Forest assessment of planted, naturally regenerated and primary tropical cloud forest

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1 SUMMARY

Several decades ago there was a land colonization programme by the Costa Rican government to support land clearance for the purpose of agriculture. This resulted in farmers clearing not only relatively flat land but even the mountainous regions of Costa Rica. Some of this (formerly) cleared land is now part of Cloudbridge Nature Reserve. Cloudbridge has a reforestation project going on and is recovering the forest by actively replanting areas or letting the forest recover through natural regeneration. So the objective of this research is to assess if: there is a difference in successional state between planted and naturally regenerated forests, and to assess how similar these forests are to the untouched primary forest. This was done by monitoring tree growth and comparing different forest characteristics to find out if there were any differences in forest structure.

Forest monitoring was conducted in 22 research plots spread throughout Cloudbridge Nature Reserve. These research plots have a 12.5 meter radius which gives them a surface area of 490.87 m^2. Trees with a DBH (diameter at breast height) of at least 10 cm or more were tagged with a tree tag number. DBH and tree height were measured for each tagged tree, as well as tree volume calculated, crown class determined and whether the tree was alive or dead recorded. For each plot the canopy closure was measured.

After all data had been collected, it was first run through a normality test to find out if data was normally distributed. The trees per hectare and canopy closure data seemed to be normally distributed so to analyse this data a one-way anova test was used. DBH, DBH increment, tree height, tree volume, crown class and wood specific gravity (WSG) data turned out to have a non-normal distribution, so the Kruskal-Wallis test was used to analyse this data. When significant results were found after using the one-way anova or Kruskal-Wallis test, the Wilcoxon signed-rank test was used to analyse which individual relationships were significant. A linear regression and correlation test was used to analyse whether wood specific gravity had any relationship with canopy closure, crown class or DBH increment.

The following results were found: *Difference in DBH:* Planted areas had a median DBH of 17.7 cm where naturally regenerated areas had a median of 17.5 cm and primary forest areas of 19.1 cm. *Difference in DBH increment:* Planted areas had a median increase of 7.5% compared to naturally regenerated areas at 4.6% and primary areas at 1.2%. *Difference in tree height:* The median tree height in the planted plots was 12.3 m, in naturally regenerated plots 12.4 m and in primary plots 15.5 m. *Difference in tree volume:* Trees within planted plots as well as naturally regenerated plots had a median volume of 0.30 m^3 compared to a median of 0.48 m^3 for primary forest plots. *Difference in trees per hectare:* Planted forest plots contain, on average, 20.3 trees, for naturally regenerated forest plots this number is 24.6 trees, and for primary forest plots 30.7 trees. Converted to trees per hectare this would be 413.3 trees per hectare for planted areas, 500.8 trees per hectare for naturally regenerated areas and 624.7 trees per hectare for primary forest areas. *Difference in crown class:* Planted areas have the highest number of crown class 1, 2 and 3 trees with a mean value of 11.1, 9.4 and 7.7 trees per plot respectively. Primary forest areas contain the highest number of crown class 4 trees with a mean value of 14.0 trees per plot compared to 13.7 for planted and 6.6 for naturally regenerated forest. *Difference in canopy closure:* Plots inside the planted area have a median canopy closure of 83.2% compared to a median of 88.2% for naturally regenerated and 93.9% for primary forest areas. *Difference in wood specific gravity:* Primary forests have generally a higher WSG with a median of 0.50 g/cm^3 compared to a median of 0.43 g/cm^3 for naturally regenerated forest and a median of 0.21 g/cm^3 for planted forests.

Of all these results, only the differences in DBH increment, tree height, trees per hectare and wood specific gravity were significant. As for the WSG relations, there seemed to be a significant correlation between all three relationships although they were weakly correlated.

It can be concluded that the structure of naturally regenerated forests is more similar to primary forest than the planted forest. In any case, both are good ways in letting the forest recover and grow back to its original state.

2 INTRODUCTION

Tropical cloud forests account for no more than 2.5% of the world's tropical forests (Bubb et al., 2004). This makes them a rare and fragile, but valuable ecosystem, because they are characterized by high biodiversity and are home to many endemic species. Cloud forests typically occur up to an elevation of 3500 m, but may start from as low as 1000 m on coastal and insular mountains. They can occur within a wide range of rainfall patterns between 500 and 6000 mm/year, but are found wherever clouds and mountain slope are frequently in contact.

Currently, forests account for about 51.5% of the land surface area in Costa Rica. This is a total forest cover of 26,296 square km (Central Intelligence Agency, 2018). The biggest threat for these forests is land clearance for agriculture and cattle farming which accounts for about 37.1% of the country's land use. Costa Rica even had one of the highest deforestation rates in the world in the 1980s (Camino et al., 2000).

