OIL PALM PLANTATIONS IN SAVANNAS: IMPACT ON BIOMASS CARBON STOCKS AND SOIL ORGANIC CARBON (SOC) DYNAMICS

MASTER THESIS IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR A MASTER DEGREE IN ENVIRONMENTAL SCIENCES AT ETH ZÜRICH

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ABSTRACT

Expanding oil palm (*Elaeis guineensis*) plantations in areas of grasslands rather than at the expense of forests promises to be a more sustainable land-use change regarding biodiversity and carbon balance. While it is rather evident that carbon storage in biomass will increase with a land-use change from grassland to oil palm, effects on carbon cycling in soil and biological activity, affecting the carbon storage capacity of soils under oil palm, are unclear. In the Llanos Orientales (Eastern Plains) of Colombia, the agricultural frontier is expanding into natural savannas with a high share of oil palm plantations. The first part of this thesis aims to quantify carbon storage in above- and belowground biomass of oil palm (OP) plantations and natural savannas (NS) in the area of the Llanos Orientales in Colombia. It is hypothesised that carbon stored in an oil palm plantation (as an average over the whole plantation life-cycle) is higher than carbon stored in natural savannas. In the second part of this thesis the aim is to investigate carbon cycling mechanisms inside oil palm plantations that influence carbon storage in soil organic carbon (SOC) and affect soil fertility. The hypothesis is that those mechanisms depend on carbon input and management patterns inside plantations, thus that management influences the carbon storage function of soil under oil palm.

Above- and belowground biomass were assessed in savannas and oil palm plantations of 2, 4 and 9 years. Using allometric equations, biomass of oil palm trees was estimated for a whole life-cycle of oil palm plantation (30 years). Soils from savannas and plantations were sampled and analysed for carbon and nutrient contents as well as for δ¹³C isotopic signature. With the differing isotopic signature of savanna (C₄-plants) and oil palm (C₃-plant), SOC derived from oil palm was calculated. To assess microbial activity, field respiration measurements were conducted. In the laboratory, basal respiration and microbial biomass were measured in an incubation experiment. SOC contents were analysed in relation to microbial activity and root densities.

Total biomass of oil palm plantations increased linearly with age. Root to shoot ratios for oil palm remained constant until the 9th year. There was an increase of 29.5 t C/h stored in biomass going from savanna to an average aged oil palm plantation (15 years). Stacking of pruned fronds inside the plantations, as well as implementation of leguminous cover crops, were found to increase carbon stocks with another 4 and 2.4-3.1 t C/ha, respectively. Considering carbon storage in soil, there were high net carbon stabilization rates for oil palm derived carbon. In a mature (9 years old) plantation, 36% of SOC was oil palm-derived in 0-10 cm soil depth. On the other hand, in the same plantation part of the savanna-derived carbon had clearly been decomposed at least in the 0-10 cm layer. Cover crops led to substantial inputs of carbon to soil in young plantations. Over all, fine roots were found to be the main carbon source, which led to higher SOC stocks under frond piles and close to the palm trunk compared to avenues between palms. SOC contents under the frond pile did not reflect the additional amount of carbon added through pruned fronds. However, in the frond pile area there was an organic soil layer that was possibly highly active, where oil palm leaflets might be decomposed, while woody parts of the fronds remain undecomposed on the soil surface. Microbial activity was enhanced under frond piles and close to the oil palm trunk. Nutrients seem to be cycled fast under the frond pile and root density was significantly higher compared to other zones at the same distance to oil palm trees.

Results from biomass measurements suggest that in terms of biomass carbon storage it is indeed desirable to plant oil palm in savannas. There is a need to quantify biomass in oil palm as an averaged value over the life-cycle of a plantation, so not to overestimate carbon storage in
biomass. For decisions regarding biofuels, carbon balances should take into account land-use associated changes of carbon stocks in biomass but also in SOC. It remains an open question, if carbon balances can be positive in the context of the Llanos Orientales of Colombia, as fertilizer inputs might be high. The here found results suggest that implementation of cover crops and leaving pruned fronds inside plantations cannot only increase carbon storage in biomass, but also carbon storage in soil. Input of organic matter lead to a highly active microbiology below the frond pile, where nutrients and carbon seem to be cycled fast. High root densities indicate the agronomic importance of this management practise. For environmental and economical sustainability of the oil palm production system, management practises to improve carbon storage and nutrient cycling should be considered and investigated more. On the other hand, fertilization and inputs of more labile carbon through the oil palm cultivation lead to decomposition of savanna-derived SOC. The SOC content after savanna conversion to oil palm will thus depend on the balance between accelerated decomposition and higher inputs of carbon. Longer time series are needed, assessing SOC evolution under oil palm over the whole rooting depth of oil palm.
ACKNOWLEDGEMENTS

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<th>Description</th>
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<td>AGB</td>
<td>Above ground biomass</td>
</tr>
<tr>
<td>BGB</td>
<td>Below ground biomass</td>
</tr>
<tr>
<td>Cmic</td>
<td>Microbial biomass carbon</td>
</tr>
<tr>
<td>f</td>
<td>Frond pile (plantation management zone)</td>
</tr>
<tr>
<td>h</td>
<td>Harvesting path (plantation management zone)</td>
</tr>
<tr>
<td>NS</td>
<td>Natural savanna</td>
</tr>
<tr>
<td>OP</td>
<td>Oil palm</td>
</tr>
<tr>
<td>OPAL</td>
<td>Oil palm adaptive landscapes (SNF-r4d project)</td>
</tr>
<tr>
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</tr>
<tr>
<td>s</td>
<td>Inter zone (plantation management zone)</td>
</tr>
<tr>
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1 INTRODUCTION

Oil palm (*Elaeis guineensis*) cultivation is rapidly increasing in some tropical regions and is associated with the expansion of agricultural lands (Fitzherbert et al., 2008). Where oil palm (OP) replaces natural ecosystems, this leads to the loss of some provided ecosystem services. Habitat loss and concomitant biodiversity erosion that come with the replacement of primary or secondary forests by oil palm plantations, are the most prominently discussed issue (Koh & Wilcove, 2008). In south-east Asia, oil palm plantations are often replacing peat swamp forests or secondary forests (Koh et al., 2011; Koh & Wilcove, 2008). Biomass and its carbon stocks generally decrease with the land-use change when oil palm plantations replace natural forests (Kotowska et al., 2015). The topic of carbon budget and lifecycle analysis is especially of interest in the discussion around biofuels. Indeed, land-use change from forest to oil palm accounts for the largest part of greenhouse gas emissions along production chain of biofuel from oil palm (Harsono et al., 2012; Wicke et al., 2008).

In addition to biomass carbon loss, also soil organic carbon (SOC) contents have been found to be lower under oil palm than under primary or secondary forest (Sommer et al., 2000). This has implications on the role of soil as long-term carbon storage, but also on soil fertility. Soil organic carbon is associated with many physical, chemical and biological indicators of soil fertility. For example, Guillaume et al. (2016) found that SOC losses with conversion of forest to oil palm were related to the degradation of soils and the decrease of some fertility parameters. Thus, SOC content directly affects the agronomic (economic and environmental) sustainability of every production system.

To meet future demands, it is clear that more environmentally, agronomically and socially sustainable solutions for oil palm production systems have to be found and encouraged by society and politics. Corley (2009) estimated future demand for edible palm oil, taking into account that different vegetable oils can substitute each other. As yields of oil per area are very high for oil palm compared to other vegetable oils, Corley (2009) stressed the advantages of the crop for production of edible oil. Additional demand for palm oil by the biodiesel industry is also predicted to further increase in the future (Corley, 2009).

To find more sustainable solutions for oil palm production, it has been suggested that oil palm can generate economic benefit as well as contribute to carbon storage, if planted in areas of low productivity or on degraded land (Koh & Wilcove, 2008; Sanquetta et al., 2015; Schroth et al., 2002). Corley (2009) estimated a high projected consumption of edible palm oil to require an additional 53 M ha of production area and concluded that this area could be found in grasslands and permanent pastures over Indonesia, Brazil and especially Colombia, with no need for further deforestation. Compared to other oil palm production areas, in Colombia oil palm is already planted mainly in areas of savannas or on lands originally deforested for other crops (Castilla, 2004; Corley, 2009). Colombia is the biggest producer of palm oil in the Americas. For example, in 2013, 481’737 ha were planted with oil palm (Departamento Administrativo Nacional de Estadística, 2016). Of this area, 49% is located in the departments Meta and Casanare in the Llanos Orientales of Colombia. Besides a variety of other introduced crops, there are also large areas converted into pastures of different productivity (Rippstein et al., 2001). Nonetheless, large areas of the Llanos in Colombia are still natural, unmanaged savannas (NS). The Llanos savanna region extends over 45 M ha in Colombia and Venezuela (Romero-Ruiz et al., 2010). In the last 40 years, the agricultural frontier expanded from the Andes towards Venezuela into those savannas,
especially in the well-drained Altillanura (Rippstein et al., 2001; Romero-Ruiz et al., 2010). There are different authors that advocate for, or expect further expansion of oil palm plantations into the Llanos of Colombia because of comparably low environmental and economic costs (Castiblanco et al., 2013; Garcia-Ulloa et al., 2012). Thus, the establishment of oil palm plantations in those pasture lands and savannas might be an opportunity to develop a more sustainable palm oil production system. In particular, one of the challenge is to target a land-use change which would be favourable for the ecosystem carbon budget and, more specifically, which would prevent SOC loss.

Most studies on biomass and carbon in oil palm have been done in South-east Asia. Allometric equations have been established to relate biomass to age or height of palm trees (Asari et al., 2013). For South America, there have been some biomass studies on oil palm (Castilla, 2004; Sanquetta et al., 2015). However, there are no empirical studies quantifying the change of carbon storage in biomass with the land-use change from savanna to oil palm. Furthermore, soil and climate conditions, management and genetic material might influence oil palm growth (Castilla, 2004). According to Romero-Ruiz et al. (2010), the expansion of agriculture into the Llanos is driver for major changes in ecological processes like hydrology, nutrient cycles and greenhouse gas emissions. In particular, the expansion of agricultural land might alter carbon stocks in soil and associated soil characteristics. Frazao et al. (2013) found that SOC was 35-46% lower under oil palm than under pasture in Brazil. On the other hand, Goodrick et al. (2014) found an increasing but not significant trend of SOC with conversion from grassland to oil palm. Soils in the well-drained Altillanura are especially susceptible to compaction, erosion and other changes in physical properties through cultivation (degradation) (Rippstein et al., 2001). Therefore, there is a need to assess SOC changes and underlying mechanisms with the land-use change from natural savanna to oil palm on the well-drained soils of the Llanos orientales.

The situation at the study site close to Puerto Gaitan, in the well-drained Altillanura, with a very clear and long previous land-use (natural savanna) and low estimated SOC contents, represents ideal conditions to study changes in carbon stocks with the land-use change. Management practises like weeding, pruning of fronds, fertilizing and harvesting with machinery lead to characteristic management zones in oil palm plantations. It has been shown that these practises affect root distributions as well as soil characteristics (Frazao et al., 2013). Therefore, this work especially focusses on the role of these management zones.

