Examensarbeten 2016:1

Fakulteten för skogsvetenskap
Institutionen för skogens ekologi och skötsel

Tree cover and tree traits affects soil carbon and soil compaction in Parklands in Central Burkina Faso

Photo: Gustaf Dal

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Tree cover and tree traits affects soil carbon and soil compaction in Parklands in Central Burkina Faso

Trädslutenhet och trädegenskaper påverkar markbundet kol och jordkompaktering i agroforestrylandskap i centrala Burkina Faso

Gustaf Dal

Keywords / *Nyckelord:*
Burkina Faso, soil, soil organic carbon, dry bulk density, parklands, trees, agroforestry, vegetation density, tree density

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Abstract

Burkina Faso is a country with an insufficient agricultural production and this is partly due to the fact that the population is growing and also because of environmental factors such as drought, erosion and poor soils. The most common agricultural system in this part of the world is the parkland which can be defined as farmlands with scattered well-grown trees. Trees contribute with soil organic material (SOM) which is the most common limiting factor for crop growth and which in turn improves soil fertility and water infiltration.

This study mainly aimed at identifying the correlation between tree cover and soil organic carbon (SOC) and dry bulk density (DBD). Different tree variables such as breast height diameter (dbh), crown width and species were also taken into account.

There were indeed correlations between the proximity to trees and SOC, even though the correlations were rather weak. The correlation strength varied between plots with low(>0-10%), medium(>10-40%) and high(>40%) vegetation densities based on normalized difference vegetation index (NDVI). The medium dense plots had the overall highest significant correlations between distance to trees and SOC (R^2=0.25 for both closest and next closest tree). The low density strata had no significant correlations between SOC and distance to trees. The high density plots had only significant correlations between second closest tree and SOC (R^2=0.086) and between “the dbh of the second closest tree divided by the distance to the same tree” and SOC (R^2=0.075). The correlation between SOC and NDVI was only almost significant with a P-value of 0.052. However, strata 4 had significantly higher SOC than strata 2 and 3.

DBD in general had higher correlation with distance to trees than SOC. The medium density vegetation plots however, had no significant correlations with DBD. There were significant negative correlations between DBD and both vegetation density (R^2=0.26) and tree density (R^2=0.25) respectively. In conclusion, there are significant correlations between both SOC and DBD with proximity to trees and different tree parameters even though they are rather weak. Since strata 4 had significantly higher NDVI, one can suggest that there some correlation between SOC and NDVI. This could in theory be used for SOC assessment with remote sensing techniques but more studies are needed on this topic.

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Introduction

Demography

Burkina Faso is a landlocked country in West Africa. Its land area is 274 000 km^2 and is inhabited by 17 million people which gives a population density of 62 people per km^2 (2011) (NE 2012). At the moment, Burkina Faso is among the poorest countries in the world by any standards (Gray 2004). About half of the population makes a living on 1 US dollar per day and mean life span is about 55 years for men and 57 years for women (NE 2012). Still the population is growing. After the independence in 1960 the population began to grow rapidly. In the eastern regions, an average growth of 4% percent a year has been recorded. This puts pressure on agriculture which in turn becomes more and more intensified. This causes lots of issues concerning land-use, water and natural resources (Gray 2004). Ninety percent of the population in 2009 was occupied by agriculture and this stands for 29% of the total GNP (NE 2012). Even though Burkina Faso is a land of agriculture, the food production is not enough for its population. Poor soils, drought and erosion make the land difficult to cultivate (NE 2012).

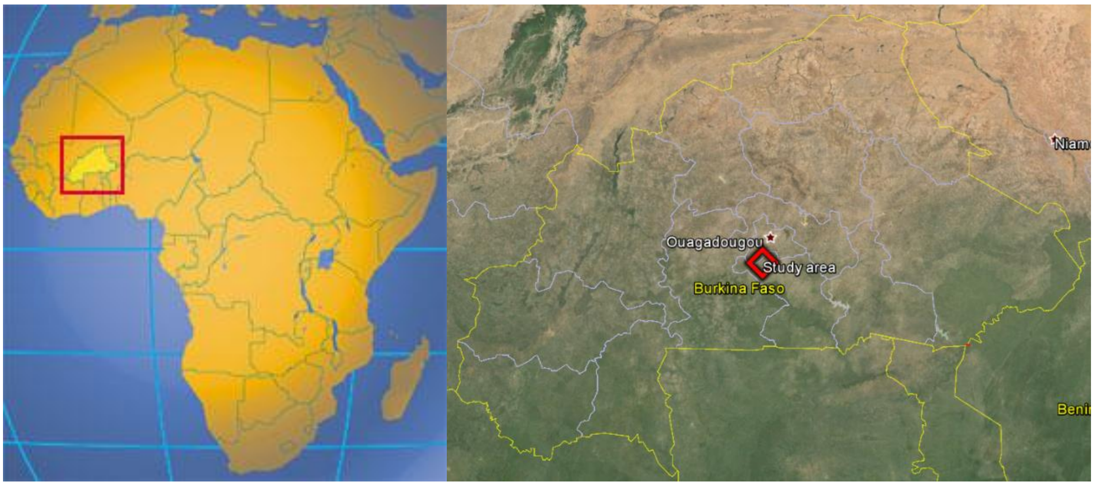

Figure 1: (Left fig) The location of Burkina Faso (nations online). (Right fig) The location of the study area (google earth).

Parklands

The most common agricultural system in these parts of the world is agroforestry parklands. Parklands in the African agricultural landscape are usually defined as, scattered trees in densities around and above 10% crown cover, with crops beneath and in between the trees (Gijsbers 2003). Another definition mentioned by Boffa (1999) is “deliberate retention of trees on cultivated or recently fallowed land”. Trees in parklands give many ecological services, such as food, fodder, firewood, building material, soil fertility, water conservation, medicines and other environmental protection just to mention a few (Boffa 1999).

The trees positive effects on soil are based on several mechanics such as “soil microbial activity and structure”, atmospheric inputs, nitrogen fixation, dung deposition, pre-existing soil fertility and management practices (Boffa 1999). There are many different cultivated tree species in parklands and a few dominating examples are *Vitellaria paradoxa* (Shea tree), *Adansonia digitata* (Baobab tree) and *Parkia biglobosa* (Néré).

Soil properties

Soil organic matter (SOM) is the most limiting factor for crop growth on semi-arid land (Bayala et al 2007). SOM is the main source of important nutrients such as P and N. Furthermore, SOM improves soil physical properties and importantly helps infiltration of rainwater and thus prevents runoff and erosion (Buresh RJ and Tian G 1997). According to a study on the origin of organic matter in parklands by Bayala et al (2007), trees are the dominating source of SOM. A previous MSc student was able to show a relationship between soil organic carbon (SOC) and the distance to trees in parklands in the community of Saponé which is located south of Burkina Faso's capital city Ouagadougou (Joelsson-Hedemyr 2012). From a global perspective, it's very interesting how much atmospheric carbon can be sequestered by trees and stored in the soil as SOM. Especially on dry-land soils that usually contain low amounts of carbon. These soils have great potential to sequester both organic and inorganic carbon if managed correctly by for example afforestation, grazing control, and water harvesting (Squires et al 1998; LAL 2003).

Little is known about the connection between SOC and other tree variables such as diameter breast height (dbh), crown width and species rather than just distance to trees, both as individual variables and combined. This study aims at filling this gap of knowledge. It also takes into account the vegetation and tree densities around the SOC-samples in order to assess their correlations with SOC. The vegetation density is based on normalized difference vegetation index (NDVI) which gives a percentage of vegetation cover over an area.

As water is becoming increasingly scarce with increasing demand in production of food and bioenergy, there is increasing doubt in policy and research about the overall synergy between trees and groundwater resources. Especially, there are worries that plantation of too many trees in landscapes with water scarcity problems can deplete the groundwater. This could cause water shortage and trade-offs between carbon sequestration and water resources in societies and agriculture (Jackson et al 2005, Malmer et al 2009). However, one problem is that most research made in the tropics on this topic is from closed forest plantations and the understanding of lower tree density landscapes mixed with agriculture is very low (Malmer et al 2010).

"Trees, carbon and water – trade-off or synergy in local adaptation to climate change" is a research project sponsored by SIDA. One of the project aims is to resolve the processes behind groundwater recharge from increased infiltration under trees and the larger water use by trees and to see how the balance is affected by different tree densities (trees, carbon and water project).

Objective and hypothesis

The objective of this study was to assess the relationship between SOC and the distance to trees in combination with size, spatial structure and density of trees using variables such as vegetation density (NDVI), tree density, dbh, species and canopy size.