From the 1950's, there was a lack in available land for agriculture. This resulted in farmers clearing forests even on the steepest slopes of the Costa Rican mountainous regions. These cleared pasture areas were usually abandoned after several years, leaving the area deforested and degraded. Nowadays there is an increase in the forest cover due to farm abandonment and reforestation practices throughout the country (Allen et al., 2015)

Deforestation for cattle and crop farming is what happened in the areas that are now part of Cloudbridge Nature Reserve. But, as part of the reforestation program of Cloudbridge most land is now forested again or being replanted. Cloudbridge is located on the Pacific slope of the Talamanca mountain range, adjacent to mount Chirripó (Figure 1). Cloudbridge uses replanting or natural regeneration as their methods for reforestation. The aim of this research is thus to assess how similar these replanted and naturally regenerated areas are in comparison to the primary forest. And maybe also find out which of the reforestation methods in most cases has the desired effect on the forest structure. This assessment was done in addition to previously obtained data.

For the forest monitoring, 22 of the plots inside the reserve were used for this research (Figure 2). The plots are located along the trails and scattered over the different forest types. Research plots have a 12.5 m radius which gives a surface area of 490.87 m^2. Inside these plots all trees with a DBH of 10 cm or more were marked with a tree tag number.

FIGURE 1: LOCATION OF CLOUDBRIDGE NATURE RESERVE IN COSTA RICA

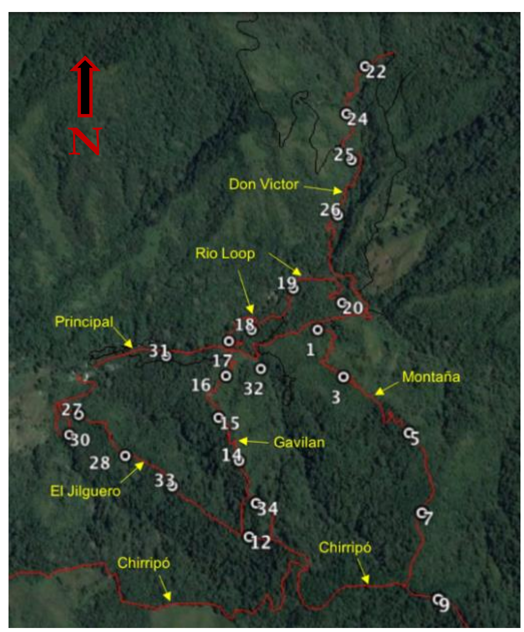

FIGURE 2: MAP OF THE RESEARCH PLOTS IN THE RESERVE

2.1 PROBLEM STATEMENT

The objective of this research is to assess if the efforts of Cloudbridge by the replanting of clear cut areas have a different effect on the forest structure compared to naturally regenerated areas. And also, how similar both of these areas are to the primary forest of over at least 70 years old. This leads to the following research question: Is there a difference in forest structure between planted, naturally regenerated and primary forest within Cloudbridge Nature Reserve?

To be able to answer this question, it was divided into the following sub-questions:

- Is there a significant difference in DBH between planted, naturally regenerated and primary forest?
- Is there a significant difference in DBH increment between planted, naturally regenerated and primary forest?
- Is there a significant difference in tree height between planted, naturally regenerated and primary forest?
- Is there a significant difference in tree volume between planted, naturally regenerated and primary forest?
- Is there a significant difference in canopy closure between planted, naturally regenerated and primary forest?
- Is there a significant difference in the number of trees per hectare between planted, naturally regenerated and primary forest?
- Is there a significant difference in crown classes between planted, naturally regenerated and primary forest?
- Is there a significant difference in wood specific gravity between planted, naturally regenerated and primary forest?

In addition to these sub-questions, this research also looked at the relationship between the amount of sun light received by trees, tree growth and wood density. This was done in order to answer the following question: Is there a relation between available sunlight and wood density?
The hypothesis for this question was that: Less sunlight results in lower growth rates and thus denser wood (Siliprandi et al., 2016).

To be able to prove or reject this hypothesis the following sub-questions were created:

- Is there a significant relationship between DBH increment and wood specific gravity?
- Is there a significant relationship between canopy closure and wood specific gravity?
- Is there a significant relationship between crown class and wood specific gravity?

3 MATERIALS & METHODS

This chapter will explain the methods and materials that were used in conducting the research.

3.1 TREE ENUMERATION

The measurements were done inside the existing research plots throughout the reserve. Inside these plots all trees were already marked with a tag in previous years. When revisiting a plot, a list with the tree tag numbers of the trees that were supposed to be inside that plot was taken. So first, all previously tagged trees were located and if necessary retagged if the tag had fallen off. As well, new tags were added to trees that grew to have DBH of 10 cm or larger in the last year. If a certain tree was supposed to be there, but could not be located it was noted down as dead.

