as intensive, 500 to 1 000 trees planted every year since 2009. In 2002 and 2003, 20 000 trees were planted, then from 2004 to 2008 the number of planted trees decreased to 5 000 trees a year. In addition, some trees (around 10-20) are planted along the trails every year to strengthen and stabilize them.

The reserve is now more focused on their research and education goals although they still continue the planting activity.

4. The expectations of the internship

The expectations of the internship were clearly defined upon my arrival in the reserve by my tutor (POWELL Jennifer, June 2018). Thus, the important data for comparison of structure between planted and natural regrowth areas are: trunk diameter, height, canopy closure, and, finally wood density in order to study differences in carbon storage. Identification of tree species was not a priority for this project, because the number of species is very high in these forests and identification is very difficult, as the leaves are sometimes very high and trunks covered with epiphytes, lichens, mosses or ferns.

All these measures have been identified to determine if there is a difference between planted and natural regeneration areas in order to try to find out which of the two methods is the most effective at regenerating a forest to the primary forest state.

B/ Methods

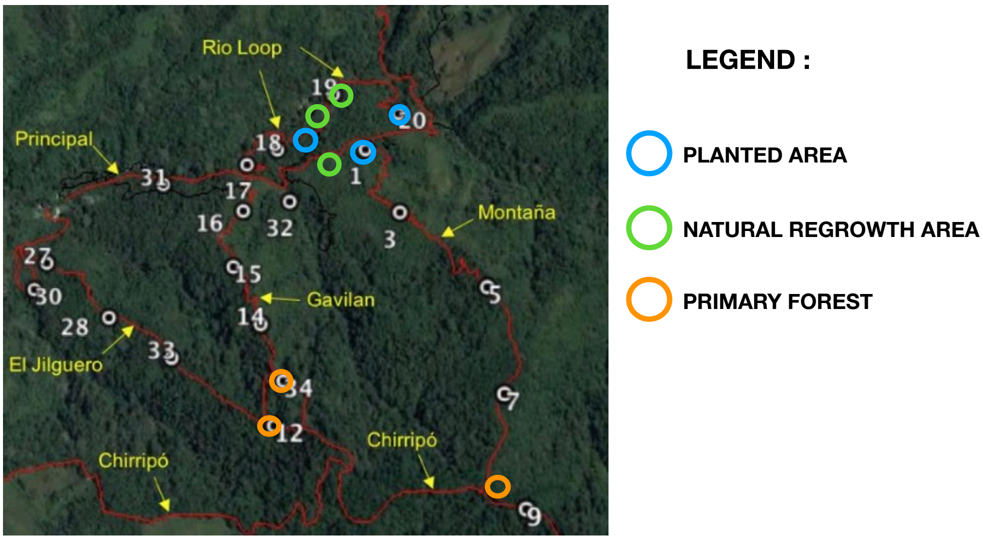
1. Study area

There are three types of habitat in the reserve, namely planted, natural regeneration areas and, finally, primary forest. My study areas were in each of these habitats with three plots per habitat type.

1.1 Plot choice

My natural regeneration and planted plots were selected to have a forest of similar age, around 20 years, while the primary plots consisted of forest over 70 years old. The natural regeneration and planted plots were located along the Rio, Principal, and Montaña trails, while the primary plots were located at the top of the El Jilguero, Gavilan, and Montaña trails (figure 4). The plots have a diameter of 25 meters, in which all trees of 5 cm in diameter and more are studied.

Figure 4 : Plots locations



1.2 Marking plots

Some plots already existed, and the trees greater than 10 cm in diameter had already been measured, and I was able to use the pre-existing data (this concerns three of my plots: two in primary forest and one in the planted area). For the pre-existing plots, I completed the data to add trees between 5 and 10 cm in diameter. However, I was not able to use the other pre-existing plots, as some were a mixture of planted and natural regeneration areas. So, I created six new plots.

When setting up the natural regeneration plots, they needed to be placed far enough inside the forest to avoid planted areas next to the trails. New plots were marked in the center and in each cardinal direction to 12.5 meters, for an overall diameter of 25 m.

Each tree in a plot was marked with a small metal tag with a unique number. The trees were marked starting in the North and moving in a circle eastward. It is important to start from the North and then move to the East to allow future researchers to easily find the trees.

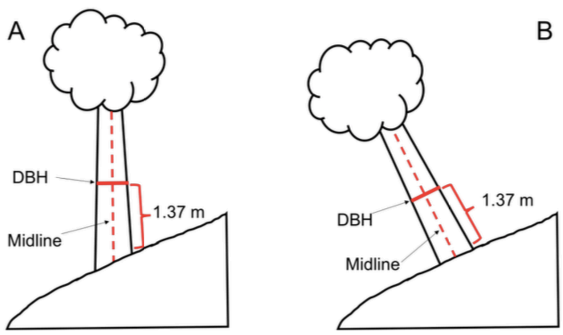
2. Data collected

In each of the nine studied plots, the diameter, height, canopy class, canopy closure, and the total number of trees was collected. In addition, in three plots (i.e. one in each habitat), wood core sampling was carried out, in order to study the density of trees and calculate the carbon storage.

2.1 Diameter

The diameter was taken at breast height (1.37 m). A mark on a bamboo pole at 1.37 m helped make sure that each diameter was taken at the same height. If a stem was at breast height, diameter was measured just below the stem. Concerning inclined trees, which are very present in this kind of forest, the diameter measurements were taken according to figure 5.

Figure 5 : Measurement of diameter for single trees



For trees with several stems, diameter was calculated using the following formula:

$$DBH_{multistem} = \sqrt{DBH1^2 + DBH2^2 + DBH3^2 \ldots}$$

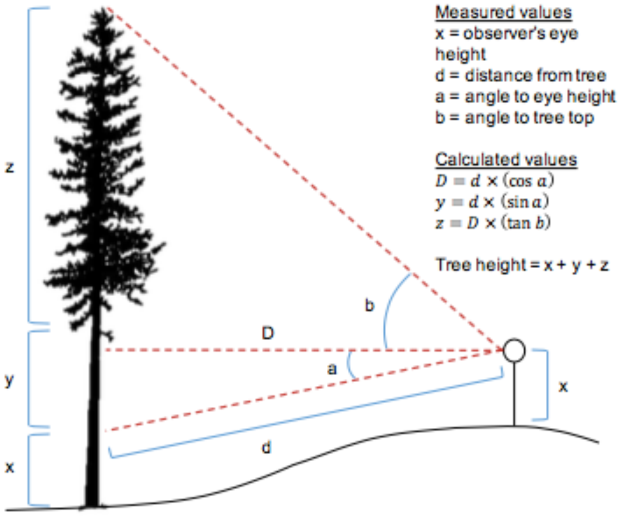
After all diameters were collected, I was able to classify the trees in five different size categories (see 2.2.3) which allowed me to study the forest structure of the different habitats..