This master thesis is embedded in the natural science part of the international project Oil Palm Adaptive Landscapes (OPAL) funded by the Swiss National Science Foundation (SNF-r4d). “The OPAL project uses natural and social sciences to build role playing games that reflect existing oil palm landscape realities. Using these games, it aims to explore alternative oil palm trajectories with stakeholders and decision makers in Indonesia, Cameroon, and Colombia, to help chart a path towards more sustainable and inclusive futures.” (www.opal-project.com, accessed 1.9.2016)

The first part of this master thesis will quantify the change in above- and belowground biomass developing with oil palm plantation of different age classes. It also provides an analysis of how the oil palm root system develops. It will give an estimate of carbon stocks in biomass for savanna and oil palm. The second part of this master thesis will focus on mechanisms showing how the land-use change from savanna to oil palm influences SOC distribution and stability (through root & frond input) and different soil fertility parameters, especially the soil microbial activity. The two parts will both have more detailed, separate introductions, hypotheses and methods.
2 MATERIAL AND METHODS

Material and methods concerning both parts of this thesis are presented in this section. Specific methods will be introduced in the respective section (3.3 and 4.3).

2.1 STUDY AREA AND PLANTATIONS

The eastern planes of Colombia (*Llanos Orientales* or *Orinoquia*) represent with 17 mio ha, 6% of the South American tropical savannas (Rippstein et al., 2001). Similar ecosystems can be found in the regions of the Llanos in Venezuela (11% of South American tropical savanna) and the Cerrados in Brazil (76%). Agricultural production is very diverse: oil palm, pastures with introduced grass species, rice, corn, soya and other annual and tree crops are cultivated (Rippstein et al., 2001).

All measurements and samples have been taken in an oil palm farm which extended on about 2500 ha close to Puerto Gaitan, Department Meta, Colombia (4°05'7.0"N, 71°53'59.0"W). The average annual temperature is around 26°C and there is a distinct dry season from December to March, while 95% of the yearly rain falls between April and November (2200mm/year in Carimagua) (Lavelle et al., 2014; Rippstein et al., 2001).

![Figure 1: Location of the study site in the Llanos Orientales in Colombia and extent of the natural savannas as assessed in Rippstein et al. (2001). Plantations were located in the flat high planes. Between Bogotá and Villavicencio are the Andean mountains. Adapted from Rippstein et al. (2001).](image)

Soils in the region are mainly Oxisols with low fertility, high acidity and high aluminium saturation (Lavelle et al., 2014; Rippstein et al., 2001). In the study area, soils were well-drained and sandy. As a consequence of redox processes, some soils have layers of plinthite, that, when exposed to air, transforms to petroplinthite or laterite (Rippstein et al., 2001). In the study area soils in the slightly hilly parts of the landscape were covered with this laterite, locally called *arecife* or *serranía*.
The natural vegetation in the study region is a herbaceous savanna with some small bushes, which is drained by many small rivers. Gallery forests (locally called morichales) grow in the depressions along these rivers (Rippstein et al., 2001). The only human management of the savanna is occasional burning by local indigenous for providing better grass for deer's (González, 2011). This explicitly means that there has never been cattle grazing and, therefore, the savannas can be considered as "not managed", i.e. not fertilized. According to Rao et al. (2001) the three main landscapes of the well-drained savanna area of the eastern plains in Colombia are: flat high planes (altillanura plana, 3.5 M ha), undulating high planes (altillanura ondulada and serrania, 6.4 M ha) and fluvial terraces (1.25 M ha) (Figure 1). The plantations have been established on the table-like flat high planes (Altillanura) (Figure 2).

Field data collection was carried out during the wet season in July and August 2016. It was made sure that the investigated plantations had been established on unmanaged natural savannas to have a clear land-use history. Plantations established in the years 2007, 2012 and 2014 (9, 4 and 2 years old, respectively) were chosen for intensive data collection. Additional data on above ground biomass were taken in two older plantations established in 1993 and 1989 (23 and 27 years old). As reference sites, two savannas with similar soil conditions were chosen close to the plantation.

2.2 MANAGEMENT OF OIL PALM PLANTATIONS AND MANAGEMENT ZONES

Prior to establishment of the oil palm plantations, soils were tilled with a chisel plow to 60 cm depth and with an overturning plow to about 20 cm. Oil palm trees were then planted with a distance of 9 m between trees, leading to a palm density of 143 palms/ha. In the two young plantations, a mixture of two cover crops (seeding with 2 kg/ha Kudzu and 1 kg/ha Desmodium) was implemented after planting. However, in the two years old plantation Kudzu was very dominant at the time of sampling, while in the four years old plantation only Desmodium could be found. The four years old plantation had not been managed very carefully in the first two years. That is to say that fertilization in those years was less intensive than in the 2 years of the youngest plantation. In the 9 years old plantation, there was no time when cover crops have been implemented. The management practises lead to distinct zones with the plantation getting older.
The area around oil palm trunk is always kept free of weeds and cover crops. This area is called weeding circle (w). In young plantations, the weeding circle is determined by the length of fronds, thus it increases with age until it reaches about 2.5 m distance from the trunk in a mature plantation. At young ages, all fertilizer is applied to this weeding circle. With the beginning of harvest, after about 3 – 5 years, each second inter row between palm lines becomes a harvesting path (h), where machines circulate. From this moment on, fertilizer is spread by machines from this path, thus, covering the whole area except the harvesting path itself. Micronutrients, e.g. Bor or Magnesium, are added only to the weeding circle, even in mature plantations. Avenues between palm lines are alternately determined as harvesting paths or dirty paths (s, for *calle sucia*). Here it was assumed that this zone represents the characteristics of the remaining area after subtracting w, f and h, thus, it was denominated inter zone (s).

Table 1: Characteristic management zones in a mature oil palm plantation.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Weeding circle (w)</td>
<td>Always kept free of weeds and cover crops. Main fertilizer input zone, especially in young OP.</td>
</tr>
<tr>
<td>Frond pile (f)</td>
<td>Piled up pruned fronds, after ~4th year.</td>
</tr>
<tr>
<td>Harvesting path (h)</td>
<td>Every second path in between OP lines, trucks and tractors pass regularly, receives no fertilizer except for residual waters from the mill.</td>
</tr>
<tr>
<td>Inter zone (s, for <em>calle sucia</em>)</td>
<td>Remaining area, especially in between OP lines, no trucks passing, fertilizer application only after ~4th year.</td>
</tr>
</tbody>
</table>

Figure 3: Management zones in the 9 years old oil palm plantation. In (A) weeding circle (w) and frond pile (f) in the front and *calle sucia*, the dirty avenue, (s) in the back. In (B) harvesting path (h) on the left and on the right, after the line of palms, again the dirty avenue.

Pruning of fronds is necessary to harvest fruit bunches. Generally, for each fruit bunch harvested, two fronds have to be pruned. Additionally, in mature plantations there is one “big pruning” once a
year, where about 16–17 fronds per palm are pruned. Yield in the 9 years old plantation over the last year had been 5.65 fruit bunches/palm. Pruned fronds are placed on the frond pile (f) in the oil palm line between two palms. Harvesting in the two and four years old plantation had not yet started. Therefore, there was neither a distinct harvesting path nor a frond pile, but only weeding circle and area covered by cover crops (denominated inter zone, s).

The fruit bunches harvested on the area planted in the 9 years old plantation were directly processed in a nearby oil mill. The residues from the oil mill are then directly used as soil amendments in some of the plantations. For simplification reasons and to avoid confounding effects, these areas were avoided for the sampling campaign. In the harvesting path of the sampled area, residual water from the oil mill had been applied.

2.3 SAMPLING DESIGN

In each of the selected plantations and savannas a plot of one hectare was established for vegetation and soil sampling. Care has been taken to select oil palm and savanna plots showing comparable soil conditions. Further criteria were that within plots soil conditions were homogeneous, that there were no potential influence of rivers or groundwater and no arecife. No plots were taken in plantations that had received compost or residues from the oil mill in the past. Plots with obvious low yields were also excluded. In each plot, five trees were taken randomly and all measurements were carried out on those five trees or in their adjacent management zones. Trees that showed clear evidence of disease or other anomalies were not selected.

Around each tree, management zones were delineated, according to a regular pattern (Figure 1).

![Figure 4: Map of the plantation structure and sampling points in the different management zones and with distance to palm trees. The green stars are positions of oil palm trees. Sampling points for frond pile (F), harvesting path (H) and inter zone (S3) are at 4.5 m from the centre of the palm tree (in green) and in the centre of the respective zone. Sampling point for weeding circle (W) is at 1.35 m for young plantations and at 1.1 m for the 9 years old plantation. Additional points in distance to the palm tree (S1, S2) are at 2 and 3 m, respectively.](image-url)
Sampling points were determined on this systematic grid in weeding circle, frond pile, harvesting path and inter zone. Additionally, in the inter zone, different points in distance to the palm tree have been sampled (Figure 1).

In the two youngest plantations, there had been no harvesting and no pruning so far. Therefore, no frond piles were present and a harvesting path could not be expected to be distinct. This resulted in less points sampled for the younger plantations (Table 2).

In the savanna plots, this sampling design does not apply and the samples were taken along transects of 100 m with 5 sampling points even spaced (Table 2).

Table 2: Overview of samples and measurements taken in plantations of different ages.

<table>
<thead>
<tr>
<th></th>
<th>Savannas</th>
<th>Oil palm plantations</th>
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<tbody>
<tr>
<td><strong>Soil and below ground biomass (BGB)</strong></td>
<td>NS1</td>
<td>NS2</td>
</tr>
<tr>
<td>Along transect</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Weeding circle (w)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frond pile (f)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harvesting path (h)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inter zone 3 (s3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inter zone 2 (s2)</td>
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<td></td>
</tr>
<tr>
<td>Inter zone 1 (s1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Above ground biomass (AGB)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Palm height</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Vegetation cover</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Frond pile</td>
<td></td>
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</tbody>
</table>

2.4 Statistical analysis

All statistical analyses were done with the open source software R version 3.2.1 (R Core Team, 2016). Root and soil data was analysed with analysis of variance (ANOVA) for management zone and depth effects. Replicates were the five oil palm trees or five sampling points along the transect for savannas. Assumptions for ANOVA (normal distribution of residuals and homogeneity of variance) were tested. Differences between factors (zone, depth) were assessed with a post hoc Tukey HSD test. Age effect on oil palm biomass and the effect of distance to tree on root biomass and soil parameters was analysed with linear regressions.
3 SAVANNA CONVERSION TO OIL PALM: IMPACT ON BIOMASS CARBON STORAGE

3.1 INTRODUCTION
Oil palm plantations can store more or less carbon, compared to the vegetation they are replacing (Castilla, 2004; Sanquetta et al., 2015). While oil palm expansion at the expense of forest leads to decreasing biodiversity and great carbon emissions, it has been proposed that establishing plantations on degraded arable land or on grasslands would be more sustainable, both environmentally and economically (Corley, 2009; Koh & Wilcove, 2008; Schroth et al., 2002). Garcia-Ulloa et al. (2012) reached the same conclusion, showing a low-impact scenario for oil palm expansion in Colombia by analysing trade-offs between environmental and economic costs. They concluded that the Altillanura is one of two regions, which are suitable for expansion and see a great advantage of Colombia compared to Indonesia, because of available land of unproductive pasture for conversion.