3.2 DBH

The DBH was measured using a diameter tape and bamboo stick with a piece of tape at exactly 1.37 m high for reference. DBH was measured at 1.37 m from the ground since this is the average breast height of a man and a standard height for measuring tree diameter. When a tree was on a slope, the 1.37 m was measured from the upslope side of the tree. If a tree was split into multiple stems above 1.37 m, a single DBH was measured below the split. If the split occurred below 1.37 m, all stems were measured individually. To calculate a single DBH for these multiple stem trees the following formula was used:

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

3.3 TREE HEIGHT

The tree height measurements were based on the Pythagorean theorem (Figure 3). First the eye height of the observer (x) was measured and marked on a bamboo stick. This stick was then placed at the base of the tree to mark the observer's eye height on the tree stem. From this point the observer walked away from the tree to a point where the marked stick and top of the tree were clearly visible. This distance (d) was made as large as possible to increase the accuracy of the measurements. The observer would then use the inclinometer to measure the angle to the eye mark (a) and the top of the tree (b). With these measurement, the y, z and D were calculated to determine the total height of the tree.

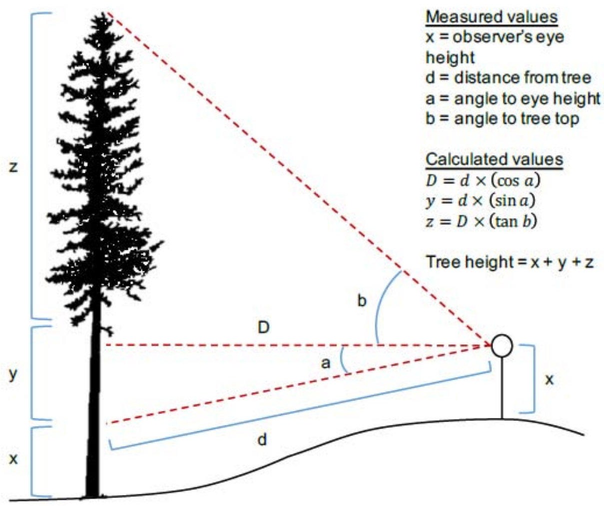

FIGURE 1: MEASUREMENTS AND CALCULATIONS TO MEASURE TREE HEIGHT

3.4 TREE VOLUME CALCULATIONS

Tree volume was calculated using the DBH and tree height data in the following formula:

$$V = \pi * \left(\frac{DBH/100}{2}\right)^2 * height$$

When a tree had multiple stems, and thus more than one DBH, the calculated DBH multistem (as described in Section 3.2) was used.

3.5 CROWN CLASS

For each tagged tree, the crown class was recorded. This was done by determining the dominance of the tree crown according to the 4 possible crown classes as listed below. See Figure 4 for a visual representation of each class.

The 4 possible crown classes (with reference to the colours in Figure 4):

1. **Dominant trees (green)**: Their crowns are above the crowns of neighbouring trees, standing out a bit from the rest. 80% or more of its canopy is fully exposed to the full sun.
2. **Codominant trees (orange):** Their crowns intermingle with many others, with 50-80% of its crown fully exposed to the full sun.
3. **Intermediate trees (red):** Their crowns are mostly below the heights of others in the stand, receiving 20-50% of the full sun.
4. **Suppressed trees (blue):** Their crowns are completely below the crowns of the surrounding trees, they receive almost no direct sunlight.

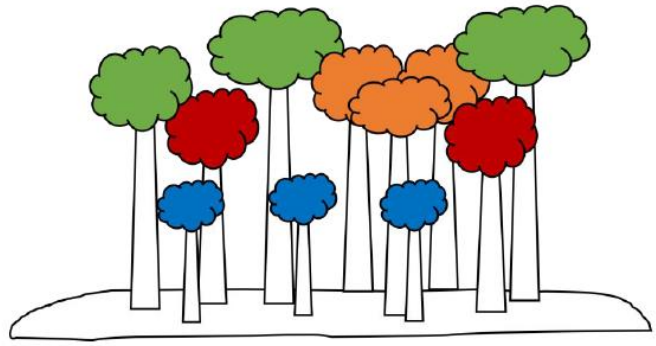

FIGURE 2: CROWN CLASSES

3.6 CANOPY CLOSURE

Canopy closure was measured using a densiometer at five points within the plot: one in the centre and the other four at 8 m in each of the cardinal directions (north, east, south and west) (Figure 5). At each of these locations, four measurements were taken and averaged to give a closure percentage for the whole plot. To measure canopy closure, a convex mirror with a grid of 24 squares engraved on the surface was used. Imagine four dots in every square and count the number of dots covered by the canopy (Figure 6). Multiply this number with 1.04 to get the canopy cover percentage.