2.2 Height

Measuring the height of the trees was one of the most complicated steps. Indeed, in cloud forests, trees grow very quickly and can quickly achieve significant heights, and the tops of the trees were sometimes difficult to see.

I used a Suunto clinometer to measure the height of trees, in order to get the angles a and b in figure 6.

Figure 6 : Height measurement



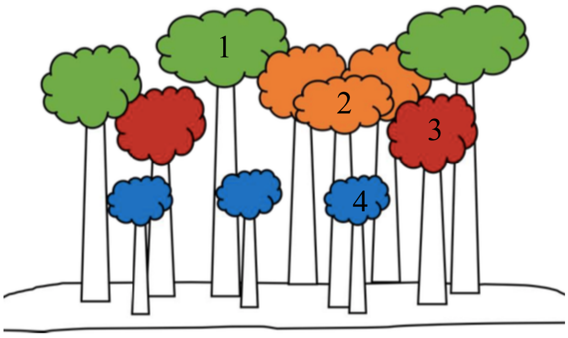
- The distance d is the distance from the observer's eye, to their eye height (as marked on a bamboo pole) on the trunk of the tree.
- x is eye height of the person taking the measurement. Thanks to a marked bamboo pole, it was easy to see where the eye level was to measure angle a.
- y = sin(a)*d
- z = tan(b)*cos(a)*d

The height of the tree is determined by adding x, y and z.

2.3 Crown classes

The class of each tree was also noted. The trees are classified into four categories as shown in figure 7.

Figure 7 : Crown classes



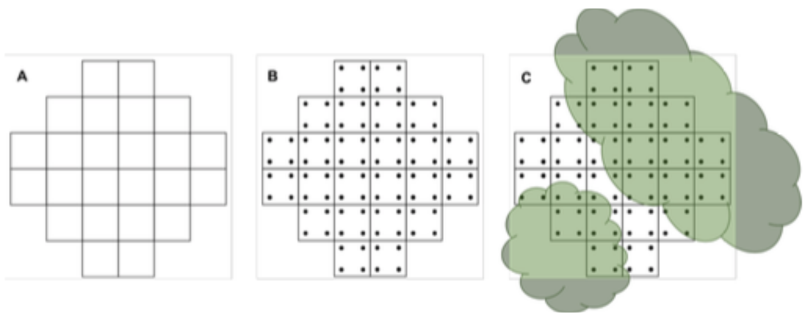
1 : Dominant trees with at least 80% sun arriving directly on the leaves
2 : Co-dominant trees with at least 50-80% sun arriving directly on the leaves
3 : Intermediate trees with only 20-50% sun arriving directly on the leaves
4 : Suppressed trees without sun contact

According to the protocol, the crown classes were determined based on the proportion of sun which falls directly on the crown. This means that small trees in an open area with direct sun contact were rated 1.

2.4 Canopy closure

Canopy closure was measured using a densiometer. This convex tools allows a view of the canopy and measures the amount of light reaching the tool. It is composed of 24 different squares (figure 8a), and it is imagined that in each square, there are four points (figure 8b). The number of these points that are in shade are then counted (figure 8c). However, as the tools has 24 squares, there is a total of 96 points, so we have to multiply by 1.04 to get the percentage of canopy closure.

Figure 8 : Densiometer illustration



For example, in figure 8, there are 69 points in the shade, so the canopy closure is 69*1,04=71,8%.

Canopy closure was measured at the centre of the plot and 8 meters from the centre in each cardinal direction. At each of these locations, four measurements were taken in each direction (N, E, S, O). The average canopy closure at each location was then calculated.

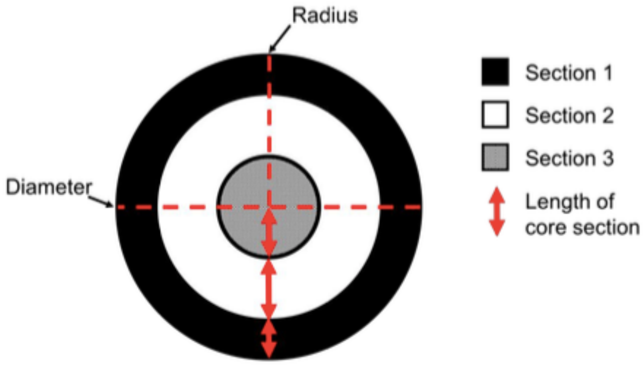
2.5 Wood density

Wood core sampling allows the determination of the density of each tree and the calculation of an estimate of the amount of stored carbon. This step is difficult because wood sampling is a tricky task. It is important to be careful to never force the increment borer, because it is very fragile and sometimes sampling is very difficult. Wood samples were all collected at the same height on the tree, namely 1.37 m.

Core samples were collected on each tree in the three selected plots, namely one plot in each different habitat.

Once all the cores were collected, samples were cut into sections according to variations of colour or visible differences in texture. If no difference was visible across the sample, it would be cut in half (in case there were non-visible differences in density in each section). Figure 9 below shows the example of a tree which will be divided into three section to calculate wood density.

Figure 9 : Illustration of the different wood sections



The samples were then set in a container with water for more than two hours to saturate them with water. Then, in a container with water on a balance, each wood section was submerged in the water in order to measure the weight difference and get the green volume, with 1 g corresponding to 1 cm^3.

Each sample was dried in an oven for two hours and a half or three hours at 150 ° C until a constant weight was reached, so I could get the dry mass of the different sections.