There are no empirical field studies that quantify the change in biomass and associated carbon stocks from savanna or grassland to oil palm and no studies quantifying oil palm biomass in the Llanos Orientales. Although oil palm as a monocotyledonous plant has very fixed growth patterns, growth might depend on genetic material as well as soil and climatic conditions (Castilla, 2004). Root biomass depends on the soil type (Corley, 2016). However, age and different vegetative parameters have been shown to be strongly correlated, which makes it possible to use allometric equations to estimate above ground biomass (Asari et al., 2013).

Above and belowground biomass have been studied in oil palm plantations of Brazil of different ages and carbon storage in biomass compared to literature values of other land-uses including pasture (Sanquetta et al., 2015). Using allometric equations with an assumed total height of 12 m and a palm age of 25 years, Castilla (2004) estimated a carbon stock of 80 to 120 t/ha in biomass for oil palm in Colombia and mentions a gain of 70 t C/ha compared to pasture. However, as oil palm plantations are generally replanted after 25 to 30 years of cultivation (Corley, 2016), it is important to quantify biomass change from savanna to oil palm looking at the average biomass over the whole life-cycle of a plantation.

A special interest lies in the development of the root biomass with plantation age, as differences in the root system compared to the savanna root system might lead to changes in root input and thus to effects on soil organic carbon (Jobbagy & Jackson, 2000). This will further be discussed in the second part of this thesis (section 4). The root system architecture of oil palm has been studied in detail by Jourdan & Rey (1997a). The oil palm is a monocotyledonous plant. Therefore, roots do not show secondary thickening. The thickest size class with a diameter of 6-10 mm are primary roots. They are separated in vertically downward growing and horizontal ones. From the primary roots, secondary roots (2-4 mm) branch, then tertiary which are branched (0.7-1.2 mm) and quaternary’s (0.1-0.3 mm, 1 to 4 mm long) (Corley, 2016). The main absorbing roots are tertiaries and quaternaries, which are addressed as “fine roots”. Horizontal primary roots carry much more secondary roots than the downwards growing. From horizontal roots, secondary roots grow upwards and downwards, with a little more growing upwards. When the secondary roots reach the surface, they branch, which results in a mat of fine root on the surface.
Inside plantations, differences of root biomass and properties depending on management zones have been observed: root density in the top soil has been reported to be higher under pruned fronds (Henson & Chai, 1997). Yahya et al. (2010) found that compaction due to harvesting, leads to changes in soil physical properties, which change growth and distribution of oil palm roots.

This first part of the present master thesis aims at (A) quantifying development of above- and belowground biomass with plantation age for the specific region of the well-drained savannas in the Llanos Orientales in Colombia. Further it aims at quantifying the change in carbon stocks in biomass due to the land-use change from savanna to oil palm (B), specifically by comparing carbon stocks in savanna with the one averaged over the life cycle of an oil palm plantation; and (C) it gives a detailed picture of how the oil palm root system develops until reaching maturity and how different management zones affect this development. The implication of this root system development for soil organic carbon will be discussed in the second part of this thesis.

3.2 RESEARCH QUESTIONS AND HYPOTHESES

Main question: How do the carbon stocks in biomass change with the land-use change from savanna to oil palm plantation?

ABOVEGROUND AND BELOWGROUND BIOMASS
- How does aboveground biomass (including oil palm trees, oil palm litter and understory/cover crops) develop with the age of a plantation?
- How does belowground biomass (including roots of oil palm and others) in the different management zones develop with the age of a plantation?
- How does the vertical and horizontal distribution of oil palm fine and coarse root biomass develop with oil palm age?
- How do above- and belowground biomass, averaged over the life-cycle of a plantation, compare to savanna biomass?

Hypothesis 1: While the above-ground biomass obviously increases with aging of plantation, the belowground biomass increases concomitantly, resulting in an unchanged root-shoot ratio.

Hypothesis 2: In young plantations, no oil palm roots can be found in the intermediate zone (s). On the contrary, the inter zone is dominated by cover crop roots. In mature plantations, the oil palm roots dominate in all management zones.

Hypothesis 3: Fine root density in the topsoil (0-10 cm) depends on management zone, because of different nutrient (fertilizer, litter) inputs, differences in moisture, different compaction levels. In contrast, coarse root density only depends on distance to trees.

Hypothesis 4: The sum of above- and belowground biomass for an average over the life-cycle of an oil palm plantation is higher than in savannas.

CARBON CONTENT OF BIOMASS AND LITTER
- What are the carbon contents of the different biomass compartments (oil palm fronds, roots, frond pile, understory)?
- How does the carbon stock in the biomass compartment, averaged over a lifecycle of an oil palm plantation, compare to savanna?

Hypothesis 5: In accordance to biomass, the total carbon stock in biomass increases from savanna to oil palm plantation. While this trend is obvious in the above-ground compartment because of biomass development, it applies also to the below-ground compartment. On average over the lifecycle of oil palm plantations, carbon stocks in biomass are higher than in natural savannas.

3.3 MATERIAL AND METHODS

ABOVEGROUND BIOMASS ESTIMATION
Aboveground biomass measurements included palm tree biomass, cover crop and understory biomass, frond pile biomass, and, in the savanna, the herbaceous vegetation. Epiphytes were present, but their biomass was considered to be negligible, especially considering that they are generally cleaned out by the workers.

For savanna vegetation, as well as for the cover crops in the two young plantations, biomass was cut at soil level on one square meter. For savannas, the square meter was randomly taken close to each of the root sampling point along a transect. Cover crops were sampled in the centre between two palm trees. Understory in the 9 years old plantation was negligible. In fact, also in earlier years the plot had always been free of cover crops, as their use is a rather new practise. Of these vegetation samples, total dry mass was measured and, after cutting the sample into small pieces, a subsample was taken to measure carbon and nitrogen contents and isotopic carbon signature ($\delta^{13}C$).

For the oil palm biomass, allometric equations using tree height were applied in the following age classes: 2 (planted in 2014) and 4 (2012) years old (“young” plantations), 9 years (2007; “mature” plantation), 23 (1993) and 27 (1988 or 1989) years (“old” plantations)(Table 2). Height was measured on ten palm trees in each plantation at the base of the youngest leaves. The same height measurement was also used by Kotowska et al. (2015) (personal communication).

The allometric equation (1) used by Kotowska et al. (2015) and Asari et al. (2013), was used to calculate dry mass of single palm trees.

$$\text{dry weight [kg/palm]} = 71.797 \times \text{height [m]} - 7.0872$$ (1)

However, equation (1) has been developed for palm trees aged 6 years and more. Therefore, for the two young plantations, the allometric equation (2) of Thenkabail et al. (2004) that was developed with 5 palms aged between one and five years was also tested (Figure 5).

$$\text{dry weight [kg/palm]} = 0.3747 \times \text{height [cm]} + 3.6334$$ (2)

However, these two allometric equations resulted in comparable values for the two young plantations and only lead to different results for older plantation (Figure 5). As the equation (1) is based on more data, it was applied for all ages.
Figure 5: Comparison of oil palm trees biomass calculated with two different allometric equations. It can be seen, that the differences for young trees are negligible.

Frond pile biomass was measured by weighing directly in the field 4 frond piles in the 9 years old plantation. Subsamples of each frond pile were taken to assess water content. Additionally, on one frond pile, the subsamples were taken according to the apparent decomposition state of the different frond pile layers. Water content, C and N content of those samples were analysed. It was assumed that the frond pile biomass does not increase substantially in the older plantations. In the young plantations, no frond pile was present, because no fronds had been cut yet, as harvesting had not started.

**BELOWGROUND BIOMASS (AND SOIL SAMPLING)**

Roots and soil were sampled in the 2, 4 and 9 years old plantation (Table 2) together with a cylindrical corer of 5cm diameter at three depth intervals (0-10, 10-20 and 20-30 cm). This depth was chosen, as most of the OP roots are found in the top layer until 30 cm, even though depths of several meters were reported (Corley, 2016). Rao et al. (2001) found over 80 % of the root biomass in the first 30 cm of natural savannas of the Llanos region (Carimagua).

At the field site camp, samples were stored in open plastic bags to let water evaporate. Samples were then air-dried for some days in open containers. Once dry, they were sieved at 2 mm and roots separated. Roots were rinsed with water to remove attached soil particles and air-dried and stored in paper bags. Soils samples were again stored in plastic bags kept open to allow for possible residual water to evaporate. Further methods regarding soil samples and analysis, are described in the second part of this thesis (section 4.3).
Finally, roots were dried in an oven at 60°C for 48 hours and dry biomass of roots was determined for all samples. For the samples from oil palm plantations, root biomass was separated into primary, secondary and fine oil palm roots as well as cover crop roots.

**UPSCALING**

Density of oil palms was of 143 palms/ha in all plantations. This gives a distance of 9 m between individual palm trees and, with a triangular design, results in 7.8 m spacing between lines. For a single palm this gives a “basic unit” of 70.2 m² area. To upscale the palm and frond pile biomass to one hectare, the resulting values were multiplied by the palm density, as there is one frond pile per palm. Upscaling of the cover crop biomass was done by multiplying values by the effectively covered area, which is the total area without the weeding circles for the young plantations (Table 3). In the mature plantation (9 years), no understory was present.

To upscale belowground biomass to one hectare, the respective extents of management zones were measured in the field (Table 3). For reasons of simplicity, the extents of the weeding circle were estimated to be like in the young plantations for all ages. Although the size of the weeding circle is probably increasing with the age of the palm tree, it seems more prudent to choose a smaller extent for this zone so as to avoid overestimation of total roots biomass. This is also justified because in the young age the fertilizer is spread only to that area. In the mature plantation, there were no significant differences between root biomass summed over the measured depth. Therefore, upscaling of biomass was done with data for these 3 points pooled (Table 3).

Table 3: Extents [%] used for weighting the different management zones depending on age, based on geometrical assumptions presented in Figure 4. The basic unit is of 70.2 m² per palm.