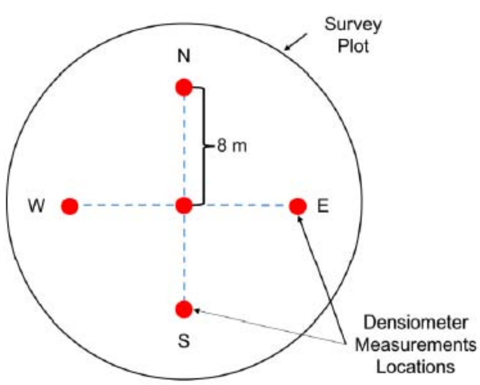

FIGURE5: LOCATIONS OF THE FIVE MEASUREMENT POINTS INSIDE A PLOT

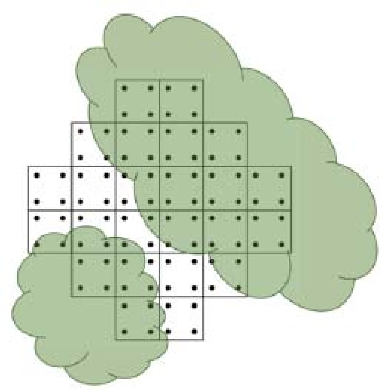

FIGURE 6: IMAGINE FOUR DOTS IN EVERY SQUARE AND COUNT THE NUMBER OF DOTS COVERED BY THE CANOPY

3.7 WOOD SPECIFIC GRAVITY (WSG)

For this part an increment borer was used to take wood samples from the trees. Samples were taken from each tagged tree from the outside to the core of the tree. After a sample had been taken it was examined for clearly visible changes in wood colour and/or texture, and divided according to these transitions. If no changes were visible, the core was cut in half. Once a sample was divided into segments, the length of these segments was measured. Then they were stored in a straw, sealed off and labelled with the number of the tree.

Later, the green volume and oven-dry weight of the samples were measured. The green volume is the volume of the wood when fully saturated with water. This was measured by first soaking each core section in water for at least half an hour to ensure adequate swelling. Then a container capable of holding the samples and water, leaving a little space between the samples and the container, was placed on an electronic scale. Using a thin needle, the samples were submerged into the water without making contact with the container. The reading on the scale was then recorded as the green volume of the core section.

The oven-dry weight was measured by drying the core samples in an oven between 100-105˚C until they reached a constant weight. Often samples were air-dried prior to putting them in the oven. Core samples were placed in labelled baking cups and left in the oven for several hours. During this time, measurements were done to see if samples had maintained weight. Then the final weight was recorded as the oven-dry weight of the core section.

4 DATA ANALYSIS

To analyse the DBH increment per individual tree, the percentage increase was used instead of the actual growth. This was done to emphasise the relative tree growth. So using the data from 2017 the following formula could be used to calculate the percentage increase from 2017 to 2018:

$$(DBH2018 - DBH2017)\ /\ DBH2018 * 100$$

When comparing the DBH data from 2017 and 2018 some trees had shrunk or grown too much to be realistic, probably due to measurement errors. To determine whether a tree had grown too much to be realistic, the theoretical possible growth per tree was calculated. Based on a mean annual increment of 1.5 cm in DBH for tropical trees (Clark & Clark, 1999; Karyati et al., 2017; Kueh Jui Heng et al., 2011; Schneider et al., 2014; Singh, 2015), the formula used to calculate possible growth per tree was:

$$DBH2018 - (DBH2017 * 1.5)$$

All trees that were smaller than last year or where the DBH increase was bigger than the theoretical possible growth were excluded from further analysis.

Before doing any statistical tests, all data first went through a normality test to find out if data was normally distributed. The trees per hectare and canopy closure data appeared to be normally distributed so for these a one-way anova was used to analyse the data. DBH, DBH increment, tree height, tree volume, crown class and wood specific gravity were non-normally distributed, so for these the Kruskal-Wallis test was used.

After finding significant results with the one-way anova or Kruskal-Wallis test, the Wilcoxon signed-rank test was used to analyse which individual relationships were significant.

To analyse whether wood specific gravity was associated with canopy closure, crown class or DBH increment a correlation and linear regression analysis was used.

CLOUDBRIDGE NATURE RESERVE

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5 RESULTS

5.1 DBH

Planted areas had a median DBH of 17.7 cm where naturally regenerated areas had a median of 17.5 cm and primary forest areas of 19.1 cm (Figure 7).

The Kruskal-Wallis test gives a P-value of P=0.8027 which indicates there is no significant difference in DBH between the forest types.