With this data, I was able to determine the density of each section of the sample thanks to this formula :

$$WSG_{section} = W/V$$

With :

- $WSG_{section}$: density of each section of the sample
- W : dry mass of each section of the sample
- V : green volume of each section of the sample

Overall wood density for each tree was calculated using this formula :

$$WSG_T = \frac{(WSG_1 \times P_1) + (WSG_2 \times P_2) + (WSG_3 \times P_3) \dots}{N}$$

With :

- WSG_r : wood density
- WSG_1 : wood density of the section 1
- WSG_2 : wood density of the section 2
- WSG_3 : wood density of the section 3
- P_1 : proportion of the section 1 (surface of the section 1 / total surface)
- P_2 : proportion of the section 2
- P_3 : proportion of the section 3
- N : number of different section in the sample

2.6 Aboveground biomass and carbon storage

Aboveground biomass determination is really very complicated, because trees are different in terms of species, height, structure, density, etc. Models are currently available to assess aboveground biomass more accurately. Concerning rainforests, as is the case for my study, it is very difficult to establish precise equations because they can contain hundreds of different species per hectare. So, mixed models should be used. The mixed model used for my study is the model of Chave et al. (2005) because it uses available field data for the calculation. The necessary data are: wood density, diameter, and height. The following formula allows an estimate of the aboveground biomass.

$$AGB_{est} = 0.0776\ (\rho D^2 H)^{0.940}$$

With:

- AGB : aboveground biomass estimate
- ρ : wood density (WSG_r)
- D : DBH
- H : height

Finally, with the aboveground biomass estimate, it is easy to estimate carbon storage because it is assumed that 50% of the above-ground biomass stores of carbon. For tropical forests, the percentage of stored carbon in above ground biomass is better estimated at 47% (IPCC, 2006). Thus, thanks to the following formula, it is relatively easy to estimate carbon storage:

$$C_{AGB} = AGB \; x \; 0.47$$

With :

- CAGB : carbon storage estimate
- AGB : aboveground biomass estimate

3. Limitations in data collection

After the end of my data collection, my database amounted to 460 trees with 121 trees in planted area, 160 trees in natural regrowth area, and, finally, 179 trees in primary forest.

I met some difficulties, especially during the measurements of height and density.

Concerning the heights, the main difficulty was not being able to clearly see the tops of the trees. In addition, during the measurement of the distance between the tree and the observer, it was difficult to keep the measuring tape straight because of the dense vegetation.

The imprecision of the heights is important because there is uncertainty in: the distance measurement, in angles a and b (especially angle b to the top of the tree), in the Suunto instrument, and some heights were identified by different observers because some volunteers came to help me.

Concerning the wood density, it was sometimes very difficult to get wood samples, and some completely impossible because the wood was too hard. For trees with very large diameters (>65 or even 70 cm in diameter) the measuring tool was too small or too fragile, meaning these trees had to be excluded from the wood density study. In addition, imprecision of the wood density also occurred because, during wood sampling, I was not always sure that I had each wood section, as the center of the tree was sometimes eccentric. During the weighing of the dry samples, it would have been preferable to have a more precise scale for small samples. The weighing was done with a scale precise to one 100th of a gram.

C/ Results and statistical analysis

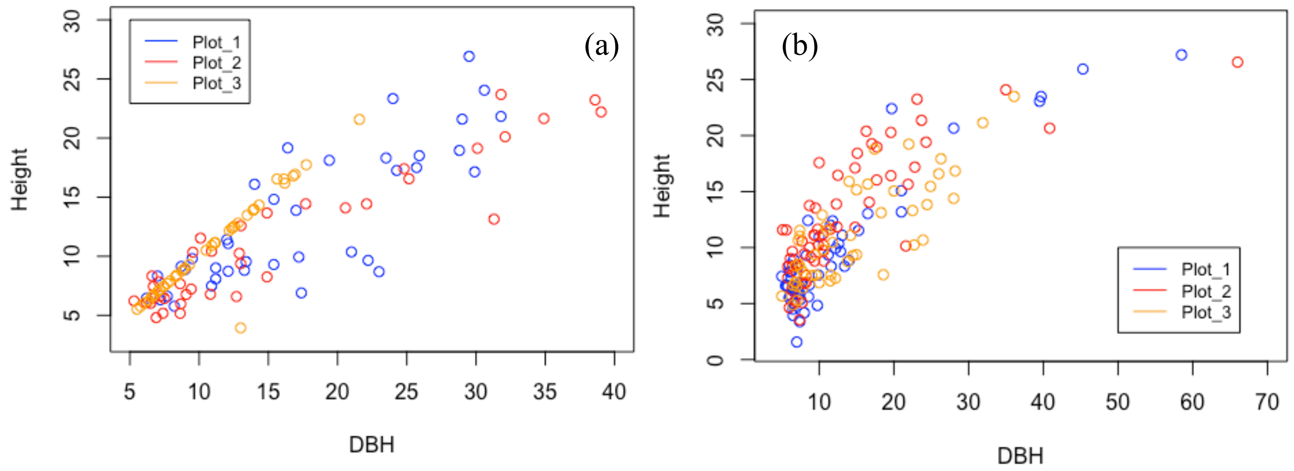
1. Relation of tree height to diameter

Upon initial examination of the graphs comparing the height vs. diameter relationship in the planted and natural regeneration areas, I found aberrations were the heights were too large for the corresponding diameter. The trees with the aberrant measurements were revisited in the field to check the height.

In addition, for all of my study, I removed dead trees from the database, because they distorted the results. Indeed, some big living trees with broken limbs influenced the results.

After verification and correction of the tree heights, tree height was plotted against DBH for both planted and natural regenerations areas (figure 10), with 121 trees found in planted area and 160 in natural regeneration areas.

Figure 10 : Relationship between tree height and diameter in planted (a) and natural regeneration areas (b)



The shape of the curves between the two areas is quite different. Indeed, in the plantation area (figure 10a), we get a fairly linear curve with very aligned points, particularly in plot 3. This can be explained by the lack of competition between planted trees. Each tree develops at its own pace without interaction with others, so there is no competition for the resources necessary for its growth. However, the almost perfect alignment of plot 3 is very puzzling. Plot 3 is the only plot which is separated into two by the Montaña trail. Perhaps, this characteristic plays a role in the development of trees as the opening of the trail brings more light and encourages 'independent' growth of each plant in a more consistent pattern than other plots.

In the natural regeneration areas (figure 10b), the shape of the curve is exponential as opposed to linear like in the planted areas. This situation can be explained because, in a natural regeneration area, there is more competition between trees than in the plantation area. As such, the trees start a race for the light and they focus on growing tall at first. After they succeeded in getting access to the sun, they reduce their vertical growth to focus on horizontal growth.

Once more, it would have been interesting to know trees species, as between light and shade species behaviour is different and may play in the structure of the forest in the years to come.