<table>
<thead>
<tr>
<th>zone</th>
<th>OP 2 years</th>
<th>OP 4 years</th>
<th>OP 9 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>weeding circle</td>
<td>w</td>
<td>12.6</td>
<td>11.8</td>
</tr>
<tr>
<td></td>
<td>s1</td>
<td>34.7</td>
<td>16.1</td>
</tr>
<tr>
<td>inter zone</td>
<td>s2</td>
<td>-</td>
<td>46.8</td>
</tr>
<tr>
<td></td>
<td>s3</td>
<td>52.7</td>
<td>25.3</td>
</tr>
<tr>
<td>frond pile</td>
<td>f</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>harvesting path</td>
<td>h</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

For comparison with savanna, the carbon stock averaged over the lifecycle of an oil palm plantation was calculated. Oil palm plantations are generally replanted after 25 to 30 years, most importantly because palms get too high for harvesting (Corley, 2016). In the study area, age of replanting is around 30 years. As growth of oil palm biomass resulted to be linear (Figure 6), an age of 15 years was assumed to represent the biomass averaged over the lifecycle. The oldest, intensively sampled plantation was 9 years old, therefore, it was decided to extrapolate belowground biomass based on some assumptions for the 15 years old plantation. Root to shoot ratios have been reported not to change with age (Corley, 2016; Sanquetta et al., 2015). Therefore, the calculated root to shoot ratio of the 9 years old plantation was used for the extrapolation of root biomass in older plantations. According to data reported in Corley (2016) from Tinker (1976), the amount of fine roots stays more or less constant with age compared to an increasing total root biomass. Therefore, the fine root biomass measured in the 9 years old plantation was assumed also for the old plantations.
**CALCULATION OF CARBON STOCKS**

Carbon and nitrogen contents and isotopic signature of carbon for some biomass samples were assessed. Biomass samples were chosen so to represent the different biomass compartments: oil palm fronds and roots, frond piles, as well as above and belowground biomass samples for cover crops and savanna. Oil palm fronds were assumed to represent the oil palm biomass, therefore, no samples of the trunk have been taken. After drying for 48 hours at 60°C, samples were ground and then analysed at the University of Göttingen with an isotope ratio mass spectrometer (Delta Plus, Finnigan MAT, Bremen, Germany). For carbon stocks in the biomass, the carbon contents were multiplied by the dry biomass calculated per ha of plantations. Carbon isotopic signature of biomass samples was used to determine the isotopic signature of savanna versus oil palm carbon for the second part of this thesis (see section 4.3).
3.4 RESULTS

**DEVELOPMENT OF ABOVE- AND BELOWGROUND BIOMASS WITH OIL PALM PLANTATION AGE**

The biomass of oil palm trees increases linearly and accounts for most of the increase in total biomass of the system (Figure 6). The regression over all five measured plantations shows a linear increase of 3.27 t/ha*year in oil palm tree biomass:

\[
\text{dry biomass [t/ha]} = 3.27 \times \text{age [years]} \quad (R^2=0.95)
\]  

Cover crops were only present in the young plantations, as their use is a rather new practice in the region. In the 9 years old plantation, no understory was present. Frond piles were not present in the two young plantations, as pruning of fronds is only started together with harvesting after about 4 or 5 years. The frond piles in the 9 years old plantation resulted in 9.1 ± 4.5 t/ha of dry biomass with 143 frond piles per ha of plantation. This value was assumed to remain constant in a plantation after reaching maturity.

![Figure 6: Development of biomass in different compartments of an oil palm plantation.](image)

AGB=aboveground biomass. BGB=belowground biomass. OP=oil palm. CC=cover crop.

All compartments were measured until the 9th year. Extrapolation of further ages with measured tree heights (see section 0).
Root biomass increased exponentially with age in the three measured plantations (Figure 6). For the mature, 9 years old, plantation a total OP root dry mass of 16.9 ± 1.3 t/ha was calculated for the top 30 cm. The calculated root to shoot ratios were 0.47, 0.49 and 0.46 for 2, 4 and 9 years old plantation, respectively. As described in methods, the value of the mature plantation has been used to extrapolate root biomass for the two old (23 and 27 years) plantations.

**Total biomass in oil palm and savanna**

Oil palm plantations are normally replanted after about 30 years, when palms get to high for efficient harvesting. As oil palm AGB increase was found to be linear with plantation age (equation 3), the value of a 15 years old plantation can be taken as an approximation of the average biomass over the lifecycle of a plantation. Values for the different biomass compartments, calculated from the above-mentioned regression, or taken as constant values, are shown in Table 4 together with the corresponding carbon contents and resulting carbon stocks. For an oil palm plantation aged 15 years, without the implementation of cover crops, the biomass calculated from AGB, BGB and frond piles is 81.21 t/ha, corresponding to 35.6 t C/ha (Table 5). Compared to this average value over the lifecycle of an oil palm plantation, the measured savannas show a total biomass of 5.26 t/ha, corresponding to 2.1 t C/ha. Leaving the pruned frond in the plantation on frond piles, can contribute about 10% to the total biomass. Additionally, the use of cover crops might further increase biomass stocks of the oil palm system up to 5 to 7 t/ha. This shows how the carbon stock in biomass increases with the land-use change from savanna to oil palm and might be influenced by management decisions.

Table 4: Biomass and carbon stocks for savannas and oil palm, calculated or assumed as the average over a life-cycle of oil palm plantation. For measured compartments, the age of the plantation, means and standard deviation are indicated.

<table>
<thead>
<tr>
<th>compartment</th>
<th>age [years]</th>
<th>Dry biomass [t/ha]</th>
<th>C content [%]</th>
<th>Carbon stock [t/ha]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OP AGB</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OP trees</td>
<td>15&lt;sup&gt;a&lt;/sup&gt;</td>
<td>49.05 ± 4.53</td>
<td>44.4 ± 1.2&lt;sup&gt;c&lt;/sup&gt;</td>
<td>21.8</td>
</tr>
<tr>
<td>frond pile</td>
<td>&gt; 9</td>
<td>9.11 ± 4.53</td>
<td>43.6 ± 1.0</td>
<td>4.0</td>
</tr>
<tr>
<td><strong>OP BGB</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OP total roots</td>
<td>15&lt;sup&gt;o&lt;/sup&gt;</td>
<td>23.05 ± 0.4</td>
<td>42.4 ± 1.7</td>
<td>9.8</td>
</tr>
<tr>
<td>OP fine roots</td>
<td>&gt; 9</td>
<td>8.6 ± 0.4</td>
<td>42.4 ± 1.7</td>
<td>3.6</td>
</tr>
<tr>
<td><strong>Cover crop AGB</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kudzu</td>
<td>2</td>
<td>4.53 ± 0.51</td>
<td>42.3 ± 0.6</td>
<td>1.9</td>
</tr>
<tr>
<td>Desmodium</td>
<td>4</td>
<td>6.02 ± 0.38</td>
<td>44.7 ± 0.1</td>
<td>2.7</td>
</tr>
<tr>
<td><strong>Cover crop BGB</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kudzu</td>
<td>2</td>
<td>1.2 ± 0.16</td>
<td>41.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Desmodium</td>
<td>4</td>
<td>0.99 ± 0.51</td>
<td>41.7</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>natural savanna</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Savanna AGB</td>
<td>-</td>
<td>2.98 ± 0.52</td>
<td>42.7 ± 0.7</td>
<td>1.3</td>
</tr>
<tr>
<td>Savanna BGB</td>
<td>-</td>
<td>2.28 ± 1.2</td>
<td>35.8 ± 2.0</td>
<td>0.8</td>
</tr>
</tbody>
</table>

<sup>a</sup> Calculated from regression (R<sup>2</sup> = 0.95) over all OP plantations. Biomass = 3.27 * age

<sup>b</sup> Calculated for a constant root to shoot ratio. Total BGB = AGB OP trees * 0.47

<sup>c</sup> Carbon content of OP frond

<sup>d</sup> AGB of CC is calculated as present on 85% of surface (not in weeding circle)

<sup>e</sup> Average over 10 sampling points from two different savannas
**Root distribution in oil palm and savanna**

In general, total oil palm root density increases with palm age (Figure 7). There is an evident effect of distance to palm tree in both young plantations (Figure 7, (A, B)). In the 2 years old plantation, oil palm roots have not yet reached the centre of the inter row (Figure 7, A), while in the 4 years old plantation, oil palm roots can be found everywhere, although only very little in the inter row (Figure 7, B). The horizontal distribution of OP roots has implications for fertilization. On the contrary, roots of cover crop could be found in the two young plantations in all the measured inter zone points, with most of the roots in the 0-10 cm layer (Appendix, Figure 19, (A, B)). In the 2 years old plantation there were additionally also cover crop roots in the weeding circle.

In the mature plantation, the distribution of palm roots does less depend on distance to the oil palm tree (Figure 7, C). Distance to tree had no significant effect on root density for the inter zone (s1-s3). If the weeding circle (w) is included in the analysis, the distance to tree is only significant (p<0.05) for fine root biomass for the topsoil (0-10cm) as well as for the sum of all roots over all depths (Figure 7). However, for the case of w, it is not possible to disentangle the effect on fine roots due to distance and management practice.

Looking at root distribution with age and distance to tree, the pattern of root growth can be followed. By comparing the three ages, as well as how the different zones in distance to oil palm tree are “colonized” by roots, the development of horizontally advancing roots can be observed. In the mature plantations, the biomass of primary roots increases with depth and the bulk can be found in 20-30 cm depth. However, in the two young plantations, primary roots are found mostly in the 10-20 cm layer. They seem to start colonizing new zones at a depth of 10-20cm. This can be seen in the distribution of coarse roots in s1 of 2014, as well as in s1, s2 and s3 of 2012 (Appendix, Figure 19, (A, B)).
Figure 7: Total oil palm root distribution with depth and distance in different plantation ages. Mean values (A-C) and standard errors (D-F).
Not only do roots grow further from the OP trunk with age, but also the biomass of fine roots in the weeding circle increases with age of the plantation (Figure 8). Starting at an equal value for all depths in the 2 years old plantation, fine root biomass develops much more strongly in the topsoil than in the two other measured depths. The interaction of depth and age is highly significant (p < 0.001) as tested by ANOVA. In contrast, for coarse roots the highest densities can be found in the 20-30 cm layer in the weeding circle (w) (Appendix, Figure 19).

![Figure 8: Fine root biomass in different depths in the weeding circle (point w) developing with plantation age. Error bars show standard errors, n=5. Big letters show significant differences with depth and small letters show significant differences with age (Tukey).](image)

Management zones in the mature plantation influenced root densities in the first ten centimetres (Figure 9). Effect of management zones on total root biomass, as well as fine root biomass, in the top 0-10 cm was significant (p < 0.01). Total BGB in f and w was about 2 and 1.5 times higher than in h and s3 (Table 5). Total as well as fine root biomass in f was significantly higher than biomass in other zones, except from w, in 0-10 cm (Figure 9). However, the percentage of fine roots was not significantly affected by management zones. Even though primary roots were found in f in the 0-10 cm layer (Figure 19), there was no significant effect of management zones on coarse roots. For the two deeper layers, differences between management zones were not significant.
Figure 9: Total and fine root biomass in the 0-10 cm in different management zones of a mature oil palm plantation. Letters show differences according to tukey test, p<0.05.

Compared to the savanna sites, root biomass was significantly higher in all oil palm management zones and at all depths (Table 5). After total biomass, also root vertical distribution was affected by the land-use change. While in the two savannas 68% and 54% of the roots were found in the first 10 cm, in the mature oil palm plantation the total root biomass was evenly distributed in the three sampled depths (Table 5). Only in the frond pile zone there were fewer roots in the 20-30 cm layer (only 19%) but more in the first 10 cm (52%). This increase is due to more primary and fine roots compared to other zones (see Appendix, Figure 19). In the harvesting path (h) there were slightly higher values in the intermediate depth (43%). This shows that vertical distribution is shallower in savanna than in oil palm. While under frond piles more than half of the measured root biomass can be found in the top 10 cm.

While in the mature oil palm plantation the root to shoot ratio was 0.47, in savannas, biomass was found to be more evenly distributed between AGB and BGB since the root to shoot ratios of the ten measured points were 0.75 on average.

Table 5: Mean total dry root biomass [g/m²], standard error (n=5), and percentage of total measured roots in the two savannas and in the different management zones of a mature OP plantation.

<table>
<thead>
<tr>
<th>Depth [cm]</th>
<th>Savanna</th>
<th>OP 9 years (mature plantation)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NS1 %</td>
<td>NS2 %</td>
</tr>
<tr>
<td>0 - 10</td>
<td>152 ± 30</td>
<td>68</td>
</tr>
<tr>
<td>10 - 20</td>
<td>50 ± 6</td>
<td>22</td>
</tr>
<tr>
<td>20 - 30</td>
<td>22 ± 5</td>
<td>10</td>
</tr>
<tr>
<td>0 - 30</td>
<td>224</td>
<td>230</td>
</tr>
</tbody>
</table>
3.5 DISCUSSION

DEVELOPMENT OF ABOVE- AND BELOWGROUND BIOMASS WITH OIL PALM PLANTATION AGE

Above ground biomass of 49.1 t/ha for a 15 years old plantation, compares well to the values for plantations aged 8 to 15 years of 48.4 and 63.0 t/ha for two regions of Indonesia measured by (Kotowska et al., 2015) with the same methodology.