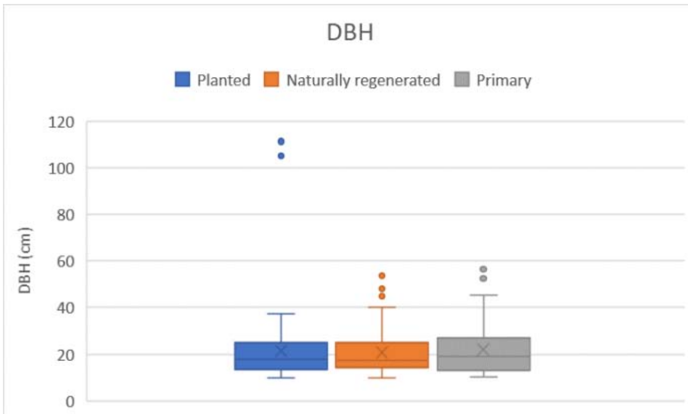

FIGURE 3: BOXPLOT OF THE DBH PER FOREST TYPE

5.2 DBH INCREMENT

Planted areas had a median increase of 7.5% compared to naturally regenerated areas at 4.6% and primary areas at 1.2% (Figure 8).

The Kruskal-Wallis test gives a P-value of P=<0.0001 (4.54E-12) which indicates a significant difference in DBH increment. The Wilcoxon signed-rank test gives P-values of P=<0.001 for all the individual relationships. This indicates that the relationships between all the different forest types are significant.

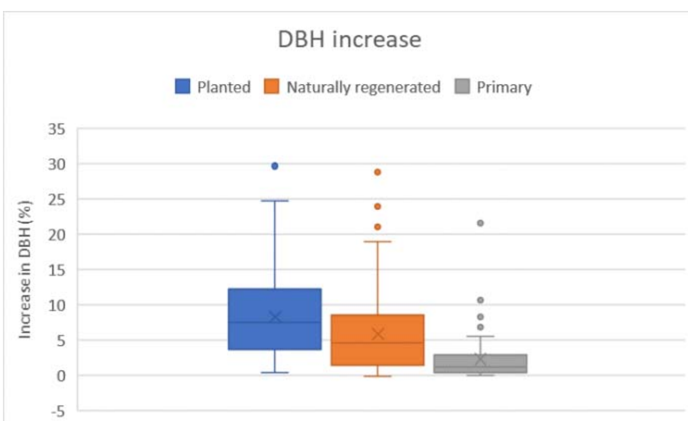

FIGURE 4: BOXPLOT OF THE DBH INCREMENT PER FOREST TYPE

5.3 TREE HEIGHT

The median tree height in the planted plots was 12.3 m, in naturally regenerated plots 12.4 m and in primary plots 15.5 m (Figure 9).

The Kruskal-Wallis test gives a P-value of P=0.0031 which indicates a significant difference in tree height between the forest types. Additionally, the Wilcoxon signed-rank test gives P-values of P=<0.0001 for all the individual relationships. Based on this, it can be stated that there is a significant different in tree height between all three forest types.

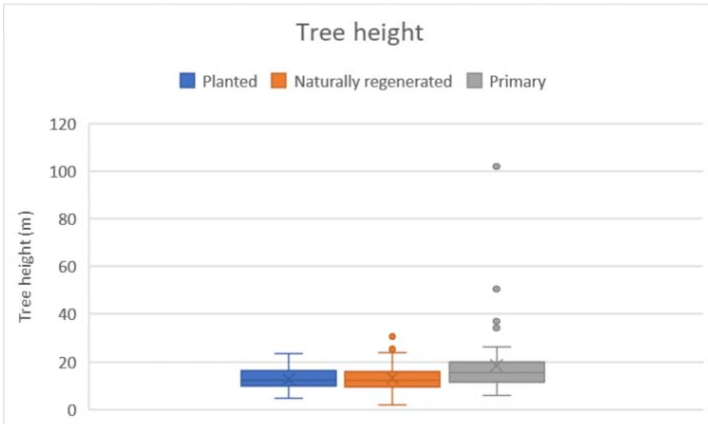

FIGURE 5: BOXPLOT OF THE TREE HEIGHT PER FOREST TYPE

5.4 TREE VOLUME

Trees within planted plots as well as naturally regenerated plots had a median volume of 0.30 m^3 compared to a median of 0.48 m^3 for primary forest plots (Figure 10).

The Kruskal-Wallis test gives a P-value of P=0.246 which indicates no significant difference in tree volume between the forest types.