The hypothesis was that SOC would increase and DBD decrease with increased tree dbh, canopy size and proximity of trees to the soil sample

This data can be used in further studies to determine the amount of soil carbon in parklands by looking at tree crown diameters and spatial vegetation/tree densities with remote sensing techniques at a landscape level.

Material and Methods

Area, location and spatial layout

The study area is located in Saponé which have a hot semi-arid climate and an altitude of 345m. The mean annual rainfall is 794 mm unevenly distributed over the year, August being the wettest and January being the driest month. Mean temperature is 27.6 °C (Climate-data.org).
The soils are nutrient poor sandy loamy regosols (Bayala et al 2002) and the most common crops are millet and sorghum which are usually cultivated without fertilizers (Bayala et al 2007).

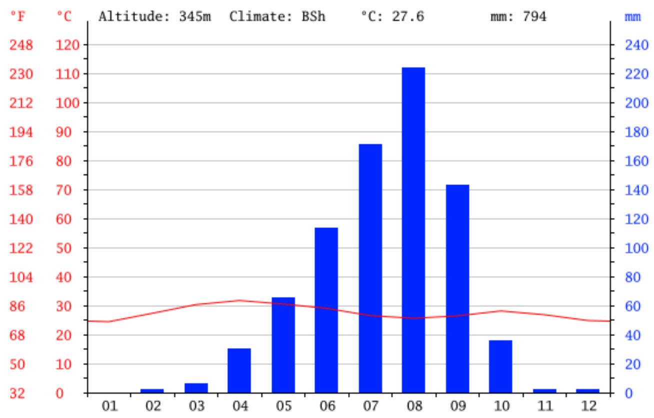

Figure 2: The monthly average temperature and rainfall for Saponé over the period 1982-2012. (http://en.climate-data.org/location/885895/)

Worldview-2 is a very high resolution sensor (VHR) with the potential to distinguish trees and other vegetation and thus collect tree cover data as well as vegetation densities (Cho et al 2012). In this study, Worldview-2 was used to collect vegetation density data over a 10 x 10 km area in Saponé. The working area was then divided into a grid consisting of 50x50m cells/pixels, each one having its own vegetation density. All the cells were then stratified into four different levels of vegetation density according to the Normalized Difference Vegetation Index (NDVI). 1 = no vegetation, 2 = low density (>0-10%), 3 = medium density (>10-40%) and 4 = high density (>40%) (figure 3). The data for NDVI were collected during mid-October. Density level 1 was not used as there were no trees to relate SOC and DBD with. I randomly picked 7 plots out of each of the strata 2-4 for a total of 21 plots. The webpage "random.org" was used for the randomizing. One important note is that the NDVI assess all sorts of vegetation and not just that of trees. This means that NDVI alone can´t define if an area is covered by trees or other vegetation such as bushes, grass and crops. Data on total crown cover during November-December 2012 were available for 17 of the 21 plots (Karlson 2012). The tree density is calculated by dividing the total crown cover for each plot by the total area of the plot (50*50 = 2500 m^2). The three stratifications based on NDVI had significantly differing vegetation density (Figure 4).

In each plot, soil sampling transect stretched from the center point to one of the four plot corners. The corners were arranged to north-west, north-east, south-west and south-east in relation to the center point. Direction of transects were determined by coin flipping. Along the transects, soil sampling was made in ten points with three meters interval with the first point at three meters distance from the center. Soil samples for SOC were taken on each of those ten spots. DBD samples however, were only taken for every third point, point nr 1, 4 and 7 (Figure 5)

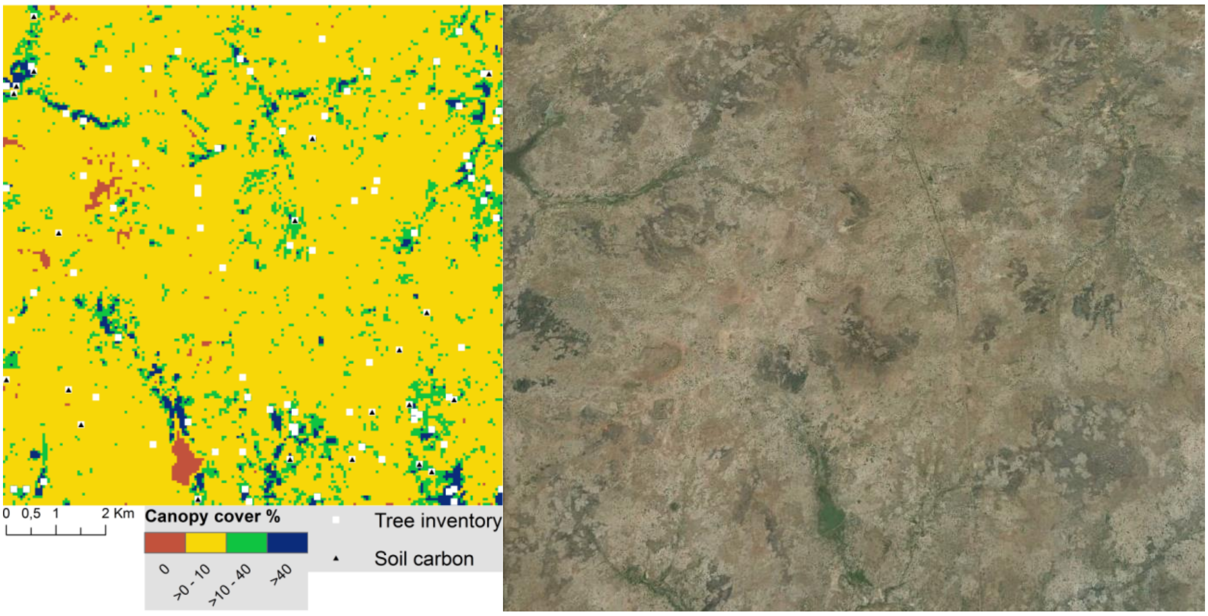

Figure 3: (Left fig) A worldview-2 image of the 10 x 10 km study area in Saponé. The white squares represent the field plots and the colors represent the four different stratifications of NDVI (Ostwald et al 2013). (Right fig) Satellite image over the study area (google earth).

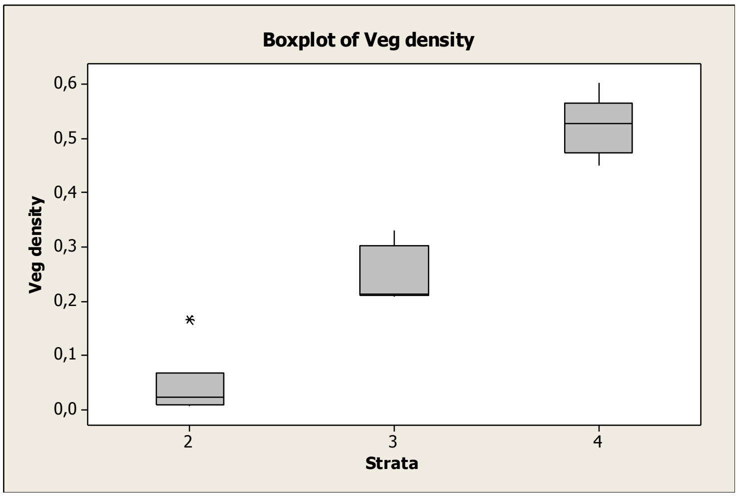

Figure 4: This boxplot visualizes the distribution of vegetation densities (% cover *100) within the different NDVI-based stratas in order to clarify that they are well separated in terms of NDVI. $P < 0.0001$ and $R^2 = 0.93$.

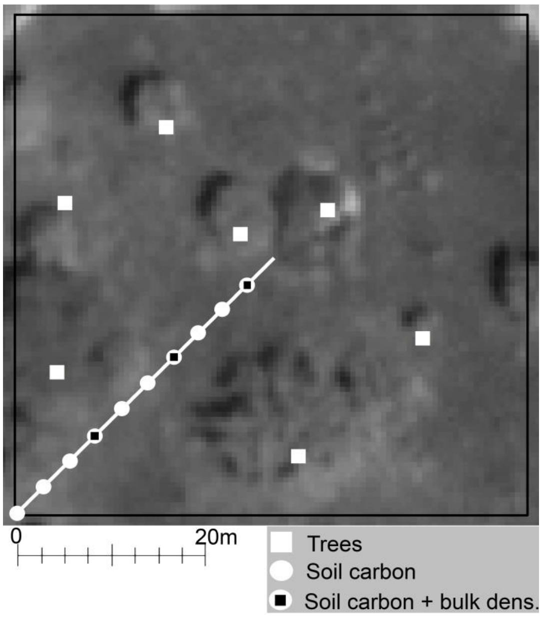

Figure 5: Plot design on a panchromatic image with a transect line for the soil samples which in this case has its direction randomized to south west. The white squares are trees, the white dots are sample points for SOC and the black squares are sample points for DBD. (Photo from Ostwald et al 2013)

Dry bulk density sampling

The soil samples for DBD were taken at 0-5 cm depth with 5 cm high metal cylinders. The metal cylinders had sharp lower rims and were carefully forced into the soil by hitting a piece of wood placed onto the cylinder with a hammer. The cylinder was then removed without losing sampled soil and the soil was either emptied into a plastic bag or stored in its cylinder depending on cylinder size. For the first 14 plots I used 200 ml cylinders which I emptied in plastic bags and reused. This was done because I did not have one cylinder per sample. For my last 7 plots I received and used smaller cylinders (100 ml). These small cylinders were in sufficient amount and possible to seal tight and could be used to transport and store samples until analysis. This possibly reduced error by reducing the number of times of transfer of soil, to maintain the correct volume sampled.