In this study, the sum of AGB and BGB was 81.21 t/ha for a 15 years old plantation (Table 4). The equation of Sanquetta et al. (2015) yield a total dry biomass of 52 t/ha for a 15 years old OP plantation. In Syahrinudin (2005), total system biomass was 117.9 and 157.9 t/ha for a 10- and 20-year-old plantation, respectively. However, their data included trunk bases, which adds a considerable amount of root biomass.

Biomass was found to be linearly increasing with plantation age (Figure 6). This is due to a linear growth of oil palm tree biomass, adding a biomass of 3.27 t/ha*year (equation 3). Data from Syahrinudin (2005) suggest a logarithmic growth curve. It has to be mentioned, that the only small difference in AGB between the 2 and 4 years old plantation might be explained with management. The 4 years old plantation apparently had not been managed carefully in the first two years and fertilization only started at an age of two years.

Oil palm BGB increased exponentially until the 9th year, but was assumed to grow with the same rate as AGB afterwards by choosing a constant RSR to extrapolate (Figure 6). In Sumatra, Syahrinudin (2005) found oil palm root biomass of 16.1 t/ha for a 10 years old plantation, supporting our value of 16.9 t/ha for the 9 years old plantation (Appendix, Table 7). However, they found 12 t/ha for a 3 years old plantation, while here the 4 years old plantation had only 3 t/ha. They measured until a depth of 5m, also with a root auger. They report however, that more than 50% of the total roots were found in the first 60 cm. As hypothesised, root to shoot ratios were more or less constant with age (until the 9th year of oil palm) (Hypothesis 1).

It is clear that with the chosen approach to measure root biomass, a large part of OP coarse roots directly growing down from the trunk were missed. Syahrinudin (2005) uprooted palms and found that, depending on palm age (3, 10, 20, 30 years), the so-called trunk base added another 10, 55, 45 and 46% to the root biomass sampled with an auger. On the other hand, also in savannas the root measurements were not taken directly under the grass sod but adjacent to them. This might lead to underestimation of the up scaled total root biomass for both land-uses, as discussed in the following.

TOTAL BIOMASS IN OIL PALM AND SAVANNA

Some authors compare carbon stocks in biomass of savanna and oil palm plantations at the end of a plantation lifecycle (Castilla, 2004; Sanquetta et al., 2015). However, the carbon sequestered in this way, will be released as soon as oil palm is replanted. If the two land-use changes should be compared, it seems reasonable to compare the savanna not to the maximal carbon stock, but the average carbon stocks over the lifecycle of a plantation.

As not all compartments could be measured in all plantation ages, some assumptions had to be made, like for example for the frond pile in the 15 years old plantation. This limits to a certain extent exact quantitative conclusions. The biomass of frond piles might vary over the age of a
plantation, as the number of fronds pruned is yield dependent and decomposition rates influence standing dead biomass.

The found values for root to shoot ratio of around 0.47 are much higher than the value of 0.30 that Yuen et al. (2013) suggest for oil palm. Sanquetta et al. (2015) even found that roots make up only about 15% of total biomass. Corley (2016) states that there is actually a lack of root to shoot data for oil palm. The chosen root to shoot ratio for extrapolation affects the biomass calculated for a 15 years old “average of lifecycle” plantation. With a value of 0.3 instead of 0.47, total OP BGB in a 15 years old plantation would be 14.7 t/ha instead of the calculated 23.1 t/ha. This corresponds to an 11.5% lower value for total live OP biomass (63.8 instead of 72.1 t/ha). Fine roots represented 50% of the total root biomass sampled in the 9 years old plantation. This is much higher than the reported values between 5 and 14% from Tinker (1976) reported in Corley (2016). However, the high percentage of fine roots might be due to the fact that in this study areas with higher percentages of coarse roots, like the trunk base or depths below 30cm have not been measured. In any case, the assumption that fine root biomass remains constant after reaching maturity seems to be rather prudent and has no influence on the estimation of total root biomass and carbon stock calculations.

The AGB estimates from savanna seem not to vary greatly across the area of the Llanos in Colombia and Venezuela: according to Rao et al. (2001), studies assessing production of aboveground biomass of the unfertilized savannas in the Llanos of Colombia or Venezuela varied between 1.2 and 4.8 t/ha. Our value of 2.98 t/ha is in this range and can, therefore, been taken as a representative estimate for this land-use. The value of 2.28 tons root biomass per hectare of savanna is also in line with the about 2.3 t/ha reported for the region (Rao et al., 2001). However, seasonality of AGB might play a role for savannas. Without fertilization, Rao et al. (2001) found 3.84 t dry mass/ha in the wet season, while only 0.24 t/ha in the dry season. Only a negligible amount of shrubs was present in the sampled savannas, however, in other areas there might be a higher shrub density.

**Biomass and carbon stocks with savanna conversion to oil palm**

The land-use change from savanna to oil palm leads to a strong increase of carbon stocks from 2.1 to 35.6 t C/ha associated with a 15-fold increase in total biomass (Table 4). As hypothesized, biomass and associated carbon stocks increase not only aboveground but also belowground (Hypothesis 5). The increase in total biomass and associated carbon stocks is in contrast to other settings for oil palm cultivation, where oil palm plantations replace natural forests. This was also found by others: Sanquetta et al. (2015) compare the 40 t C/ha found for oil palm in Brazil with that of pasture (8 t C/ha), forest (123 t C/ha) and agriculture (5 t C/ha). Castilla (2004) speaks of a gain of 70 t C/ha compared to pastures and a 130 t C/ha loss compared to forest. Both authors compare pastures to oil palm plantations at 25 years. Nevertheless, our values compare well to the ones found for Brazil by Sanquetta et al. (2015).

The biomass from savanna to oil palm increases differently for AGB and BGB. While living AGB increases 16-fold from savanna to oil palm, BGB only increases about tenfold (Table 4)(Hypothesis 4). These numbers are much higher than the factors by which biomass decreases after conversion of forests to oil palm (Kotowska et al., 2015; Pransiska et al., 2016). If land-use change implies a loss of natural forest, it is mainly the AGB that drives the loss in biomass and carbon stocks. For example, Kotowska et al. (2015) found that total tree biomass in natural forests (384 t/ha) in
Sumatra were more than 4 times higher than in rubber (78 t/ha) or OP monoculture plantations (50 t/ha).

Changes in AGB can differ greatly, depending on the ecosystem that is replaced by OP. However, belowground biomass plays a considerable role for carbon storage in biomass. Land-use conversion from natural forests to oil palm or rubber plantations has been shown to reduce total root mass and with it C and N stocks by more than 50% (Pransiska et al., 2016). Kotowska et al. (2015) also found higher belowground productivity in natural forest than in rubber or oil palm plantations. Compared to this, the here measured fine root biomass in the 9 years old plantation was already more than three times higher than in natural savannas. Total oil palm root biomass increases by a factor of more than seven from savanna to a 9 years old plantation. This shows that not only in the aboveground compartment, but also belowground, there is an increase in biomass if oil palm is planted on savanna.

Yuen et al. (2013) estimated below ground biomass of oil palm plantations aged between 9 to 16 years to be in the range of 3-8 t C/ha. Here, 9.8 t C/ha in oil palm roots were found. This might show a slight over estimation of root biomass with the used methodology, especially considering that trunk bases were not sampled here. On the other hand, carbon allocation to roots might also be higher than in other studies. This would also explain the comparable high root to shoot ratios found and the high amount of fine roots compared to other findings (discussed above). The carbon accumulation rate in oil palm AGB alone corresponds to 1.45 t C/ha*year with equation (3) and a carbon content of 44.4% for oil palm biomass (Table 4). Thenkabail et al. (2004) found the carbon accumulation rate in AGB to be about twice as high with 2.97 t C/ha*year. This could be due to faster growth at a young age, as they measured palms up to an age of 5 years. It could also be a further indication, that here circumstances favour an allocation of carbon to the roots rather than to biomass. This change in physiology might be due to the low soil fertility in the well-drained Altillanura. It is difficult to say how representative the findings are for the whole area or even for the region of the Llanos Orientales.

**Management Practises Influencing Carbon Stocks**

Two major managing practises affecting carbon stocks in biomass in oil palm plantations could be identified. Firstly, leaving the pruned frond inside the plantation on a frond pile can contribute to about 10 % of the total biomass (Table 4). Secondly, the use of cover crops can further increase biomass stocks of the oil palm system up to 5 to 7 t/ha.

The value for frond piles could vary, as pruning of fronds might decrease with plantation age or decreasing harvest, while material might accumulate, if decomposition rates are lower than production rates. However, frond piles might have also an effect on nutrient cycling and water storage. SOC stocks, for example, have been found to be up to 26% higher under frond piles than in the inter zone in a 25 years old plantation (Frazao et al., 2013). High root densities below the frond piles and roots growing up into the decomposing fronds could also indicate the frond pile as an area of accelerated nutrient cycling (Table 5). TDR measurements associated with field respiration measurements (see second part of this thesis) showed that water contents under the frond pile were less variable than in the inter zone or weeding circle. Owners, agronomists and workers in the plantation showed a major interest in the question of how to distribute pruned fronds inside the plantation. Effects on erosion protection, soil organic matter accumulation, root density, soil fertility and resulting fertilization patterns were discussed.
An interesting case is the use of cover crops in Colombia. Although there is also implementation and research on the use of cover crops in Malaysia (e.g. Samedani et al. (2015)), this practice is much more widely used in Colombia. From the biomass measured here, it is clear, that cover crops can add a considerable amount of biomass and carbon stocks to an oil palm plantation. In the two young plantations, cover crop BGB and AGB account for 40-60% of total biomass (Figure 6 and Table 4). In a plantation of 15 years, cover crops could still contribute about 5% if their biomass does not decrease with increased canopy closure. Even though the contribution to biomass may be negligible, the cover crops bring a great amount of organic matter, which might influence SOC contents in soils of OP plantations and thus contribute to the carbon sequestration of the system.

Further benefits of cover crops are improving physical and chemical soil conditions, weed and pest control (Ruiz & Molina, 2014; Samedani et al., 2015). This is why, in other visited plantations of the Colombian Llanos, shade tolerant leguminous cover crops can be found growing vigorously even in old plantations. Although, sometimes cover crops grow so well, that they can also increase work load and herbicide use to avoid competition with oil palm trees.

**ROOT DISTRIBUTION IN OIL PALM AND SAVANNA**

In the mature plantation (9 years old) high root densities were found in all zones, roots of different oil palms are thus overlapping (Figure 7, A). It is reported that roots of different oil palm trees start to interfere in the topsoil at an age of 5 years (Jourdan & Rey, 1997b). Neither coarse nor fine root density did depend on distance to palm trunk in the mature plantation (Hypothesis 3). However, in the two young plantations only very little to no oil palm roots can be found in between the oil palm lines (inter zone, Figure 7, B and C)(Hypothesis 2). This development is the reason why it is more efficient to fertilise palm trees only in the weeded circle at young ages, while for mature plantations fertilizer can be taken up from the whole surface and is thus provided on the whole surface. It also shows, that the implementation of cover crops is of great importance especially for young plantations, as oil palm roots cannot protect soil in the inter zone from erosion at that age. Oil palm roots in the old plantations were emerging from the ground, implying that there had been also erosion of the top soil. Therefore, it seems important that shade tolerant cover crops are also implemented for mature plantations.