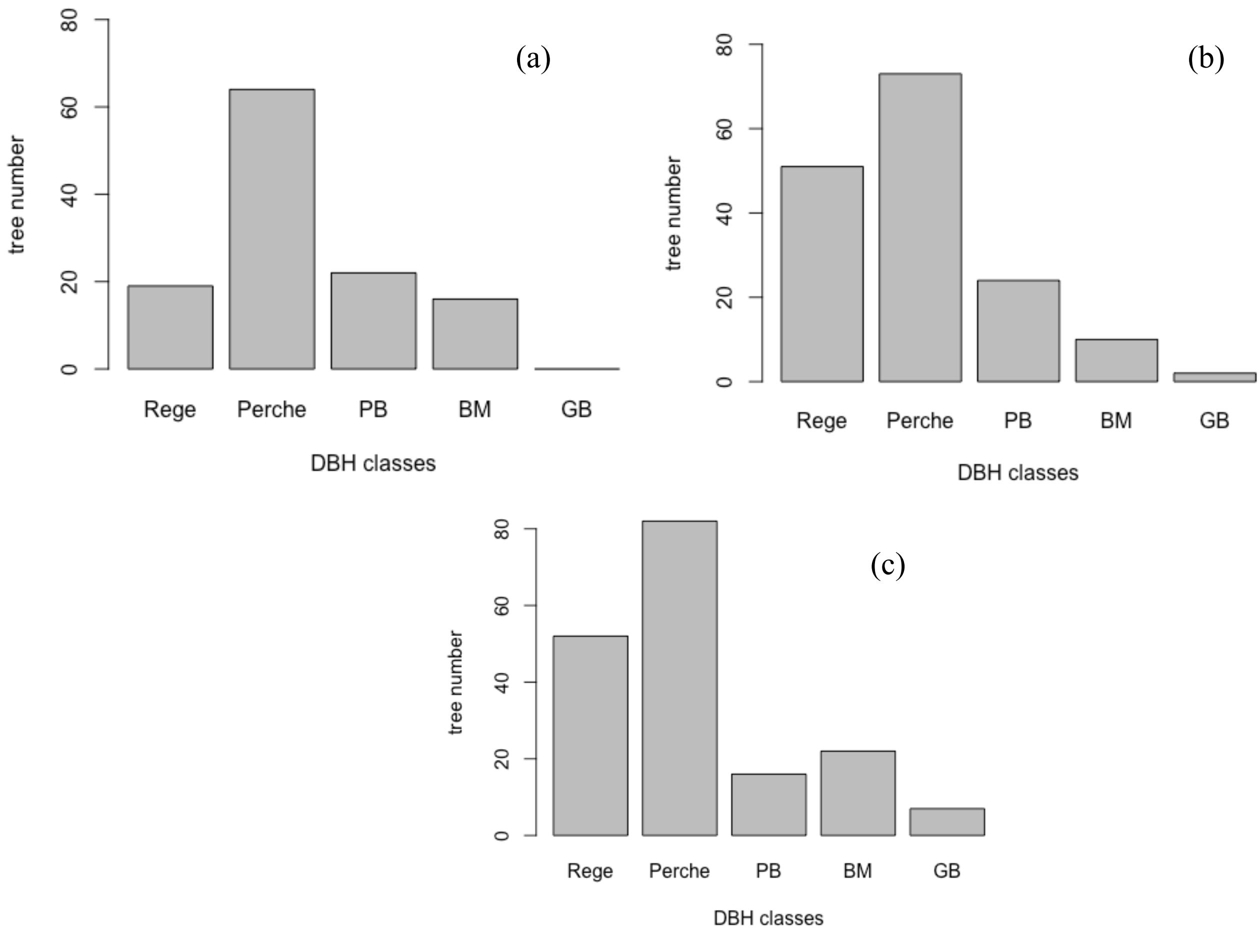
2. Is there a significant difference of diameters in both habitats

2.1 Comparison of structure by diameter classes

The difference in structure between the different habitats can be studied using diameter classes. Through the measurements of diameter, trees were separated into five categories:

- Seedling (rege): trees of diameter less than or equal to 7.5 cm
- Sapling (perche): trees of diameter between 7.5 and 17.5 cm
- Small trees (PB): trees of diameter between 17.5 and 27.5 cm
- Medium trees (BM): trees of diameter between 27.5 and 47.5 cm
- Big trees (GB): trees of diameter above 47.5 cm

Figure 11 : Number of trees by diameter classes in the planted area (a), natural regeneration area (b) and primary forest (c)



In the planted area (figure 11a), the sapling diameter class is the most abundant and is much greater than the others, and there are no big trees present. In comparison with the other habitats, planted areas seem to have very few seedlings. This may be a problem for the future, but this remains uncertain as the strong number of saplings in the planted areas is enough to ensure the next generation.

In the natural regrowth area (figure 11b), the number of seedling and sapling trees is more even than in planted area and there is a gradual decrease in the number of trees between the sapling, small, medium and big trees.

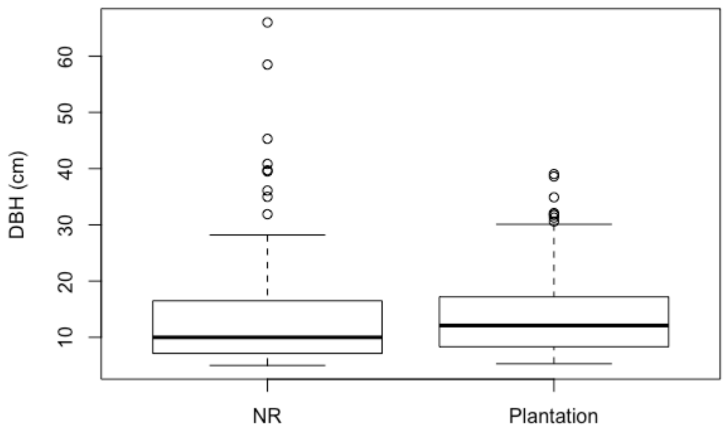
In primary forest (figure 11c), the number of big trees is higher with almost ten trees. The number of seedling and sapling trees is almost equivalent to that seen in the natural regeneration area.

Although the structure in the natural regeneration area seems closer to the primary forest than the planted forest, it is impossible to say so with certainty. Indeed, the age of primary forest is much more advanced, therefore the structure of the trees would be very different.

2.2 Statistical analysis of tree diameters

Statistical analysis comparing tree diameter was only between planted and natural regeneration areas because these forest types are the same age, while the primary forest was much older. It would be scientifically invalid to include the primary forest in these analyses due to the difference in age. The distribution of tree diameter in the planted and natural regeneration habitats is shown in figure 12.