Soil organic carbon sampling

The procedure for SOC sampling was almost identical to the DBD sampling. For all SOC samples I used the big metal cylinder (5 cm high and 200 ml) and a double sample was taken for 0-10 cm depth. I first use the cylinder to take a sample for 0-5 cm depth and then I take another at 5-10 cm depth just underneath the first one. The two samples were added into the same bag and make up one sample for 0 – 10 cm depth.
For each of the 210 sample points, SOC samples have been taken but DBD samples however have only been taken on 63 of these 210 sample spots.

Morphological tree variables

From each sample point I measured the distance to the two closest trees. Those trees were then measured for dbh and canopy width, also the species and location of the trees were recorded. The DBH was measured with a DBH tape and trees with <5 cm DBH were excluded. To be able to compare trees with single and multiple stems, in each case, I converted the multiple stems into breast height surface area which I added together and then converted back to DBH as if it only had one stem. Figure 6 shows an example of a multi stem tree. The canopy width was measured by first measuring the maximum projection of the canopy width from edge to edge. I then rotated 90° around the exact center of the measured distance and measured once again from edge to edge (Figure 7). These two measurements are added together to become the data I use for analysis.

Fig 6: Mango tree with multiple stems at breast height.

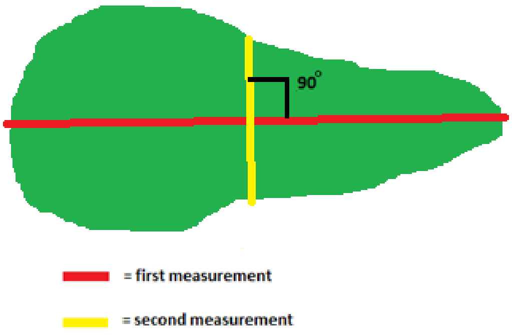

Figure 7: Example of a tree canopy from above and how the measurement band is held during the first and second measurement.

A local assistant identified the tree species and we recorded the trees location with GPS. It was not uncommon that the same tree was the closest or second closest tree for several of the sample spots in the same plot. Trees outside the plots were also measured if they were closest or next closest.

Soil organic carbon and dry bulk density analysis

The analyses for SOC and DBD were performed by "Bureau national de sols" in Ouagadougou. I dried the samples in an oven at 103 °C overnight to get the dry weight and calculated bulk densities by dividing the dry weight with the volume for each sample separately.
The SOC analysis was made by the use of Walkley and Black analysis which is a classic titration method for rapid analysis of organic carbon in soils and sediments (Walkley & Black 1934).

Statistical analysis

The statistical software minitab and excel were used for data analysis. One way Anova Tukey tests were used to see how SOC, DBD and other variables differed between the three stratas and also for carbon content between the four dominant tree species. Fitted line regressions were used for assessing the correlations between the continuous variables. The significance level was set at 95% for all tests.

Results

Tree density and NDVI analysis

Tree density had significant positive correlation with NDVI (Figure 8). When tree density is run through a tukey test with the stratifications of NDVI you will find that strata 4 (mean 0.29083) is significantly different from strata 2 (mean 0.653) and 3 (mean 0.1363). If BD is replaced by SOC in the previously mentioned regression, there is no significant correlation. I ran a tukey test for the summarized canopy width of the two closest trees as a function of NDVI stratifications and came to the result that strata 3 has the highest average (29.16) followed by strata 4 (27.88) and strata 2 (24.31). Strata 2 and 3 are significantly different from each other while strata 4 isn´t significantly different from either. It seems that intermediate NDVI has the trees with highest mean crown widths (Figure 9).

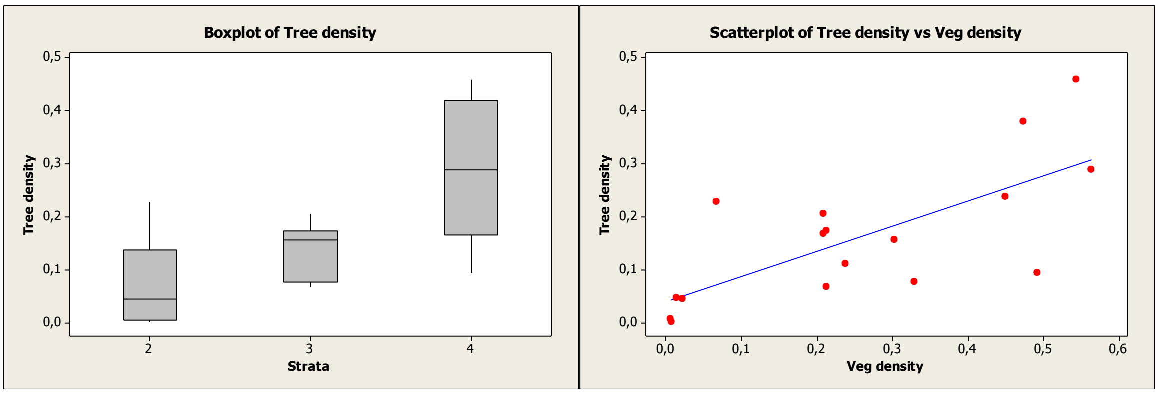

Fig 8: The two figures above shows the tree density as a function of NDVI (as boxplot of stratifications of NDVI to the left and as scatterplot of the plots NDVI to the right). For the boxplot P=0.007 and R^2=0.25, the standard deviations of tree density within strata 2, 3 and 4 are 0.0930, 0.0523 and 0.1391 respectively.

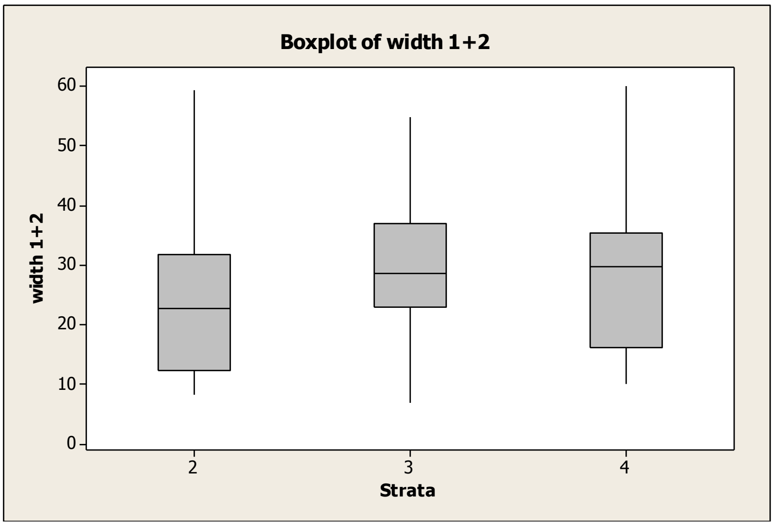

Fig 9: Boxplot of the distribution of crown widths of the two closest trees among the different stratas. P = 0.049 and R^2 = 0.02. This boxplot is based on all samples and not plot means. The standard deviations within strata 2, 3 and 4 are 13.85, 9.70 and 12.13 respectively.

Dry bulk density in relation to vegetation and trees

The mean DBD (g/cm^3) in strata 2 (1.5350) was significantly higher than the mean DBD from strata 4 (1.3854)(figure 10). The DBD in strata 3 (1.3449) however was not significantly different from either 2 or 4.

The DBD decreased significantly with increased vegetation density (Figure 11) but with very high variation which gave a low R^2 value of the linear regression.

There was a negative correlation between dry bulk- and tree densities (Figure 12). For this data set, four out of 21 plots were missing data on tree density. Also, in this case variation was high but the linear relation significant. DBD had a significant negative correlation with the logarithm of tree density multiplied by NDVI (figure 13).