The root distribution in the measured plantations followed the known pattern of oil palm root growth as described in Jourdan & Rey (1997a). Primary roots were found mainly in the deepest soil layer (20-30cm), while fine roots dominated in the 0-10 cm layer. In the frond pile, coarse roots (primary and secondary) were evenly distributed over the three depths (data not shown). However, using an auger of only 5 cm diameter limit slightly the conclusions that can be made for coarse roots, as spatial variability was quite high, which increased the chance to miss a coarse root in a zone with high density.

As hypothesized (Hypothesis 3), management zones had an effect on root densities in the mature plantation (Table 5). However, the effect was only in the 0-10 cm depth. Total as well as fine roots biomass was higher in f and w and lower in h and s for 0-10 cm depth (Figure 9). The weeding circle is difficult to compare to the other management zones, as the sampling point was much closer to the tree than the other three zones. Therefore, it is not possible to know how much the high root density can be actually attributed to management, e.g. fertilization patterns. It might just be the genetically fixed root growth pattern that leads to the higher values close to the palm trunk. They can be expected to be even higher, closer to and below the trunk, as downwards growing coarse roots are very dense under the oil palm tree (Jourdan & Rey, 1997a; Syahrinudin, 2005).
The development with time of fine roots in the weeding circle (Figure 8) shows how branching of fine roots takes place at the soil surface, as described by (Corley, 2016). This might happen where there are nutrients available, or might just be the genetically fixed growth pattern.

On the contrary, f, h and s3 were all sampled at 4.5m from the trunk, which allows a direct comparison. Increased root biomass in the topsoil (0-10cm) for f compared to s3 and h is mainly due to a higher amount of fine root biomass but also the presence of primary roots (data not shown), which are lacking from the other zones at that depth (Figure 9). Promotion of root growth under the frond pile might be attributed to more constant humidity and enhanced nutrient cycling. Frond piles could be important for cycling of nutrients and as reserves for water during the dry season, which might lead to the fact that primary roots are growing up, even into the decomposing material. A significant difference between harvesting path and the inter zone could not be observed (Figure 9). However, in h, compared to the other zones more primary roots were found in the 10 – 20 cm layer than in the 20 – 30 cm (Annex, Figure 19). Yahya et al. (2010) report that compaction through machinery reduced total root biomass under oil palm. The authors sampled on the wheel tracks, which are the most compacted part, while here, sampling points were in the centre of the harvesting path.

GENERAL IMPLICATIONS

The increase of carbon storage of 29.5 t C/ha in total biomass (Table 4) supports the propositions that from a carbon storage point of view, it is desirable to expand oil palm plantations in savannas (or pastures) rather than at the expense of forest (Garcia-Ulloa et al., 2012; Sanquetta et al., 2015; Schroth et al., 2002). Biomass of frond piles and cover crops added further carbon stocks of 4 and 5.5 t C/ha, respectively. Shade tolerant cover crops could add further benefits to mature plantations. This consideration is especially important for a sustainable use of palm oil as a biofuel, as land-use change has the largest impact on green-house gas emissions along the production line (Wicke et al., 2008). However, a carbon and energy balance in regard to biofuel production should not only include land-use change but also inputs, especially fertilizer. Fertilizer use might be much higher on these soils of low fertility than in other settings. According to Harsono et al. (2012) fertilizer production plays an important role in greenhouse gas emissions along the palm oil production line. Therefore, management practises should aim at minimizing those inputs. It remains an open question, however, if the energy and carbon balances can be positive in this setting. Biofuel production should only be considered, if this goal can be reached.

There is a great potential of oil palm compared to annual crops, not only in terms of increased biomass, but especially, because oil palm can be grown as a sort of simple agroforestry system where a lot of residues stay in the plantations (Sanquetta et al., 2015). In terms of conservation of natural ecosystems, agroforestry or tree crops plantations could help to reduce expansion of agricultural land, as they offer a long-term production from the same land (if they are well managed)(Schroth et al., 2002).

However, choosing good management practises seems to be key to finding sustainable alternatives for palm oil production. Rippstein et al. (2001) also stress the need to find agricultural practises to adapt to the extreme soil conditions in the Llanos and lead to sustainable systems. In Colombia, there is already a great interest of researchers and producers in the use of leguminous cover crops and the recycling of organic matter (e.g. returning residues of oil mills to the plantations). These management practises can be expected to have many associated benefits for soil fertility by
increasing soil carbon contents and organic nutrient inputs. This could lower the amount of fertilizer needed, thus lowering production costs and improve energy and carbon balances.

The fact that not only total root biomass but also vertical root distribution varies with biomes, has been studied in a literature synthesis by Jackson et al. (1996). Grasses were found to have shallower root systems than trees. In comparison to the natural savannas, oil palm plantations have more belowground biomass, but also a deeper rooting pattern (Table 5). Deeper roots will lead to carbon inputs to soil at lower depths, which might also affect soil carbon dynamics in the long-term. Jobbagy & Jackson (2000) found that SOC vertical distribution depends significantly on vegetation type and associated this with differences in rooting patterns as well as allocation between AGB and BGB. They mention the possible importance of vegetation change effects on SOC storage in the context of carbon sequestration.

3.6 CONCLUSION
Even though aboveground biomass compares well to values of the lower range found in other regions, belowground biomass seems to be higher, resulting in comparably high root to shoot ratios. We propose that the low fertility of soils in the well-drained Altillanura might lead to increased carbon allocation to the roots affecting the physiology of oil palms.

Comparing biomass of an average aged oil palm plantation with savanna, there was an increase of 29.5 t C/ha. This supports the findings that in regard to carbon storage and climate impact the expansion of oil palm cultivation areas into natural tropical savannas is more desirable than an expansion at the expense of natural forest. With management decisions, carbon stock in biomass can further be increased, by leaving pruned fronds in the plantations, as well as implementing cover crops. For this, a shade tolerant cover crop that can grow also under a closed canopy of mature plantations should be chosen. Those management decisions can be expected to benefit soil fertility and by recycling organic matter might also affect SOC. Therefore, they might lead to lower fertilizer use, which is desirable for agronomic practises, both in the sense of economic as environmental sustainability.

It is clear that, compared to annual crops, tree crops increase biomass and associated carbon stocks. Cultivation of tree crops might, therefore, represent a more sustainable solution for the Llanos region compared to annual crops. In the long term the effect of a land-use change on climate/carbon sequestration should be assessed by investigating long-time changes of SOC, rather than carbon sequestration in biomass, which is, after all only temporary for the time the land-use stays the same. SOC is greatly dependent of amount and distribution on carbon inputs from biomass. Apart from this, SOC content and soil fertility can be affected by management practises (frond pile, cover crops). Therefore, management might have a direct impact on long-term carbon storage.

This is why the second part of this thesis aims at understanding further how the land-use change and root distribution in oil palm plantations influence SOC contents and processes affecting SOC dynamics.
4 EFFECTS OF MANAGEMENT ON CARBON DYNAMICS AND SOC STOCKS AFTER SAVANNA CONVERSION TO OIL PALM

4.1 INTRODUCTION
As described in the first part of this thesis, carbon stocks in biomass increase with the land-use change from savanna to oil palm (section 3.6). However, long-term changes in the carbon sequestration of a given land-use are dependent on the function of soil as a carbon sink or source. Soil organic carbon (SOC) contents have been found to be lower under oil palm than under primary or secondary forest (Sommer et al., 2000). Land-use change could therefore lead to carbon emissions but also soil fertility may be affected, as soil organic carbon is associated with many physical, chemical and biological indicators of soil fertility. Guillaume et al. (2016) found that losses of more than 70% of SOC with conversion of rainforest to oil palm were correlated with the degradation of soils and decrease of chemical and biological fertility parameters. Thus, SOC content directly affects the agronomic (economic and environmental) sustainability of a production system.

Establishing oil palm plantations in the savannas of the Llanos orientales in Colombia is seen as more sustainable, and therefore a desirable alternative for oil palm development in Colombia (Garcia-Ulloa et al., 2012). However, the expansion of the agricultural frontier into the Llanos is driving changes in ecological processes like hydrology, nutrient cycles and greenhouse gas emissions (Romero-Ruiz et al., 2010). The soils of the Altiplanura in the Llanos Orientales are especially susceptible to compaction, erosion and other changes in physical properties through cultivation (degradation) (Rippstein et al., 2001). Therefore, there is a need to assess SOC changes and underlying mechanisms with the land-use change from natural savanna to oil palm.

It is unclear how cultivation is affecting these soils and especially how oil palm cultivation affects SOC and associated soil fertility characteristics. There is some literature about land-use change in grasslands and pastures, with sometimes contradictory results. Batlle-Bayer et al. (2010) review literature about SOC changes after the land-use change of Brazilian Cerrado savannas to pastures and soy-bean; they emphasize the need of good agricultural practises to minimize SOC losses. Frazao et al. (2013) on the other hand compared pasture and oil palm and found 35-46% lower SOC stocks under oil palm, while Goodrick et al. (2014) found an increasing but not significant trend of SOC with conversion from grassland to oil palm.

The situation at the study site in the Llanos Orientales of Colombia, with a very clear and long previous land-use, low estimated SOC and nutrient contents, represents ideal conditions to study changes in carbon input with the land-use change. The low carbon content of the savanna soils allows detecting the input of carbon to soil through oil palm roots and fronds. Additionally, the tool of isotopic signature to analyse SOC allows for allocating the origin of carbon either to C4-grass derived carbon (i.e. “old” carbon) and C3 carbon derived from oil palm (i.e. “new” carbon). This approach has already been used by Goodrick et al. (2014) for conversion of grassland to oil palm.

Mature oil palm plantations show distinct management zones (section 2.2) that have been shown to differ in their soil fertility status (Nelson et al., 2014). The heterogeneous input of organic material from pruned fronds and roots leads to increasingly heterogeneous SOC distribution with
the age of plantations (Frazao et al., 2013). Carbon inputs into a mature oil palm plantation happen through piling up of pruned fronds, growth of oil palm roots and root exudates as well as litter fall and root growth and exudates from groundcover plants, if present (Goodrick et al., 2016). At the end of a plantation cycle there may also be a carbon input from old palm trees, depending on the method of replanting (Bayona et al., 2015). Thus, amount and quality of carbon inputs differ between management zones and in comparison to savanna. While higher biomass inputs might lead to higher SOC accumulation, organic matter input as well as fertilization can also have priming effects that accelerate or slow down carbon cycling (Kuzyakov et al., 2000). Decomposition of soil organic matter pools is determined by amount, quality and availability of the substrates to decomposers ((Six & Jastrow, 2002) cited in (Chen et al., 2014)). SOC contents and quality further have effects on microbial communities (Lal, 2006), which in turn impact the carbon cycling. Carbon and nutrient cycling may therefore have different forms and intensities in the different management zones. Together these effects can change the SOC equilibrium for a given management zone and thereby for the whole land-use.