Figure 12 : Comparison of tree diameters between planted and natural regeneration habitats



Median value :

- NR = 10
- Plantation = 12.1

Normality of the diameter data was tested with the Shapiro-Wilk test. As the p-value was less than 2.2E - 16, normality was rejected. Therefore, the non-parametric Kruskal Wallis test was used to test the data.

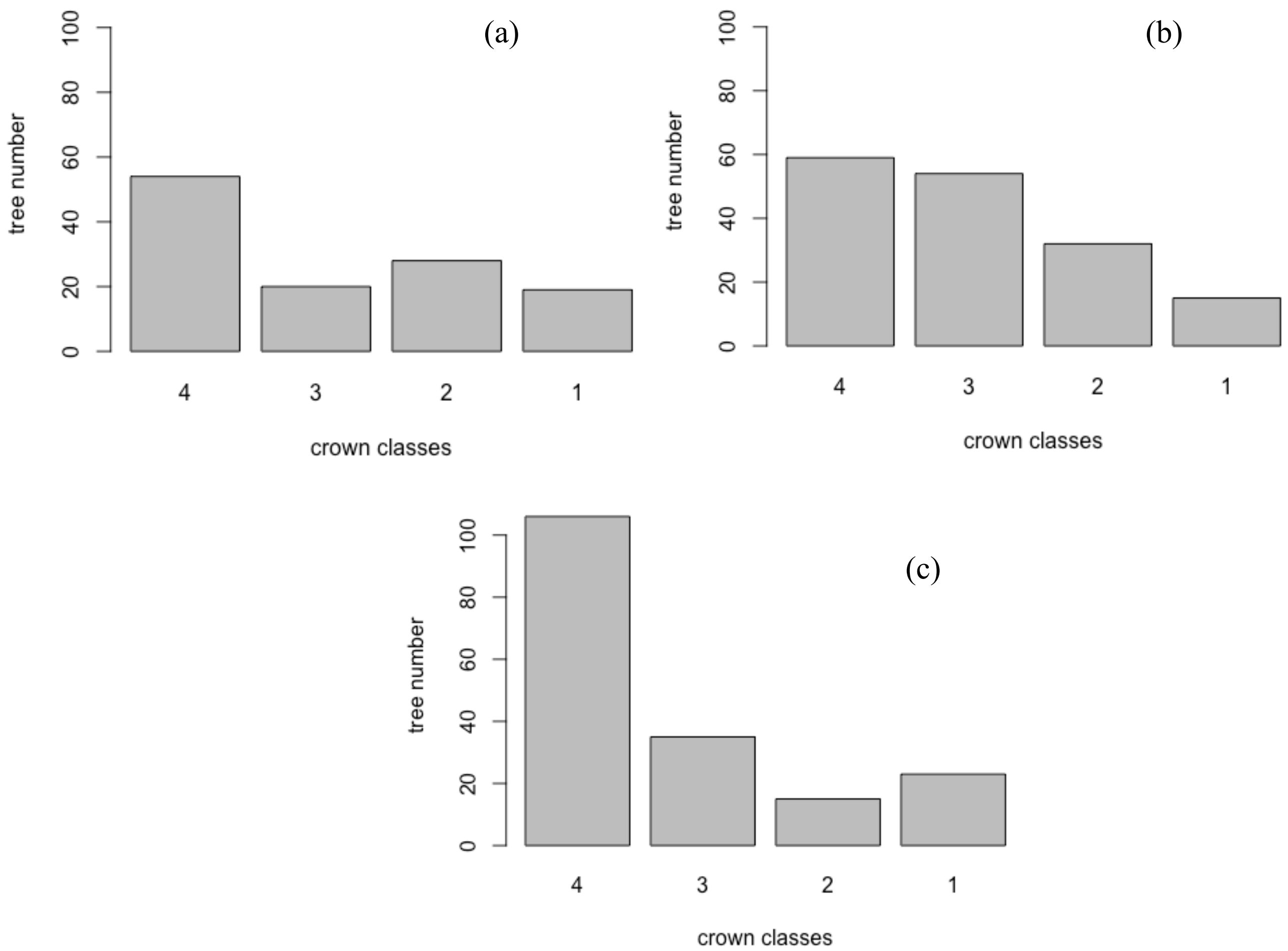
The result of the Kruskal Wallis test returns a p-value of 0.04076, less than 0.05, so we can conclude that the diameters between the two study areas are significantly different with the diameters in the planted plots a little larger than in the natural regeneration plots.

3. Analysis of crown class and tree height

3.1 Comparison of crown classes

As we saw in part B.2.2.3, crown classes for each tree were recorded, separating the trees into four categories: category 1 corresponding to the dominant trees with the most light exposure, and category 4 corresponding to the suppressed trees with the least light exposure.

Figure 13 : Number of trees by crown classes in planted (a) natural regeneration (b) and primary forest areas (c).



According to figure 13, we see, once again, in the natural regeneration habitat (figure 13b), the forest is more structured with a gradual decrease in the number of trees as dominance class increases.

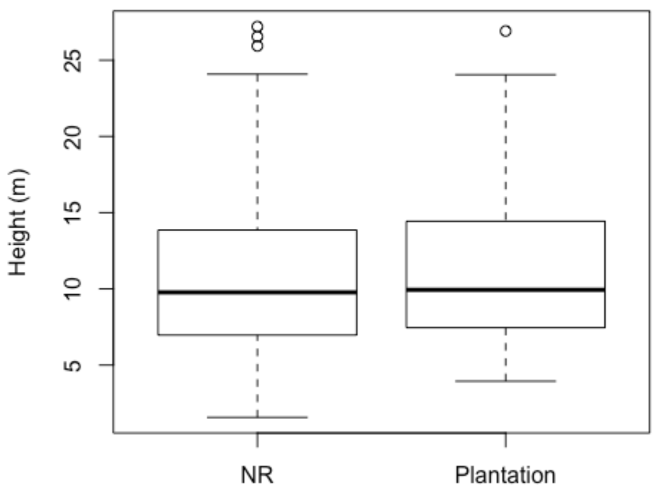
In the planted area, the forest consists primarily of suppressed trees, with the co-dominant, intermediate, and dominant trees present in more even numbers. Compared to the other two forest types, the intermediate stratum is not very well represented.

In primary forest, we see a very large number of trees in class 4, with many suppressed trees without direct access to the light. This is consistent with the large number of large diameter, dominant trees (figure 11) that create a dense, closed canopy, therefore slowing the tree growth below. The primary forest is characterized by many dominant trees reducing access to the light for the intermediate and suppressed trees.