Table 1 summarizes the R^2- and P-values of all analyzes based on DBD as a function of different tree variables and distances. There was a significant relationship between DBD and the distance to closest tree (figure 14). DBD had a significant relationship with next closest tree. Within Strata 3 alone, DBD did not have a significant relationship with distance to any of the two trees (Table 1). The correlation was strongest within strata 2 for both trees respectively and combined as functions of DBD.

Significant relationships between "crown-width divided by distance to tree" and DBD could be proven for both closest and next closest tree (figure 15). However, no strata by itself showed significant correlation between DBD and "crown-width divided by distance to tree" for second closest tree. Within strata 3 alone, DBD did not have a significant relationship with "crown-width divided by distance to tree" to any of the two trees (Table 1).

DBD had significant relationships with "dbh divided by distance to tree" to closest and next closest tree (figure 16). Strata 3 alone showed no significant relationship between DBD and "dbh divided by distance to tree" for any of the two trees (Table 1).

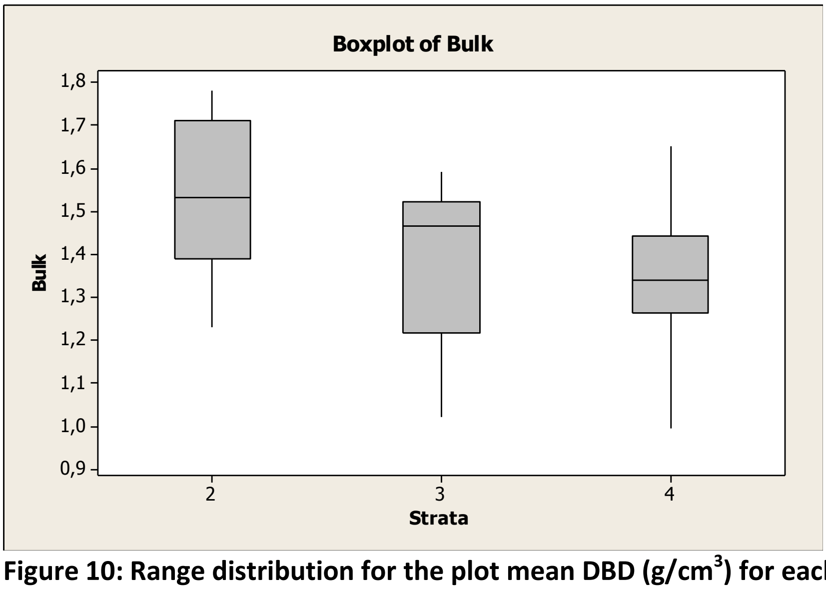

Figure 10: Range distribution for the plot mean DBD (g/cm^3) for each strata. P = 0.029 and R^2 = 0.25. This boxplot is based on plot means. Strata 2 and 4 are significantly different from each other while strata 3 is not significantly different from any of the other stratas. The standard deviation for strata 2, 3 and 4 are 0.1658, 0.1091 and 0.0969 respectively.

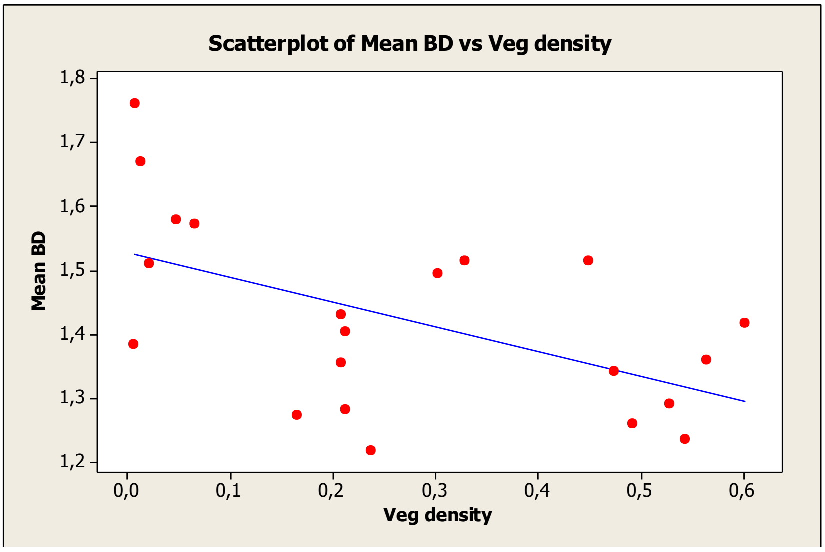

Figure 11: There is a significant relationship between DBD and vegetation density. P = 0.0011 and R^2 = 0.26. These are the mean values for each plot.

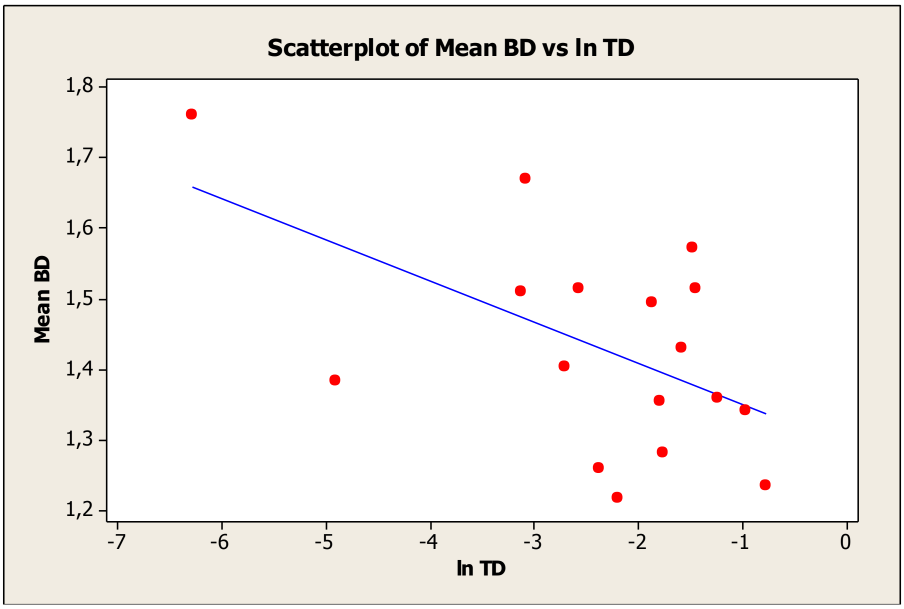

Figure 12: Plot mean DBD as a function of the logarithm of plot tree density. P = 0.025 and R^2 = 0.25.

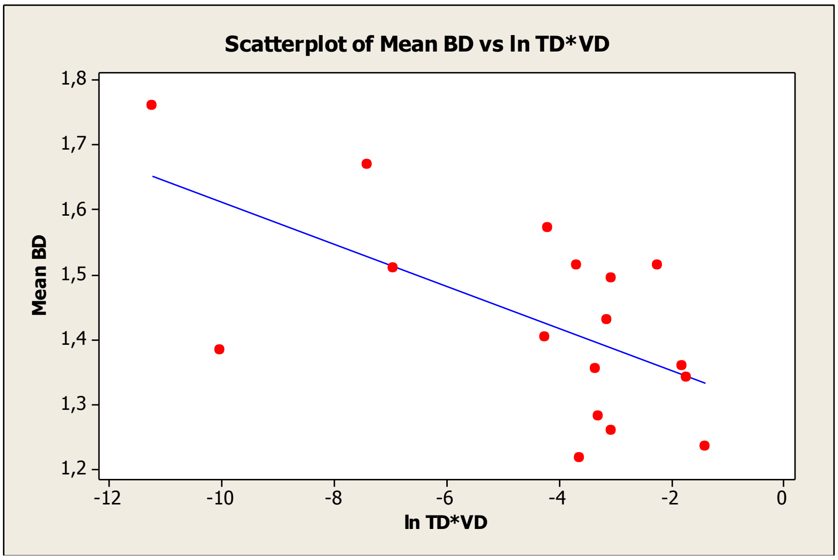

Figure 13: The scatterplot shows mean BD as a function of the logarithm of tree density multiplied by vegetation density. P = 0.01 and R^2 = 0.33.