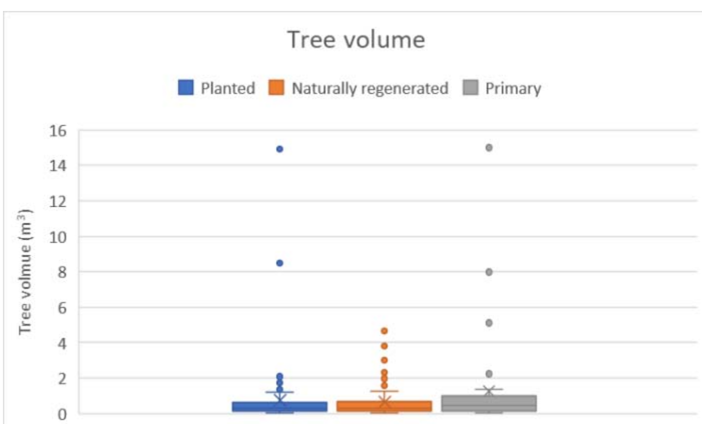

FIGURE 6: BOXPLOT OF THE TREE VOLUME PER FOREST TYPE

5.5 TREES PER HECTARE

Planted forest plots contain, on average, 20.3 trees, for naturally regenerated forest plots this number is 24.6 trees, and for primary forest plots 30.7 trees. Converted to trees per hectare this would be 413.3 trees per hectare for planted areas, 500.8 trees per hectare for naturally regenerated areas and 624.7 trees per hectare for primary forest areas (Figure 11).

The one-way anova test gives a P-value of P=0.4794 which indicates there is no significant difference in trees per hectare between forest types. Although the differences within primary forest plots are much smaller, and values generally higher, compared to naturally regenerated and planted forest plots.

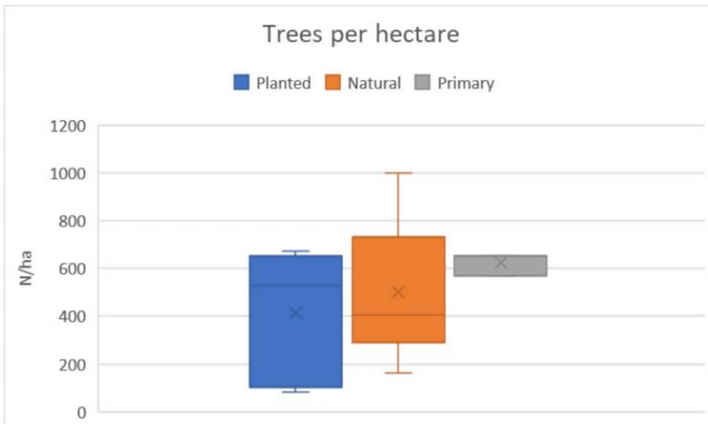

FIGURE 7: BOXPLOT OF THE NUMBER OF TREES PER HECTARE PER FOREST TYPE

5.6 CROWN CLASS

The Kruskal-Wallis test gives a P-value of P=<0.001 (9.433E-9) which indicates a significant difference between crown classes of the trees in the different forest types. Furthermore, the Wilcoxon signed-rank test gives P-values of P=<0.0001 for each individual relationship which indicates that each of these relationships is significant. So it can be stated that planted areas have the highest number of crown class 1, 2 and 3 trees with a mean value of 11.1, 9.4 and 7.7 trees per plot respectively (Figure 12). Primary forest areas contain the highest number of crown class 4 trees with a mean value of 14.0 trees per plot compared to 13.7 for planted and 6.6 for naturally regenerated forest.

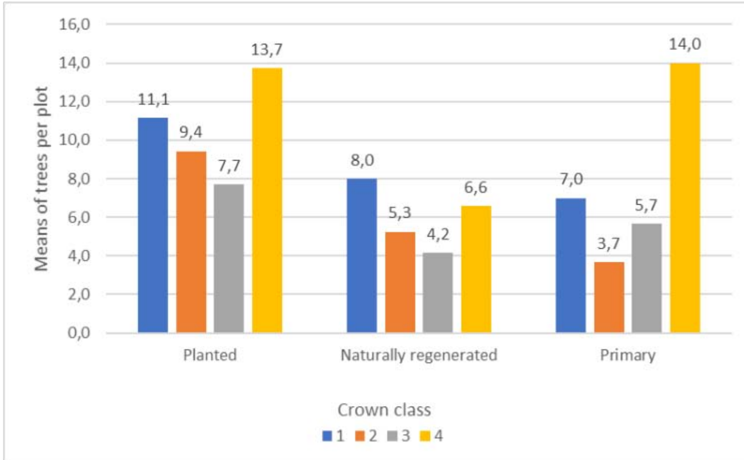

FIGURE 8: MEANS OF NUMBER OF TREES PER CROWN CLASS PER FOREST TYPE

5.7 CANOPY CLOSURE

Plots inside the planted area have a median canopy closure of 83.2% compared to a median of 88.2% for naturally regenerated and 93.9% for primary forest areas. Although it should be noted that naturally regenerated forest as well as planted forest have a much wider range compared to primary forest (Figure 13). All values range between 69.8% and 98.0%.