3.2 Statistical analysis of height

The distribution of tree heights in the planted and natural regeneration habitats are shown in figure 14.

Figure 14 : Comparison of tree heights between planted and natural regeneration habitats



Median values :

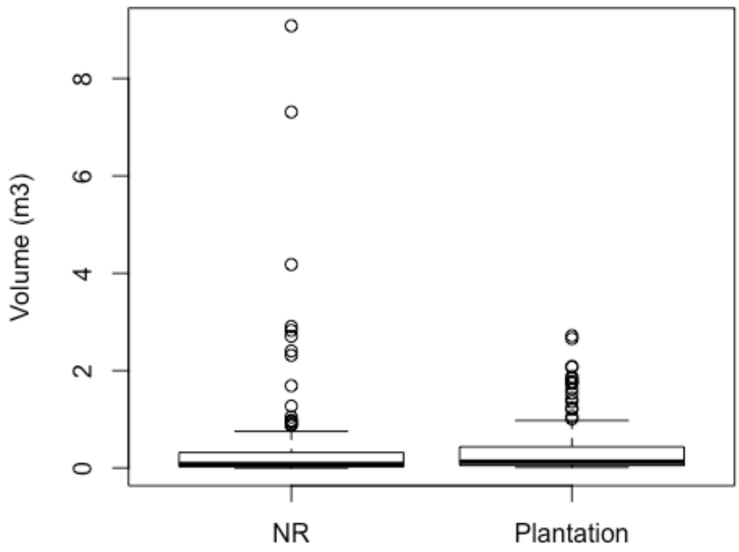
- NR = 9.77
- Plantation = 9.94

The normality of the height variable was analyzed in the same way as for the diameter with the Shapiro-Wilk test. With a p-value of 4.867e- 11, normality is rejected. Once again, the Kruskal Wallis test was used to determine if there is a significant difference. With a p-value of 0.4514, greater than 0.05, the heights are not significantly different between planted and natural regeneration habitats.

4. Statistical analysis of volume

The volume of the trees was calculated using diameter and height data, so it was interesting to determine if the volumes were statistically different between planted and natural regeneration habitats. The distribution of the volumes in both habitats is shown in figure 15. The normality of this variable was also rejected (p-value <2.2E - 16).

Figure 15 : Comparison of volumes in planted and natural regeneration habitats



Median values:

- NR = 0.08
- Plantation = 0.13

The Kruskal Wallis test returned a p-value of 0.00601, less than 0.05, so although the heights were not significantly different, the volumes are significantly different between both habitats, with a larger median volume in the plantation plots.

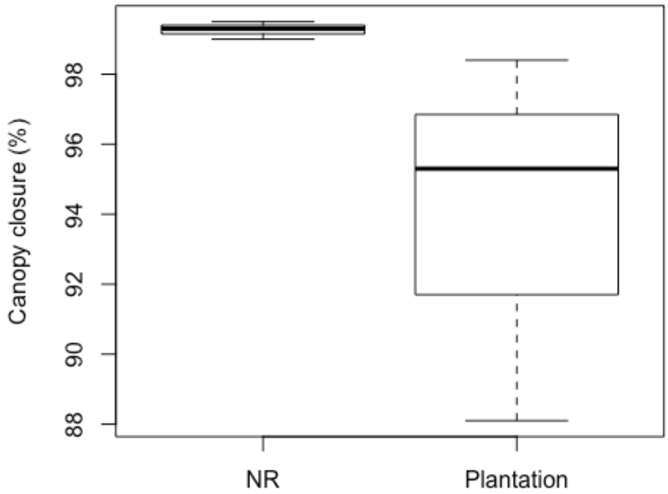
5. Statistical analysis of canopy closure

Canopy closure was recorded in each of the plots. The average canopy closure was calculated at each measurement point from 4 measurements taken in each cardinal direction. The distribution of the canopy closure in both habitats is shown in figure 16. The Shapiro-Wilk test gives us a p-value of 0.01365, thus the normality is not accepted.

Kruskal Wallis test gives us a p-value of 0.04953, less than 0.05, allowing us to conclude that there is a significant difference in the canopy closure between the planted and natural regeneration areas, with greater canopy closure in the natural regeneration plots.

However, it is difficult to draw conclusions from a difference of the canopy closure as the imprecision of the measurement is very important. Indeed, I have only six values, namely three measure in each habitat, because it is an average of the canopy closure in each plots. It would be preferable to have more results in order to compare the two habitats and to formulate hypotheses about the canopy closure and the behaviour of the species.

Figure 16 : Comparison of canopy closure in planted and natural regenerated habitats



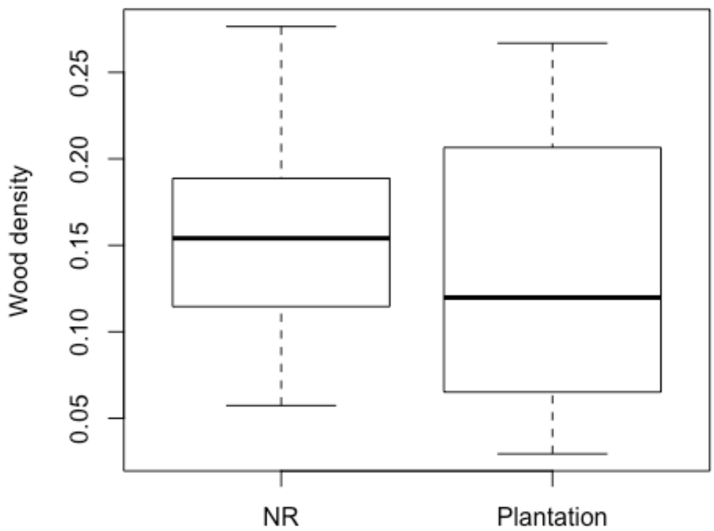
Median values:
- NR = 99.3
- Plantation = 95.3

6.Statistical analysis of carbon storage

6.1. Comparison of wood density

Wood density data was only collected in one plot from each of the three habitats, due to lack of time. Wood density was then calculated for 36 trees in a planted area and 51 trees in a natural regeneration area. The distribution of the wood density in both habitats is shown in figure 17. The Shapio-Wilk test returned a p-value of 0.08737, thus the normality is accepted. With this condition validated, a Student t-test was used for analysis.