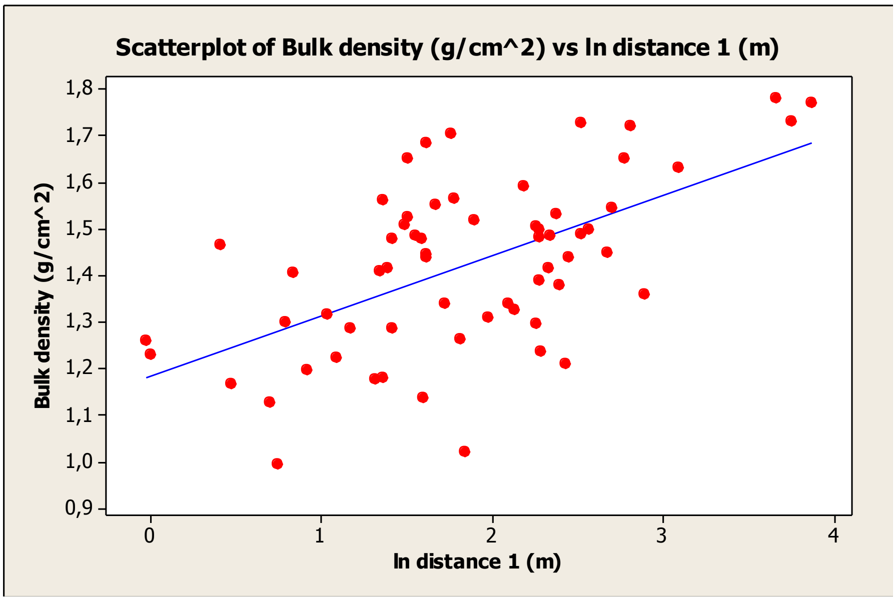

Figure 14: DBD as a function of the logarithmic distance to the closest tree gives P<0.0001 and R^2 = 0.33.

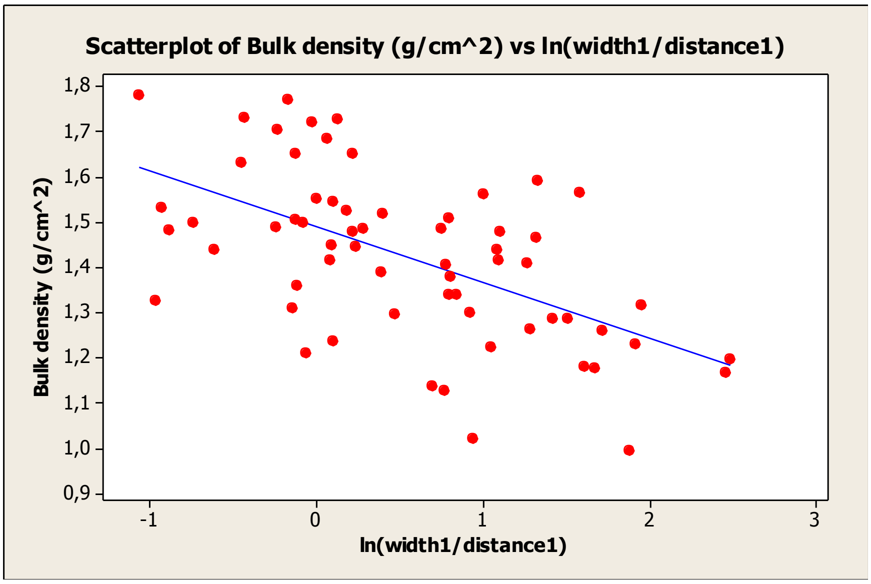

Figure 15: DBD as a function of the logarithm of canopy width divided by distance to the closest tree gives P<0.0001 and $R^2 = 0.31$.

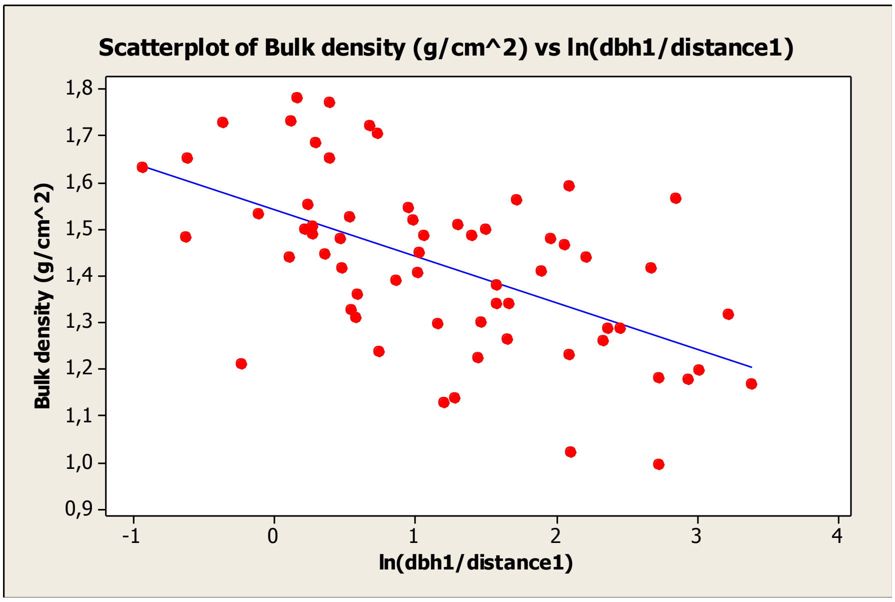

Figure 16: DBD as a function of the logarithm of dbh divided by distance to the closest tree gives P<0.0001 and $R^2 = 0.31$.

Table 1: This table collects the P- and R2-values of all combinations of bulk density (BD) as a function of the logarithmic distance (D) to closest (1) and next closest (2) tree. This is also done for crown width (W) and stem diameter at breast height (dbh) divided by distance respectively. Bulk density is categorized as total bulk density and bulk density for each strata individually. The R2-values are expressed as percentages.

		ln **D1**	ln **D2**	ln **W1/D1**	ln **W2/D2**	ln **Dbh1/D1**	ln **Dbh2/D2**
BD	**P**	**0**	**0**	**0**	**0**	**0**	**0**
	R2	**32.5**	**19.2**	**31.4**	**18.5**	**30.5**	**26.1**
BD S2	**P**	**0.001**	**0.017**	**0.001**	0.165	**0.002**	0.099
	R2	**40.5**	**22.7**	**39.7**	5.1	**38**	9.1
BD S3	**P**	0.175	0.493	0.344	0.468	0.49	0.216
	R2	4.7	0	0	0	0	3.1
BD S4	**P**	**0.044**	0.351	**0.006**	0.095	**0.001**	**0.007**
	R2	**15.4**	0	**29.6**	9.4	**39.7**	**29.2**

SOC concentration in relation to vegetation, trees and dry bulk density

There was some variation in mean SOC concentration around different species of trees. The four most common tree species as the closest tree are the following, vitellaria paradoxa (23), parkia biglobosa (19), lannea microcarpa (15), eucalyptus camaduensis (10). Each number represents the code for each species used in analyzes. Lannea microcarpa has significantly higher mean SOC content (10.02%) than eucalyptus camaduensis (5.272%) and vitellaria paradoxa (7.313%), See figure 17 and table 2.
There was some difference in mean SOC concentration between the different stratas. However, only strata 4 (1.1793%) was significantly different from both strata 2 (0.6865%) and 3 (0.7741%)(figure 18). Even though there were some significant difference between the stratas, no correlation could be proven for the relationship between SOC concentration and vegetation density, though it was close to significant with a P-value of 0.052 (figure 19).
There was a weak correlation between SOC concentration and distance to both closest (figure 20) and next closest tree. Strata 3 gave much higher correlations than strata 2 and 4 for this kind of analysis. Table 3 summarizes the R^2- and P-values of all analyzes based on SOC as a function of different tree variables and distances.
Tree crown-widths divided by distance to trees gave significant positive but weak correlations with SOC (figure 21). Second closest tree had almost twice as strong correlation with SOC when compared to closest tree. Strata 3 gave much higher correlations between SOC and “tree crown-widths divided by distance” than strata 2 and 4.
Tree dbh divided by distance to trees gave significant but rather weak positive correlations with SOC concentration (figure 22). This correlation was about three times stronger with the second closest tree than the closest tree. Strata 3 gave much higher correlations between “Tree dbh divided by distance to tree” than strata 2 and 4. SOC had a significant negative correlation with DBD (figure 23).

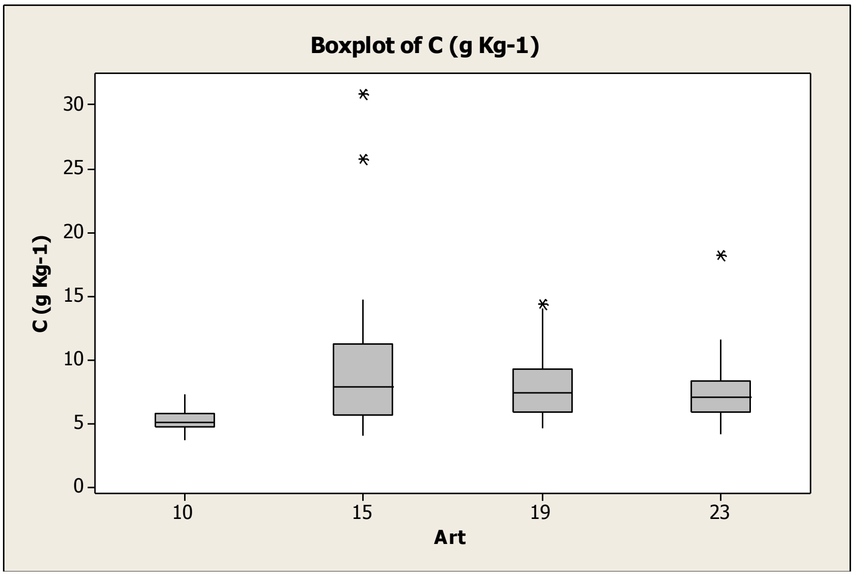

Figure 17:. A boxplot showing the distribution of SOC for each of the four major tree species. P = 0.001 and R^2 = 0.11. The tree species are vitellaria paradoxa (23), parkia biglobosa (19), lannea microcarpa (15) and eucalyptus camaduensis (10).