The understanding of carbon cycling in the plant-soil system and in the management zones of an oil palm plantation, can yield information on management effects on SOC stocks. Thus, it could give indications on which practises can help to increase carbon storage in soil under oil palm. The second part of this thesis aims at investigating the carbon stock development with the land-use change from savanna to oil palm and with oil palm plantation age. The focus lies especially on carbon cycling in the different management zones of a mature oil palm plantation. This will be done using the tool of carbon isotopes for distinguishing carbon pools depending on their origin. This part also makes use of the root biomass measurements of the first part to investigate inputs of carbon through the oil palm root system (section 3.4). To measure biological activity and have a proxy for carbon turnover, microbial biomass, basal respiration and in-situ respiration have been measured in the different management zones.

4.2 HYPOTHESIS

Main question: How do SOC stocks develop with the change from savanna to oil palm?
- How do SOC stocks develop with plantation age when up-scaled to one hectare?
- How do SOC stocks, averaged over the lifecycle of a plantation, compare to SOC stocks in savanna?

Hypothesis 6: SOC stocks are increasing from savanna to oil palm and with oil palm age. Thus from a soil fertility point of view, it is more sustainable to establish oil palm on savannas than on forests.

Main question: How do SOC stocks differ between management zones in a mature plantation?
- How are SOC stocks affected by management zones?
- How does SOC vary with distance to trees at different age stages?
- How can SOC be allocated to root input in the different management zones?

Hypothesis 7: SOC stocks differ between management zones.
Hypothesis 8: Root density, as a proxy for belowground carbon input, decreases with distance to tree. Therefore, SOC contents decrease in distance to tree. There is a correlation between root density and SOC.

Hypothesis 9: SOC levels are highest under the frond piles compared to the other management zones. This carbon can be mainly allocated to the input from decomposing fronds.

Main Question: How is microbial activity, as a proxy for carbon turnover, affected by management zone?

- How does microbial biomass differ between management zones?
- How does basal respiration differ between management zones?
- How do the management zones compare in nutrient contents (especially nitrogen)?
- How do in-situ CO₂-fluxes differ depending on management zones?

Hypothesis 10: Basal respiration and microbial biomass depend on management zone and type of carbon input. They are highest under the frond pile, where there is most of the carbon input.

Hypothesis 11: Nutrient contents depend on management zones, as a consequence of fertilization patterns and different input of organic material.

Hypothesis 12: Soil respiration as an indicator of soil biological activity and carbon stability depends on management zones. It is higher for zones that have received a higher C-input in the past (frond pile) and where there are most nutrients available (weeding circle).

4.3 MATERIAL AND METHODS

SOIL SAMPLING
Soil sampling has been carried out together with root coring as described in section 0. A few weeks after the field campaign, once back in the laboratory, soils were dried in an oven at 40°C for 48 hours. This temperature was chosen in order to keep microorganisms alive for further steps of the analyses.

Like for biomass samples, sub-samples of soil were ground and then analysed for carbon and nitrogen contents and isotopes at the University of Göttingen with an isotope ratio mass spectrometer (Delta Plus, Finnigan MAT, Bremen, Germany). Residual water contents, as assessed by drying soil samples at 105°C, resulted to be undetectable.

Bulk density samples were taken at all depths in a soil pit at the centre of each sampling site. Carbon stocks per m² (carbon density) for the different soil depths were calculated with bulk density and up-scaled in the same way as root biomass (extent of management zones, Table 3). In the mature plantation, values between the three inter zone points (s1-s3) did not differ significantly, therefore, those samples were pooled for upscaling.

CALCULATION OF C3 AND C4 DERIVED CARBON
For the calculation of the origin of carbon, δ¹³C isotopic signals measured at the isotope ratio mass spectrometer against V-PDB were used. Due to fractionation in the CO₂-uptake mechanism, C4-
plants have a different isotopic signature of carbon compared to C3-plants. As savanna vegetation consists of many C4-plants, while oil palm and leguminous cover crops are C3 plants, the origin of SOC can be deduced. Savanna biomass as a mean of above and belowground samples from the two replicated sites had a δ13C value of -13.7‰. Oil palm biomass measured in fine roots of the mature plantation had a δ13C of -28.2‰. δ13C values in savanna soil samples were -13.7, -13.1 and 12.6‰ for 0-10, 10-20 and 20-30 cm, respectively. To account for this fractionation with depth, these values were taken as reference to calculate the fraction of oil palm (or C3-derived) carbon, according to the formula (4) and (5):

\[ f_{NS} = \frac{(\delta^{13}C_{\text{soil sample}} - \delta^{13}C_{\text{OP}})}{(\delta^{13}C_{\text{NS}} - \delta^{13}C_{\text{OP}})} \] (4)

\[ f_{OP} = 1 - f_{NS} \] (5)

where \( f_{NS} \) is the fraction carbon derived from natural savannas, \( f_{OP} \) the fraction of C3-derived carbon, \( \delta^{13}C_{\text{soil sample}} \) is the isotopic signature of the respective soil sample, \( \delta^{13}C_{\text{OP}} \) is the isotopic signature of oil palm fine roots and \( \delta^{13}C_{\text{NS}} \) is the isotopic signature of savanna soils at the respective depth. The resulting fractions of C3- and C4-derived SOC were then used to calculate the respective carbon densities and stocks by multiplying with the amount of total SOC. With the C3-derived carbon density, the net C3 stabilization rate was calculated for each soil sample by dividing the C3-carbon density by the years of oil palm cultivation.

**INCUBATION EXPERIMENT**

Topsoils (0-10 cm) from the mature plantation (9 years old) and the two savannas were chosen to assess the effect of management zones on microbial activity in terms of microbial biomass and basal respiration. The five replicates of each of the two savannas as well as from zones f, h, s3 and w were incubated in the laboratory under controlled conditions. Water holding capacity (WHC) of those soils was assumed to be about 0.2 g water/soil. To achieve a WHC of about 50 to 75% for the incubation, soils were rewetted with 0.15 g water/g dry soil. These values are reported to be the optimal water content for microbial activity (MicroResp™ handbook, (Haney & Haney, 2010)). To this aim, 20 g of dry soil were rewetted with 3 ml deionised water and incubated in marmalade jars (220 ml) at 25°C for 31 days. To assure oxygen availability, jars were opened and ventilated from every week. Care has been taken, to keep constant water contents in the incubation jars. For this aim, jars were weighted regularly and rewetted once with the evaporated amount of water. These samples were used for the determination of microbial C and N.

**BASAL RESPIRATION**

Respiration after rewetting was measured with the MicroResp™ kit (Campbell et al., 2003). For this, triplicated samples of 0.5 g of each soil sample were taken after rewetting and incubated directly in the microwell plate. Long-time incubation is a new use of the microwell plate, which is usually used to assess respiration after addition of substrates. To prevent soil drying out, a moist paper towel was fixed on top of the microwell plate with parafilm and weight was checked regularly. Respiration was measured on days 1, 2, 4, 8, 15, 24 and 31 after rewetting. The procedure of the MicroResp™ kit was followed for respiration measurements. For each measurement, the soils in the micro well plate were covered between 6 and 10 hours with the indicator plate on top and incubation continued at 25°C. The indicator plate was read before and after with a spectrophotometer (Microplate reader (BioTek SynergyMX) at 570 nm). To make sure that no residual CO₂ was in the micro wells, the plate was aerated with a fan before putting the indicator plate on. The absorption of the spectrophotometer was calibrated according to indication
in the MicroResp™ handbook. Headspace volume was estimated in the end by adding water to the wells.

**Microbial C and N Contents**

After incubation of 31 days, carbon and nitrogen in microbial biomass was measured by the fumigation-extraction method (Vance et al., 1987). Five grams of soil were fumigated for 24 hours with ethanol-free chloroform (CHCl₃) in a desiccator under vacuum. After fumigation, soils were shaken one hour in 25 ml solution of 0.5 M K₂SO₄ and then filtered through a MN 640 d filter. Control samples (non-fumigated) were extracted and measured at the same time. TOC and TN were analysed with a TOC-N analyser (Shimadzu, Kyoto, Japan). Carbon in the non-fumigated samples was taken as dissolved organic carbon (DOC). The difference between fumigated and non-fumigated samples was taken as the carbon and nitrogen in microbial biomass. Carbon was corrected with a factor of 0.45 (Beck et al., 1997), nitrogen with a factor of 0.54 (Brookes et al., 1985). Microbial biomass C and N are expressed as mg g⁻¹ of oven dry soil (60°C for 48 h, residual water assessed at 105°C for 24h was not measurable). Microbial C/N ratios were calculated with the obtained values. The metabolic quotient was calculated as basal respiration per gram of microbial biomass C (Cmic).

**Soluble Phosphorous and Microbial P Content**

Extractable phosphorous was also measured for the soils of the 9 years old plantation after 31 days of incubation. For microbial phosphorus, the samples were fumigated with ethanol-free chloroform for 24 hours in a desiccator, as described for microbial C and N. Phosphorous was extracted with 0.03 N Ammonium fluoride (NH₄F) and 0.025 N hydrochloric acid (HCl) as proposed for acidic soils (Bray & Kurtz, 1945). The method yields acid soluble and adsorbed phosphorous. To this aim, 3 g of soil were extracted with 20 ml of NH₄F/HCl solution. After shaking for 15 minutes, extracts were filtered through a MN 640 d filter. Phosphorous concentration in the extracts was measured by colorimetry with an ammonium paramolybdate - stannous chloride dehydrate colorimetric reagent. Absorbance was measured with a UV/VIS spectrometer (Lambda 35, Perkin Elmer, Buckinghamshire, United Kingdom) at 660 nm. Microbial biomass phosphorous was estimated as the difference between fumigated and non-fumigated concentrations and corrected with a factor of 0.4 (0.38 for P, (Brookes et al., 1982)). Microbial biomass P is expressed as mg g⁻¹ of oven dry soil (60°C for 48 h, residual water assessed at 105°C for 24h was not measurable).

**In Situ Respiration Measurements**

**In situ** soil respiration (CO₂-emissions) in the mature plantation (9 years old) was measured with a LI-COR 8100A Automated Soil Gas Flux System (LI-COR Inc., Nebraska, USA) as a proxy for carbon stability and soil biological activity in the different management zones. To minimize possible perturbation effects (e.g. handling of the chamber) during the respiration measurements, collars of 10 cm diameter were pushed into the soils at a depth of 3 cm three days prior to the first measurement. The same locations as for soil/root sampling were chosen on five trees in the weeding circle (w), inter zone (s) and frond pile (f). A day of continuous measurements showed that daily variations were small, and that tree variability was much higher in comparison. Nevertheless, measurements were carried out always between 9 am and 11:30 am, because fluxes at that time are most representative of daily fluxes (reference?). Measurements were only carried out after at least a full night without rain. As soils are well drained, this short delay was assumed to be long enough. Rings were shaded upon the measurements time so as to keep the soil
temperature as constant as possible in all the collars. Together with each respiration measurement, air and soil temperature at 10 cm depth were measured. Water content was measured at 10 cm depth with a TDR (FieldScout TDR 100 Soil Moisture Meter, Spectrum Technologies, Inc., 12-cm rods). For correlating these measures with root biomass, at the end of all measurements, roots were sampled in all rings for the depth of 0-10 cm with a root auger (d=5cm) and dry weight of biomass was assessed.