Figure 17 : Comparison of the wood density in planted and natural regenerated areas



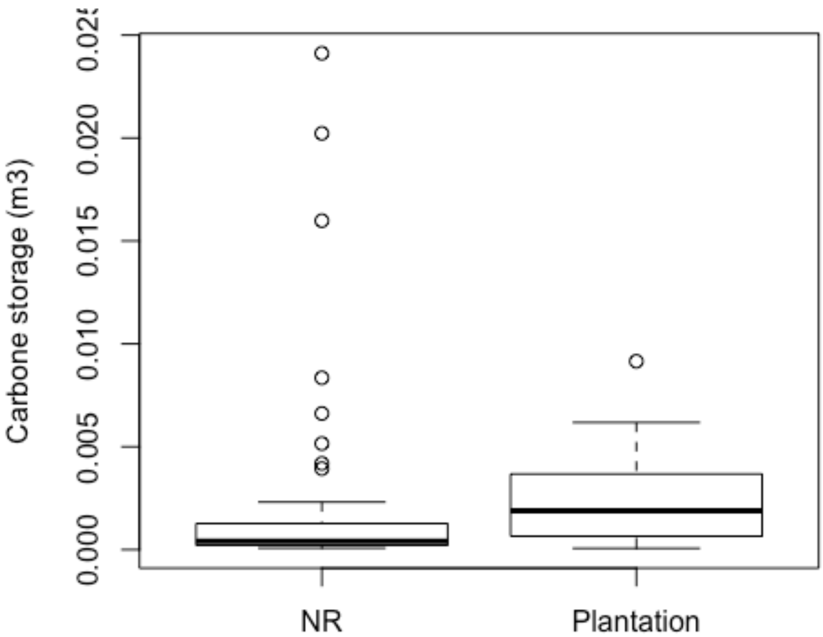
Median values :
- NR = 0.15
- Plantation = 0.12

The results of the Student t-test returned a p-value of 0.2188, greater than 0.05, so the wood density is not significantly different between the habitats.

6.2. Comparison of carbon storage

Carbon storage was estimated after calculation of estimated above ground biomass using wood density, diameter, and height data (see B.2.6). There is a chance that the results are significant because the diameter is used in the calculation, and because the diameter was already found to significant between the planted and natural regeneration habitats. The distribution of the estimated carbon storage in both habitats is shown in figure 18. The Shapiro-Wilk test returned a p-value of 4.503e-15, thus the normality is again rejected and the Kruskal Wallis was used to test for statistical significance.

Figure 18 : Comparison of the estimation of carbon storage in planted and natural regeneration habitats



Median values :

- NR = 4e-4
- Plantation = 1.89e-3

The Kruskal Wallis test returned a p-value of 0.0007537, less than 0.05, so our hypothesis is validated, carbon storage is significantly different between the both habitats. So, we can assume that the planted habitats have captured more carbon than the natural regeneration habitats of the same age.

D/ Summary of the results and discussion of the most effective method to adopt

To summarize the results, we found significantly different results for the diameter, canopy closure, volume, and carbon storage. These last two parameters are calculated from the diameter squared, so it is not surprising to find significant results. Meanwhile, results for the height and wood density were not significantly different.

In view of these results, it is not clear which is the most effective method of reforestation (planted or natural regeneration) to return the forest to a primary forest structure. The different ages between the planted and natural regenerated forests, and the primary forest makes it difficult to draw precise conclusions because the dynamics of the primary forest trees are completely different from a young forest. However, according to the figure 11, we found that when comparing the distribution of tree diameters in natural regeneration, the forest structure was closer to that of the primary forest than the planted forest was to the primary forest. Likewise, according to figure 13, we found that a natural regeneration forest had all classes of dominance, bringing once again some structure and a more secure future in the event of bad weather. Succession and recruitment in the event of disturbance is more likely to be achieved through the presence of intermediate trees, which are well represented in the natural regeneration areas unlike the planted area where the intermediate stratum was not well represented.

However, carbon storage seems to be more important in the planted habitat, which is very important when addressing the current problem of global warming. However, the difference is not very strong at the moment, so we should see how this difference evolves over time.

E/ Limit and prospects

One of the limits to my study is the lack of knowledge of the species in my plots. This data would be helpful in terms of understanding the difference in behaviour of the trees' growth, as the difference in the height vs diameter graphs could be explained by a difference in the species present in each plot. For example, the species respond differently with respect to access to light.

In addition, the measurements were collected with simple tools, particularly for the heights. A measuring device such a Vertex would help reduce imprecisions in the measurements, namely that of the instrument and that the manipulator. With the current measurement instruments, there are four possible ways to introduce imprecisions in the measurements: distance, the height to the eye of the observer, instrument, and the manipulator (pointing to the pink mark on the bamboo, the tree top and reading of angle). A Vertex would allow the measurements to be more precise.

In the future, it would be essential to identify the species in the plots to consider all the elements and conduct a complete comparison. In addition, with the species identification, a comparison with those found in primary forest would be possible and therefore which reforestation method is creating a forest composition most similar to the primary forest. A species inventory would also provide information of the diversity of the plots. This diversity is important because it would provide information on how the plots could be react in cases of bad weather and other disturbance, such as, for example, strong winds, diseases, or the ability to adapt to the challenges global warming.

I also recommend as the study continues to look at the tree growth in diameter and height to have knowledge of the average increment increase over time.

Finally, it could be interesting to consider the environmental conditions in the different habitats, as for example, the slope, soil moisture, altitude, exposure, shading, etc. Depending on the environmental conditions, there may be places where planted habitat would be better than natural regeneration and vice versa.

Conclusion

The project of reforestation at Cloudbridge, conducted since 2002, shows very significant results with a landscape that has already changed. Through the measurements that I made during my 11 weeks at the reserve, I compared the structures and characteristics of planted and natural regeneration habitats. However, these young forests, both older than 20 years, did not seem to present very marked differences in structure and characteristics. This project must be carried out over the long-term in order to study the evolution of the forest structure as these rainforests are very dynamic, meaning, their structure changes very quickly. Over time, it will also be possible to compare the tree growth in diameter and height between habitats and it would improve the analysis to see which habitat has the fastest growth and which would be most likely to quickly reach a structure similar to that of the primary forest. Moreover, in the years to come, it would be beneficial to identify the species in the plots. Species identification would give a richer understanding of the forest habitats and comparisons with the primary forest would be possible, in terms of presence of the species. With this data, it would be possible to make a more precise judgment about the reforestation method which would be most effective to achieve the goal of regenerating the existing primary forest structure, because it is currently not possible to make a final judgment on the best method.