Table 2: This table shows the mean SOC for each of the major four tree species. vitellaria paradoxa (23), parkia biglobosa (19), lannea microcarpa (15) and eucalyptus camaduensis (10). "N" is the number of sample points that has the given tree as the closest. Many trees are closest tree for more than one sample point, so "N" ≠ number of trees. Different letters under grouping means that the species are significantly different.

Species	N	Mean	Grouping	StDev
10	17	5.272	B	0.931
15	18	10.02	A	7.21
19	23	8.099	A B	2.729
23	65	7.313	B	2.189

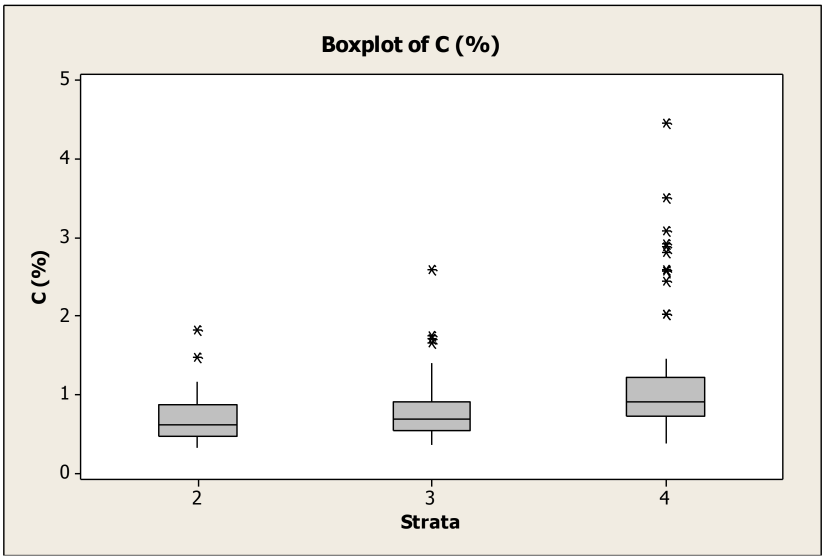

Figure 18: Tukey test of carbon content as a function of the different stratas. Strata 4 is significantly different from Strata 2 and 3. P < 0.0001 och R^2=0.13. The standard deviation for strata 2, 3 and 4 are 0.2759, 0.3662 and 0.8097 respectively.

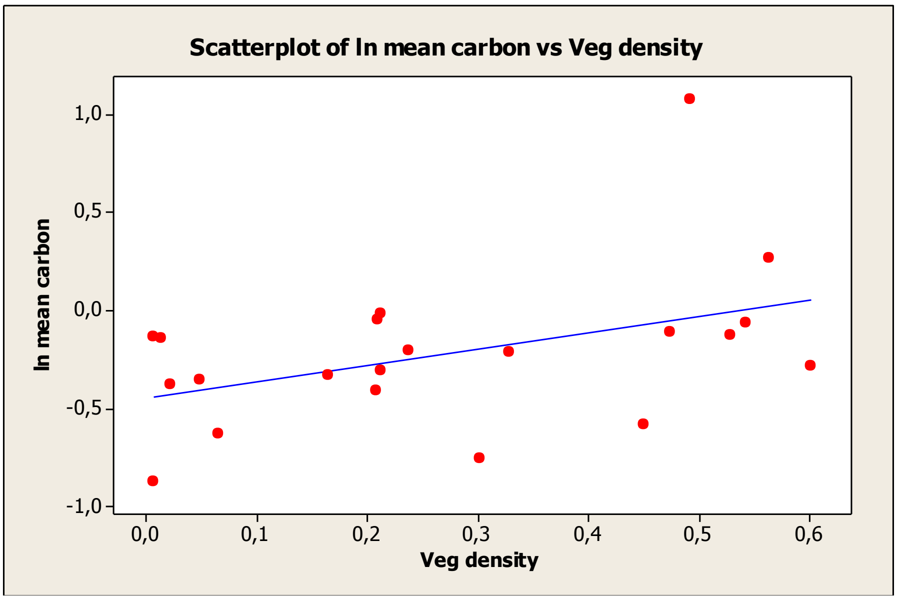

Figure 19: The logarithm of the carbon content as a function of vegetation density. Close to significant. P = 0.052 and R^2= 0.14.

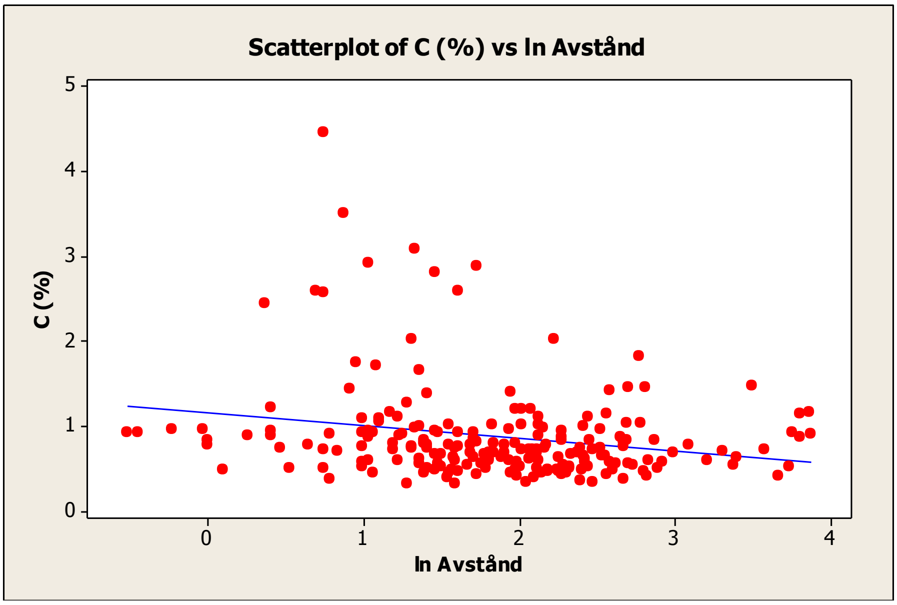

Figure 20: The carbon content against the logarithmic distance to closest tree gives P = 0.002 and $R^2 = 0.04$.

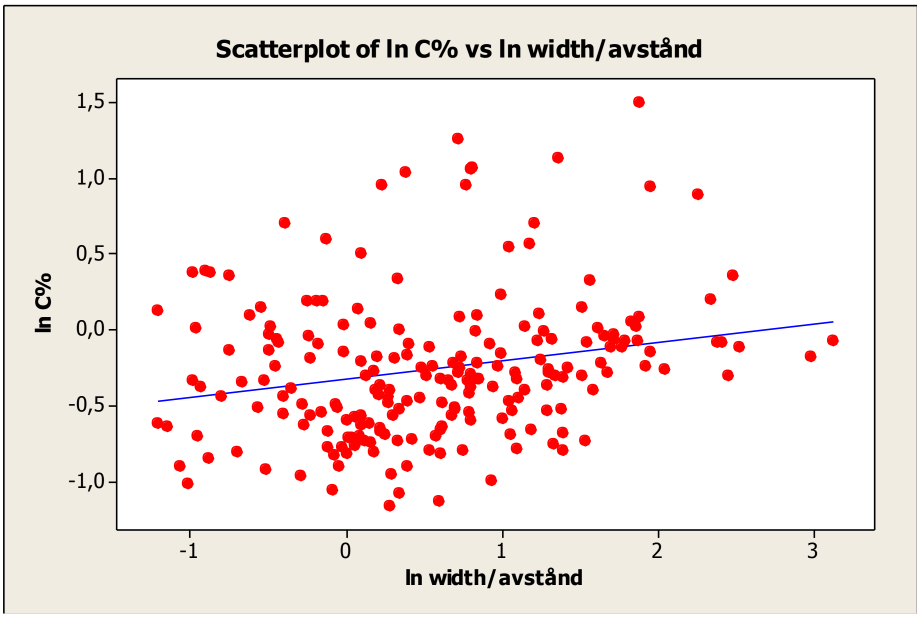

Figure 21: The logarithm of the carbon content against the logarithmic width divided by the distance to the closest tree. P = 0.001 and $R^2 = 0.05$.