The one-way anova gives a P-value of P=0.142 which indicates there is no significant difference in canopy closure between forest types. Although, Figure 13 shows that primary forest plots generally have a higher canopy closure percentage than planted or naturally regenerated forest plots.

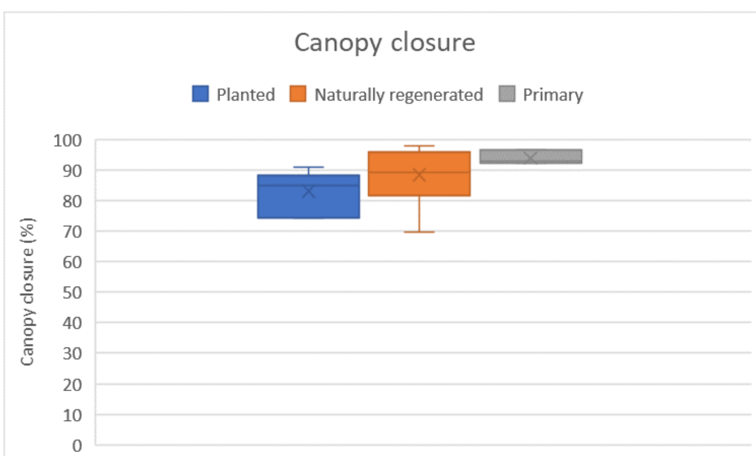

FIGURE 9: BOXPLOT OF THE CANOPY CLOSURE PER FOREST TYPE

5.8 WOOD SPECIFIC GRAVITY

The Kruskal-Wallis test gives a P-value of P=<0.0001 (1.06E-6) which indicates a significant difference in wood specific gravity (WSG) per forest type. In addition to this, the Wilcoxon signed-rank test gives P-values of P=<0.0001 which indicates that all the individual relationships between the forest types are significant. Based on this, it can be stated that primary forests have generally a higher WSG with a median of 0.50 g/cm³ compared to a median of 0.43 g/cm³ for naturally regenerated forest and a median of 0.21 g/cm³ for planted forests (Figure 14).

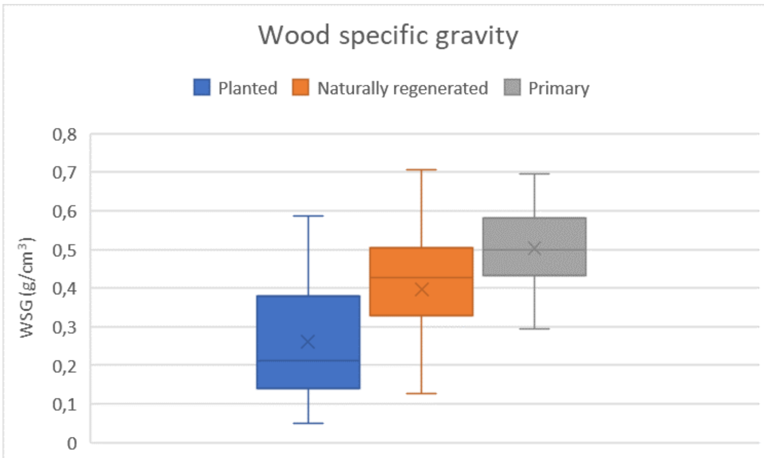

FIGURE 10: BOXPLOT OF THE WOOD SPECIFIC GRAVITY PER FOREST TYPE

5.9 WSG RELATIONS

Canopy closure

The linear regression gives a P-value of P=<0.0001 (2.644E-6) which indicates there is a significant correlation between WSG and canopy closure. This means that WSG increases with in an increase in canopy closure, although the relationship is weakly correlated (R^2=0.27). Even though Figure 15 shows there seems to be an optimum for WSG at a canopy closure of around 93%, more data is needed to say more about this.

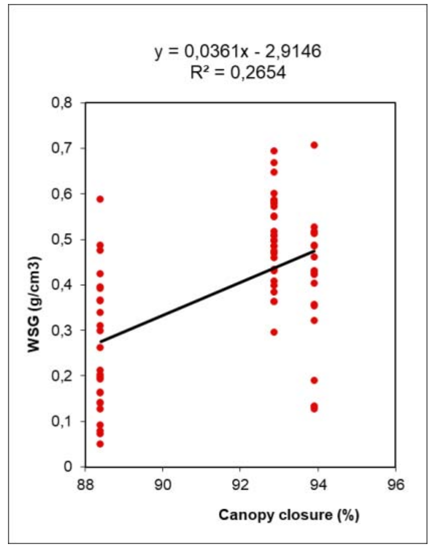

FIGURE 11: CORRELATION AND LINEAR REGRESSION BETWEEN WSG AND CANOPY CLOSURE

Crown class

The linear regression gives a P-value of P=0.0232 which indicates there is a significant correlation between WSG and crown class. Based on this, it can be stated that when crown class increases, or trees become less dominant, the WSG increases as well (Figure 16), although the relationship is very weakly correlated (R^2=0.07) So in general suppressed trees (crown class 4) were slightly more likely to have the densest wood.