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Appendices :

Appendix 1 : R Script used for analysis

```
library(sf)
library(car)
setwd("~/Documents/Stage costa rica/Rapport de stage")
data=st_read("data_compact.xlsx") #Excel complet avec données OG
habitat=st_read("data_compact_NR_P.xlsx")
canopee= st_read("canopée_P_NR.xlsx")
densite = st_read("densite.xlsx")
Plantation= head(habitat, n=121)
NR= head(habitat[122:281,], n=281)
Canop= canopee[c(-7,-8,-9),]

Plantation_1=head(habitat, n=38)
Plantation_2=head(habitat[39:76,], n=76)
Plantation_3=head(habitat[77:121,], n=121)
NR_1=head(habitat[122:175,], n=175)
NR_2=head(habitat[176:231,], n=231)
NR_3=head(habitat[232:281,], n=281)
OG_1=head(data[282:352,], n=352)
OG_2=head(data[353:411,], n=411)
OG_3=head(data[412:460,], n=460)


#Graphique Hauteur diamètre en distingant les placettes en plantation

par(mfcol=c(1,1))
with(Plantation_1, plot(x=Diam, y=Hauteur,col="blue",xlim=c(5,40),
ylim=c(3,30),
                     main="Relation hauteur diamère en zone de
plantation" ,xlab="DBH", ylab="Hauteur"))
with(Plantation_2, points(x=Diam, y=Hauteur,col="red", xlab="DBH",
ylab="Hauteur"))
with(Plantation_3, points(x=Diam, y=Hauteur,col="orange", xlab="DBH",
ylab="Hauteur"))
legend(5, 30, legend=c("Placette_1", "Placette_2", "Placette_3"),
       col=c("blue", "red", "orange"), lty=1:1, cex=0.8)

#Graphique Hauteur diamètre en distingant les placettes en NR

with(NR_1, plot(x=Diam, y=Hauteur,col="blue",xlim=c(4,70),
ylim=c(1,30),
                main= "Relation hauteur diamètre en zone de
régénération naturelle", xlab="DBH", ylab="Hauteur"))
with(NR_2, points(x=Diam, y=Hauteur,col="red", xlab="DBH",
ylab="Hauteur"))
with(NR_3, points(x=Diam, y=Hauteur,col="orange", xlab="DBH",
ylab="Hauteur"))
legend(50, 10, legend=c("Placette_1", "Placette_2", "Placette_3"),
       col=c("blue", "red", "orange"), lty=1:1, cex=0.8)

#Graphique Hauteur diamètre en distingant les placettes en OG

with(OG_1, plot(x=Diam, y=Hauteur,col="blue",xlim=c(4,80),
ylim=c(1,60),
                main= "Relation hauteur diamètre en forêt primaire",
```

```
xlab="DBH", ylab="Hauteur"))
with(OG_2, points(x=Diam, y=Hauteur,col="red", xlab="DBH",
ylab="Hauteur"))
with(OG_3, points(x=Diam, y=Hauteur,col="orange", xlab="DBH",
ylab="Hauteur"))
legend(60, 20, legend=c("Placette_1", "Placette_2", "Placette_3"),
       col=c("blue", "red", "orange"), lty=1:1, cex=0.8)

#Classe de diamètre
PL_Ordre = factor(Plantation$Classe.diam, c("Rege", "Perche", "PB",
"BM", "GB"))
plot(PL_Ordre, ylab="Nombre arbres", xlab="classe de diamètre",
     ylim= c(0,80), main="nombre arbres par classe de diamètre en zone
de plantation")
NR_Ordre = factor(NR$Classe.diam, c("Rege", "Perche", "PB", "BM",
"GB"))
plot(NR_Ordre, ylab="Nombre arbres", xlab="classe de diamètre",
     ylim= c(0,80), main="nombre arbres par classe de diamètre en zone
de
     régénération naturelle")
OG_Ordre = factor(OG$Classe.diam, c("Rege", "Perche", "PB", "BM",
"GB"))
plot(OG_Ordre, ylab="Nombre arbres", xlab="classe de diamètre",
     ylim=c(0,80), main="nombre arbres par classe de diamètre en forêt
primaire")

#Crown_class
plot(factor(Plantation$Crown.class, c("4","3","2","1")), ylab="nombre
arbres", xlab="classe de dominance", ylim= c(0,110),
     main="Classe de dominance en zone de plantation")
plot(factor(NR$Crown.class, c("4","3","2","1")), ylab="nombre arbres",
xlab="classe de dominance", ylim= c(0,110),
     main="Classe de dominance en zone de régénération naturelle")
plot(factor(OG$Crown.class, c("4","3","2","1")), ylab="nombre arbres",
xlab="classe de dominance", ylim= c(0,110),
     main="Classe de dominance en forêt primaire")

#Boite à moustache
a=boxplot(habitat$Diam~habitat$Type, main="Boite à moustache des
diamètres dans les deux zones d'études") #boite à moustache diam par
zone étude
b=boxplot(habitat$Hauteur~habitat$Type, main="Boite à moustache des
hauteurs dans les deux zones d'études") #boite à moustache hauteur par
zone étude
c=boxplot(habitat$Volume~habitat$Type, main="Boite à moustache des
volumes dans les deux zones d'études")
d=boxplot(canopee$Canopee~canopee$Type, main="Boite à moustache de la
fermeture de la canopée
          dans les deux zones d'études")
e=boxplot(densite$WSGr~densite$Type,  main="Boite à moustache des
densités dans les deux
          zones d'études")
f=boxplot(densite$Cagb~densite$Type,  main="Boite à moustache de
l'estimation du stockage de carbone
          dans les deux zones d'études")
```

```
#Valeur de la médiane [3] des boites à moustaches
a$stats
b$stats
c$stats
d$stats
e$stats
f$stats

# test de normalité : test de Shapiro-Wilk
shapiro.test(habitat$Diam)
shapiro.test(habitat$Hauteur)
shapiro.test(habitat$Volume)
shapiro.test(canopee$Canopee)
shapiro.test(densite$WSGr)
shapiro.test(densite$Cagb)

#test kruskal Wallis
kruskal.test(Diam~Type, data=habitat)
kruskal.test(Hauteur~Type, data=habitat)
kruskal.test(Volume~Type, data=habitat)
kruskal.test(Canopee~Type, data=canopee)
kruskal.test(Cagb~Type, data=densite)
kruskal.test(Crown.class~Type, data=habitat)

# test de student
t.test(WSGr~Type, data=densite)
```