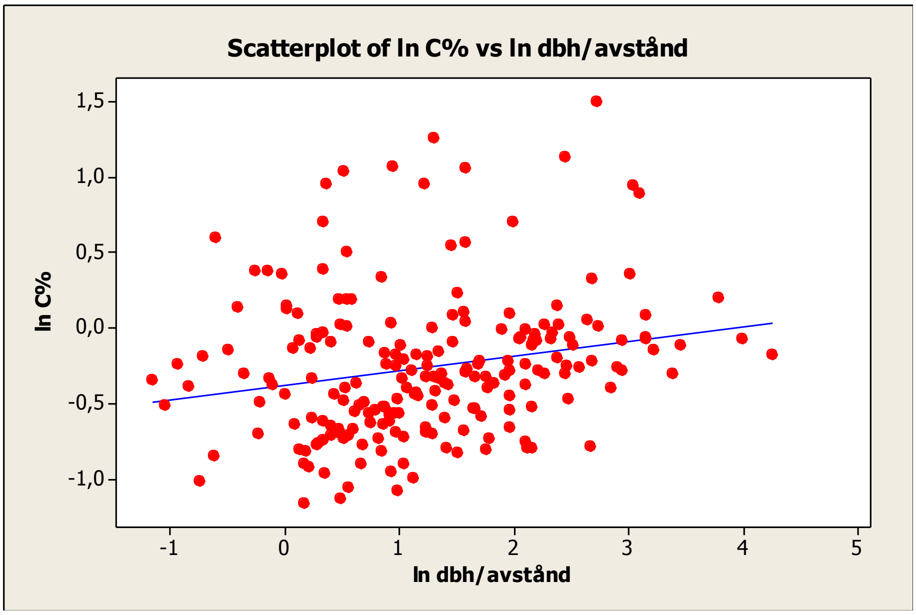

Figure 22: The logarithm of the carbon content against the logarithm of the dbh divided by the distance to the closest tree. P = 0.002 and R^2 = 0.04.

Table 3: This table collects the P- and R2-values of all combinations of soil organic carbon (SOC) as a function of the logarithmic distance (D) to closest (1) and next closest (2) tree. This is also done for crown width (W) and stem diameter at breast height (dbh) divided by distance respectively. Soil organic carbon is categorized as soil organic carbon for all stratas together and soil organic carbon for each strata individually. The R^2–values are expressed as percentages.

		ln D1	ln D2	ln W1/D1	ln W2/D2	ln Dbh1/D1	ln Dbh2/D2
SOC	**P**	**0.002**	**0**	**0.001**	**0**	**0.002**	**0**
	R2	**4.2**	**6.3**	**4.7**	**8.5**	**4.1**	**12.6**
SOC S2	**P**	0.119	0.279	0.502	0.883	0.164	0.178
	R2	2.1	0.3	0	0	1.4	1.2
SOC S3	**P**	**0**	**0**	**0.001**	**0.007**	**0.007**	**0.017**
	R2	**25**	**24.8**	**12.8**	**9.1**	**8.8**	**6.7**
SOC S4	**P**	0.147	**0.008**	0.701	0.24	0.555	**0.013**
	R2	1.6	**8.6**	0	0.6	0	**7.5**

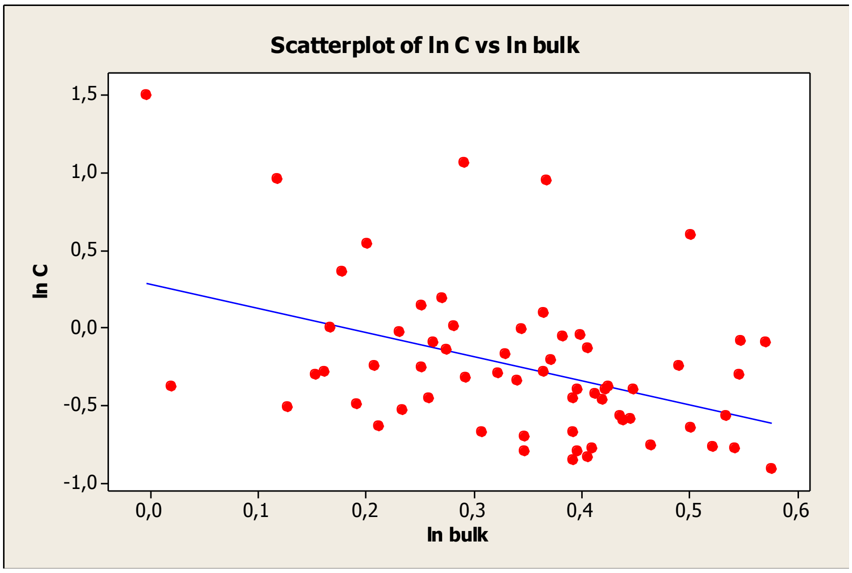

Figure 23: The logarithm of the carbon content as a function of the logarithm of DBD. P =0.001 and R^2 = 0.16.

Discussion

Dry bulk density

For the DBD analysis, the third strata gave insignificant relationships with low explanation rate in relation to dbh, canopy width and distance for both closest and second closest trees. Meanwhile strata 2 and 4 gave very strong and significant correlations overall. So for some reason there were little to zero correlation between DBD and distance to trees in strata 3. One speculation is that the density of trees in strata 3 causes the plot to have rather homogenous DBD. When you deviate from this homogeneity by adding or subtracting trees (going towards strata 2 or 4) the homogeneity stops and variations correlated with distance to trees becomes more evident (figure 24). It seems that dbh is the most important factor for DBD in strata 4. One theory is because the distance to trees always is rather small in strata 4 and most of the soil is affected by green mass because of the high NDVI. By adding dbh as a variable, it might give some ideas of the temporal perspective. How long time there has been trees in the plot for example. This pattern cannot be seen when doing the same analysis for SOC instead of DBD.

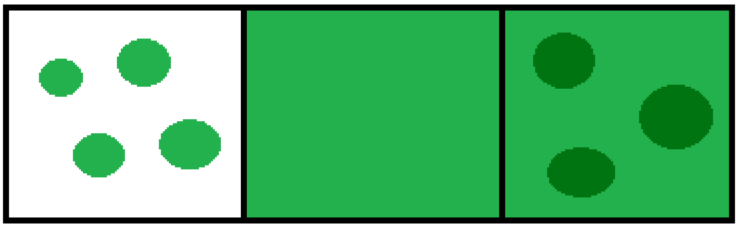

Figure 24: Conceptual figure of tree influence on DBD. Different shades of green symbolize different densities of tree influence on DBD of the soil.

Soil organic carbon

Similar to the DBD analysis, SOC analysis showed similar patterns when comparing different NDVI stratifications correlations with distance to trees. However, in this case strata 3 were the strata with the strongest overall correlations and significance levels. Strata 2 had zero significance and strata 4 were mostly insignificant. In other words, SOC and DBD analyses are each others opposites when it comes to the level of significance between different stratas.

One theory why strata 3 is more significant than both 2 and 4 for SOC could be that the areas of influence from trees are so minor in strata 2 and that the area influence from the many trees in strata 4 causes the whole plot to become evenly influenced and thereby homogenous. Strata 3 on the other hand has a tree density that causes enough influence while not becoming overwhelming, thus finding a balance that can be correlated (figure 25). Also note that the trees are often in clusters and not always evenly distributed over the plots. Clusters of trees causes more tree influence than single trees so the correlation with distance becomes more evident.
DBD have overall stronger significance and correlations with tree influence than SOC. That could be an explanation why some stratas give better correlation with SOC and some with DBD. They require different tree densities to reach homogenous tree influence over the whole plot.
For some reason, the next closest tree gives higher correlations with SOC than the closest tree when analyzing all the stratifications together as one, However, when divided into the three different

stratifications, stratification 3 closest tree correlation exceeds that of the next closest tree, This is probably more truthful since stratification 3 is the most significant stratification as previously mentioned.
There is a significant correlation between SOC and DBD which is reasonable since they are both affected by tree influence. The correlation is rather weak however.

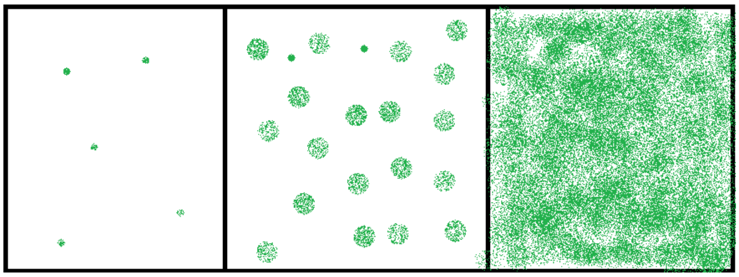

Figure 25: Conceptual figure of tree influence on SOC. The green area represents the tree influence on SOC in the soil.