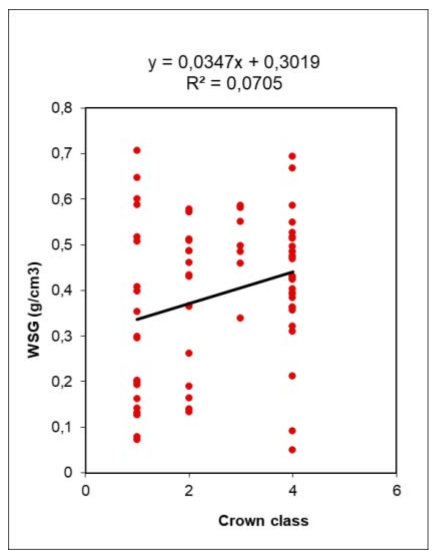

FIGURE 12: CORRELATION AND LINEAR REGRESSION BETWEEN WSG AND CROWN CLASS

Tree growth

The linear regression gives a P-value of P=0.0007 which indicates there is a significant correlation between WSG and DBH increase. Based on this, it can be stated that when the annual tree growth (DBH increase) is larger, WSG is lower (Figure 17), although the relationship is weakly correlated (R2=0.25). So fast growing trees have generally a lower wood density than slower growing trees.

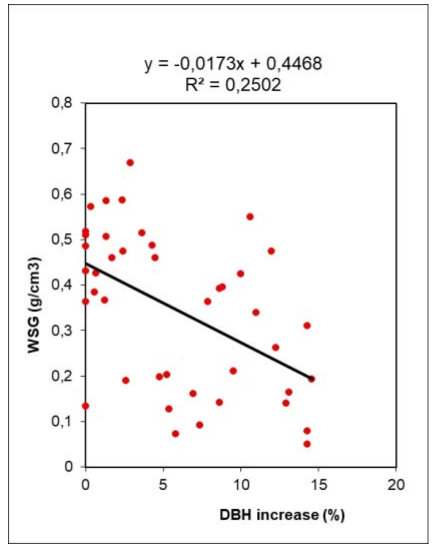

FIGURE 13: CORRELATION AND LINEAR REGRESSION BETWEEN WSG AND DBH INCREASE

6 CONCLUSION & DISCUSSION

Significant results were found for DBH increment, tree height, crown class and WSG. Primary forest has generally the highest trees and planted forest has a greater DBH increment and the most amount of crown class 1, 2 and 3 trees. This could be explained by the fact that primary forests are older and thus had more time to grow which results in taller trees. But these primary forests have already reached the climax stage in their succession, whereas the planted forests are still in the process of succession and have thus a higher growth rate.

Naturally regenerated forest has values that are more similar to the primary forest. For example, the results for DBH increment, tree height and WSG of naturally regenerated forest are more similar to those of the primary forest. This means that the structure of the naturally regenerated forest is more similar to primary forest than the planted forest. Or at least, is more likely to result in having the same forest structure as the primary forest sooner than planted forest.

The correlation analyses showed significant results for all correlations between WSG and DBH increment, crown class and canopy closure. WSG increases with both an increase in canopy closure and crown class, whereas WSG decreases with an increase in DBH increment. Although more data should be collected to be more certain about these correlations. This means that the hypothesis can be cautiously accepted because the correlations are not very strong, and the analysis was done with a relatively small set of data. So for any further research, increasing the database is highly recommended, as this will result in more reliable outcomes.

Taking all of the above into account, the main research question can be answered by the following statement: There is a difference in forest structure between planted, naturally regenerated and primary forest within Cloudbridge Nature Reserve. Although most results were not significant and differences usually not very big. This means that more emphasis should lie on the sub-questions instead of this main research question.

A point for discussion is the landslides in the area of Cloudbridge Nature Reserve. These have affected the forest structure and thus the results of this research. So for further research, it should be assessed if these areas are still representable for their forest type if a major part of the plot is located inside a landslide area. If not, these areas should for example be excluded or reclassified for further research. Anyway, it would still be interesting to keep these plots for monitoring the forest and the regeneration of these areas.

Further improvement to this ongoing research project could be made by looking more into the tree species. More analysis could be done by looking at species composition per forest type. Or, for example, by looking at correlations between tree species and WSG. It will be interesting for Cloudbridge Nature Reserve to know if planted or naturally regenerated forests are more similar to primary forest regarding tree species composition. Because the tree species in planted forests are mainly determined by humans.

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