Canopy width vs strata

Few trees with lots of space are allowed to grow wider (strata 2) but strata 3 and 4 should be more supporting for tree growth. The result showed that trees in strata 3 had slightly wider crowns (significantly different from strata 2 but not from 4). However, the correlation is rather low and the level of confidence is barely significant ($P = 0.049$ and $R^2 = 1.94\%$). The width of tree crowns may be higher by average in strata 3 but so is the variation. When a forest becomes dense enough, trees will go for height rather than width to be able to compete for sunlight.

Variability in relation to design

In general

It is difficult to measure the total tree influence on a soil sample when only taking into account the two closest trees. Because as you get closer to some trees you also increases distance to others. This becomes more evident in the plots with higher tree densities. Also, beyond the two closest trees there is a huge blind spot, there could be a jungle there or no trees at all, you only get a hunch from the NDVI and eventual tree density. Perhaps it would have been better if each soil sample point had a constant radius in which total tree influence were measured. This would require lots of tree measuring for each soil sample, especially in high tree density plots. For the next study in this topic, it would be a good idea to use the already total inventoried plots if they haven't changed too much over the last few years.

Tree species and translations

The two tree species with the highest mean SOC among the four major tree species are Lannea microcarpa (10.02) and parkia biglobosa (8.099). Parkia biglobosa has a positive effect on the soils P and organic C contents (E O Uyobisere & K A Elemo 2002). Lannea microcarpa has no known remarkable effect on SOC and yet it has the highest mean SOC in this study, it also has the highest standard deviation of 7.21 which is much more than the second highest of 2.729.

Lannea microcarpa and parkia biglobosa are not significantly different from each other and parkia biglobosa is not significantly different from any of the other two major tree species as well.

Tree and vegetation density

High vegetation density plots can be covered by trees but they can also be covered in brushes, crops and high grass. Some plots have veg-dens < tree-dens, which should be impossible since tree-dense is already added to veg-dense. There are a few possible explanations, some plots may have been harvested between dates for veg-density and tree-density data collections. Or, seasonal changes in vegetation and tree green mass could have changed during the same interval. Also, some trees like adansonia digitata, lannea microcarpa and lannea acida are leafless during the time of measurement. The crown is still measured even though it has no leaves and this can cause tree-density > veg-density.

One can ask what effects there would have been on the strata based results if the NDVI ranges had been different. For example, most of the study area is covered by strata 2 density areas and this could have been more specified if strata 2 were divided into two or more stratas with more narrow NDVI ranges. Note that the difference of just 1% NDVI within a strata 2 plot has a much greater impact than it would have had in the other stratas.

Tree density data is missing for 4/21 plots (plot nr 404, 421, 219 and 227). This is because the plots were shared with another study. That study, conducted by Martin Karlson included the data collection for tree densities in roughly 100 plots. Some of those plots were never inventoried and among those were four of my plots.

One uncertainty is the measurement of tree variables when the trees have been pruned. It can be a tree with enormous trunk but it has no branches, this can give somewhat misleading results when trying to determine tree influence (Picture x and x). In my plots, 7% of the trees had been pruned with varying intensity. This estimate is based on the number of pruned trees divided by the total number of trees among both closest and next closest trees.

Figure 26: Pruned trees in a more dense vegetation plot (left photo) and a pruned tree in a less dense vegetation plot (right photo).

Dry bulk density sampling

When collecting the samples for DBD it is very important that you are careful in order to not affect the density by accidently compressing the soil. There is always a risk that we haven't been that careful, especially early on when we weren't that good at it. Also, a few samples may have been swapped within a plot during sampling. However, I doubt this has caused any problems with my data.

SOC sampling

Wood splinters could have ended up in the SOC samples from pieces of wood used to force the metal cylinders into the soil. This can increase the amount of SOC within the affected samples. This risk was much higher for the soils with hard pan more commonly found in strata 2 (Figure 27).

Figure 27: Leonard is taking the last sample from the soil with hard pan (left photo). You can see that the metal cylinder have been crooked (right photo).

Conclusions

Just like hypothesized, there are significant correlations between both SOC and DBD with proximity to trees and different tree parameters. There is lots of variation however, especially considering SOC. The correlation strengths also differ a lot between NDVI based stratifications and if it's the closest or next closest tree.

Tree influence based on distance, dbh and crown width had much higher correlation with DBD than with SOC, there were however differences between the stratas. For DBD analysis, stratification 3 were much less significant and with weaker correlations than the other two. For SOC analysis it is the other way around and thus strata 2 and 4 gave stronger and more significant correlations.

There is a significant correlation between DBD and tree density. SOC on the other hand have no significant relationship with tree density.

Vegetation density have a significant relationship with DBD but only almost with SOC (P=0,052). However, strata 4 have significantly higher mean SOC content than strata 2 and 3. This indicates that there is some positive correlation between vegetation density and SOC which in theory could be used for calculating SOC storage with remote sensing techniques. However, the estimates will probably be very rough. More studies on this subject could be useful.

SOC and BD have weak but significant correlation with each other.

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Personal communication

Martin Karlson (2012)

Appendix with equations

Figure 4, Boxplot of vegetation density among stratas:

Strata	N	Mean	Grouping
4	7	0,52186	A
3	7	0,24429	B
2	7	0,04671	C

$P<0{,}0001$ $R^2=93{,}25\%$

Figure 8, Boxplot of tree density among stratas:

Strata	N	Mean	Grouping
4	5	0,29083	A
3	7	0,13630	B
2	5	0,06530	B

$P=0{,}007$ $R^2=44{,}14\%$

Figure 8, Scatterplot of tree density vs vegetation density:
"Tree density = 0,0403 + 0,471 Veg density" P=0,001 R^2= 48,3%.

Figure 11, Scatterplot of mean DBD vs vegation density: **"**Mean BD = 1,53 - 0,386 Veg density" P=0,011 R^2=25,6%

Figure 12, Scatterplot of mean DBD vs the logarithm of tree density: "Mean BD = 1,29 - 0,0580 ln TD" P=0,075 R^2=14,3%

Figure 13, Scatterplot of mean DBD vs the logarithm of tree density multiplied with vegetation density: "Mean BD = 1,29 - 0,0323 ln TD*VD" P = 0,01 R2 = 32,8%

Figure 14, Scatterplot of DBD vs distance to closest tree: "Bulk density (g/cm^2) = 1,18 + 0,130 ln distance 1 (m)" P<0,0001 R^2=32,5%.

Figure 15, Scatterplot of DBD vs the logarithm of the width of the closest tree divided by the distance to the same tree: "Bulk density (g/cm^2) = 1,49 - 0,123 ln(width1/distance1)" P<0,0001 R^2=31,4%.

Figure 16, Scatterplot of DBD vs the logarithm of the DBH of the closest tree divided by the distance to the same tree: "Bulk density (g/cm^2) = 1,54 - 0,0998 ln(dbh1/distance1)" P<0,0001 R^2=30,5%.

Figure 17, Boxplot of SOC among tree species:

Art	N	Mean	Grouping
15	18	10,018	A
19	23	8,099	A B
23	65	7,313	B
10	17	5,272	B

P= 0,001 R^2=11,04

Figure 18, Boxplot of SOC among stratas:

Strata	N	Mean	Grouping
4	70	11,793	A
3	70	7,741	B
2	70	6,855	B

$P<0{,}0001$ $R^2=13{,}14\%$

Figure 19, Scatterplot of the logarithm of SOC vs Vegetation density: “ln mean carbon = - 0,445 + 0,828 Veg density” P = **0,052** R^2=14,1%

Figure 20, Scatterplot of SOC vs distance to closest tree: “C (%) = 1,15 - 0,148 ln Avstånd” P = 0,002 R^2=4,2%.

Figure 21, Scatterplot of SOC vs the logarithm of the width of the closest tree divided by the distance to the same tree: “ln C% = - 0,330 + 0,122 ln width/avstånd” P = 0,001 R^2=4,7%.

Figure 22, Scatterplot of SOC vs the logarithm of the DBH of the closest tree divided by the distance to the same tree: “ln C% = - 0,381 + 0,0981 ln dbh/avstånd“ P = 0,002 R^2=4,1%.

Figure 23, Scatterplot of the logarithm of SOC vs the logarithm of DBD: “ln C = 0,281 - 1,55 ln bulk” P =0,001 R^2=16,1%

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