STATISTICS
General description of statistical tests are described under 2.4. For respiration in the field as well as measurements of basal respiration during incubation in the laboratory, repeated measurement analysis of variance was used to investigate differences between management zones.
4.4 Results

Soil Organic Carbon Stocks and Origin of Carbon

There was a trend of decrease of SOC stocks with time under oil palm plantation (Figure 10). However, the two young plantations and the two savanna sites had rather similar SOC stocks, while the nine years old plantation had much lower SOC values. In the two years old plantation we even found slightly higher SOC contents compared to the mean of the two savannas. The effect of age was significant for both 0-30 cm and 0-10 cm (p<0.01). However, since there were high variations between the two savanna sites (pooled in Figure 10), it is hazardous to make a statement on the short term trend in SOC of oil palm cultivation. For further information, it is worth to consider the stocks in SOC derived from C4-savanna and C3-oil palm. It can be seen that over the measured soil profile from 0 to 30 cm, C3-derived carbon increased with plantation age, while C4-derived carbon decreased. This trend is even stronger in the 0-10 cm layer. Thus, in the surface soil layer of the mature plantation, on average 36% of total carbon was C3-derived.

![SOC stocks (0-30 cm)](image1)

![SOC stocks (0-10 cm)](image2)

Figure 10: Development of SOC stocks with age of plantation. C4-derived means carbon coming from savanna biomass. C3-derived is carbon from oil palm or cover crops. Data for the two measured savannas were pooled to have a starting point (zero years of oil palm cultivation). To show the high variability of the two reference sites, error bars represent standard deviation.

In the mature plantation, total carbon stocks as well as C3-carbon stocks differed between management zones (Figure 11). For the top soil (0-10 cm) there was a significant effect of management zones on total C density (p=0.006), but only s1 is significantly different from f and w (Tukey). C3 (oil palm-derived) stocks under f and w were only significantly higher than in s1 and s2 (Tukey) for the top soil. Oil palm-derived carbon stocks increased slightly with distance to the trunk (s1>s2>s3), but this trend was not significant. In w the stock of C4-derived (savanna-derived) carbon was lower than in the other zones, but this difference was not significant. However, w had highest total carbon stocks together with f. For the lower depths, all differences were less pronounced. This shows how the oil palm cultivation increases heterogeneity in SOC distribution close to soil surface.
Net carbon stabilization rates, calculated as the C3-derived carbon stock divided by age of plantations, differed considerably between management zones and ages of plantations (Figure 12). For the 9 years old plantation, stabilization rates were highest in frond piles and weeding circle and lower for all the points in between palm lines (h, s1-s3). On the other hand, stabilization rates in young plantations were as high as the values for frond pile and weeding circle in the mature plantation. The value in s1 for the youngest (2 years old) plantation was especially high.

Figure 11: Carbon density according to depth in different management zones of a mature OP plantation. Horizontal lines show the mean value (red) and the standard error (grey) of the savanna references for the respective depth. Error bars show standard errors.

Figure 12: Net carbon stabilization rates for soil depth 0-10 cm at different measurement points in all ages of oil palm plantations.
Total root biomass, as measured in the first part of this thesis, correlated badly with SOC stocks. However, fine root biomass could explain 71% of the variation in C3-stocks in different ages and at different depths for the weeding circles (Figure 13).

C/N ratios differed considerably depending on biomass compartment (Table 6). This is showing the different quality of the plant materials and may have implications for their decomposition.

![Figure 13: Correlation of oil palm fine roots with stocks of C3-derived carbon in weeding circles of oil palm plantations including all ages (2, 4 and 9 years) and depths (0-30 cm). Linear regression (black) with R²=0.71 is plotted.](image)

<table>
<thead>
<tr>
<th>compartment</th>
<th>C/N ratio</th>
</tr>
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<tbody>
<tr>
<td>OP Petiole</td>
<td>139</td>
</tr>
<tr>
<td>OP Rachis</td>
<td>113</td>
</tr>
<tr>
<td>OP Leaflet</td>
<td>19</td>
</tr>
<tr>
<td>frond pile mean</td>
<td>68</td>
</tr>
<tr>
<td>frond pile (OF)</td>
<td>29</td>
</tr>
<tr>
<td>OP coarse roots</td>
<td>116</td>
</tr>
<tr>
<td>OP fine roots</td>
<td>62</td>
</tr>
<tr>
<td>Desmodium AGB</td>
<td>36</td>
</tr>
<tr>
<td>Kudzu AGB</td>
<td>18</td>
</tr>
<tr>
<td>Savanna AGB</td>
<td>65</td>
</tr>
</tbody>
</table>
**Incubation Experiment: Respiration and Microbial Biomass**

Respiration of the soils incubated in microwells peaked on the first and second day after rewetting the soils (Figure 14). The frond pile samples already showed high fluxes on the first day after rewetting. On day four after rewetting, fluxes were already much lower, reaching constant values on day eight. Higher fluxes on day 18 might be due to some disturbance because of differences in moisture of the paper towel put on top of the respiration plate. On day 24 the incubation had to be done for 25 hours (instead of 6 to 10 hours), due to technical problems. It can be seen that for this date differences between samples were smaller than on other days. To calculate basal respiration, a mean over the days 8, 15, 24 and 31 was taken.

![Graph](image_url)

**Figure 14**: Respiration during incubation of top soils (0-10 cm). Days after rewetting soil are shown. NS1 and NS2 are the two savanna sites. F, h, s and w, are oil palm management zones of the mature plantation.

It is evident that many of the measured parameters showed similar patterns for the four measured main zones (f, h, s3 and w) (Figure 15), even though linear regressions show no significant relations between different parameters. For total (Figure 9) and fine root density, soil organic carbon contents and basal respiration, values were higher in w and f than in h and s3. All of those parameters are related to the carbon cycle. Also basal respiration expressed as CO$_2$ respired per mg SOC (Figure 15) and microbial biomass (Cmic) (Figure 16) followed this pattern. On the contrary, microbial biomass itself (Cmic) and C/N ratio of microbial biomass had lowest values in f and w (Figure 16).
Figure 15: Effect of management zones on total OP root biomass, total carbon stocks, basal respiration and respiration per mg soil organic carbon. Different letters represent significant differences between management zones (tukey tests, p<0.05)). Red lines represent mean and standard error (dotted) of the 10 savanna samples.

Some of the fertility parameters were measured for savannas and plantation zones (no significance tests were done). DOC and microbial biomass were lower in all oil palm management zones compared to savanna (Figure 16 and Figure 17). Metabolic quotient was higher than savanna in f and w, indicating increased activity of microorganisms compared to savanna in those two zones (Figure 16). Soil C/N ratios were lower than in savannas for all zones except for the frond pile, indicating fertilization effects in w, s3 and h and possible N limitation under the frond pile (Figure 17).

C/N and C/P ratios in soil were especially low in w, indicating high nutrient concentrations (Figure 17). There were significant differences between management zones for DOC. Carbon to nutrient ratios and DOC contents can give indications on the quality of carbon in the respective zones.
Figure 16: Microbial biomass (Cmic), microbial stoichiometry (C/N and C/P) and metabolic quotient (CO2-production/microbial biomass). Different letters represent significant differences between management zones (tukey tests, p<0.05). Red lines represent mean and standard error (dotted) of the 10 savanna samples.

Figure 17: Carbon to nutrient (N and P) ratios in soil and dissolved organic carbon (DOC), corresponding to extractable C. Different letters represent significant differences between management zones (tukey tests, p<0.05)). Red lines represent mean and standard error (dotted) of the 10 savanna samples.
**Turnover and Biological Activity: In-situ Respiration**

Fluxes averaged over five measuring days decreased in the order weeding circle > frond pile > inter zone, with significant higher respiration rates in w than s (Figure 18). Variations were smaller under the frond piles than in the other zones. This holds true also for daily variations (Annex, Figure 21). Correlation of fluxes with roots per zone was not significant.

![In-situ respiration in different management zones](Image)

Figure 18: *In-situ* respiration in different management zones (frond pile, inter zone and weeding circle). Data from 5 measurement days were averaged, points display means over 5 measurement points and standard errors. Letters show significant differences according to tukey tests after repeated measurement ANOVA (p<0.05).
4.5 DISCUSSION

SOC STOCKS AT THE INVESTIGATED SITES
There was a trend of decrease in SOC over the time under oil palm cultivation (Hypothesis 6). (Figure 10). The effect with time under oil palm cultivation was significant, but there were other factors affecting SOC (linear regression resulted in $R^2=0.3$). However, the two savannas and the two young plantations did not differ significantly in SOC stocks. Only the 9 years old plantation had significantly lower SOC stock than the other sampled sites. It is clear that for a definitive answer on how SOC develops with oil palm age, more sites or longer time series would be needed. After an effect of the land-use change on SOC, there are alternative explanations for the low value in the mature plantation. First, the great variability between sites: even though savannas were chosen close to the plantations, values differed greatly between the two savanna sites and plantations. Therefore, it is not possible, with our space for time substitution approach, to deduce the actual SOC concentrations of the original reference savannas, before oil palm was planted. Initial SOC stocks, before oil palm establishment, might have been already lower at the site of the mature plantation. At the respective depth, SOC stocks of savannas were always higher than all management zones (Figure 11). Contents at 20-30 cm depth might reflect the original homogeneous distributed levels of the initial savanna, as the values between zones do not differ (Figure 11). Second, bad management of the plantation might have led not only to a loss of carbon itself, but may also have led to a considerable amount of erosion and thus to a loss of top soil. This could be seen by slight differences in topography inside the plantation, as well as the mat of oil palm fine roots that was exposed to air at some places. This methodological limitation clearly shows that more site replicates or points with age are needed for a precise investigation of the land-use change effect on SOC. However, despite the factors of natural site variability and different management practises, it is hard to imagine from the here found results that SOC contents could increase with the land-use change.

On the other hand, SOC stocks in the two young plantations were similar to the savanna reference sites (Figure 10). This could be attributed to similar initial conditions and reflect the natural variability of carbon stocks. But, there seemed to be also an effect of the use of cover crops. The high carbon input under cover crops can be seen in the carbon stabilization rates (stock of C3-carbon accumulated per year) (Figure 12). Rates for the inter zone points (s1 – s3) in young plantations were comparable to rates in the weeding circles and much higher than stabilization rates in the inter zone of the mature plantation. The rates show a considerable input of organic material and accumulation of C3-carbon under cover crops. The surprisingly high rate in s1 for the 2 years old plantation could be due to sample handling or temporal variation, since this point was sampled about 1 month later than all others. It could also indicate that at this point, where roots of oil palm are interacting with cover crops; there is a high input of organic matter to the soil. The result suggests that with this management practise, carbon contents might be at least maintained with the land-use change from savanna to oil palm. Nevertheless, it remains unknown how the effect of cover crops over a longer period would affect carbon contents, as in the older plantation there had never been any cover crops. Certainly, research should address this question for finding a sustainable management practise.

EFFECT OF MANAGEMENT ZONES ON CARBON CYCLING
From the results of the three analysed plantations, SOC could stay constant or decrease with the land-use change. This means that despite a higher input through higher biomass (as found in part
one of this thesis, section 3.6), new carbon from the oil palm input is not added to the total SOC, but rather replaces SOC derived from savanna.

Frazao et al. (2013) found no overall change of carbon with plantation age, but spatial heterogeneity increased with plantation age, with increasing SOC close to the trunk and decreasing SOC in between palm lines. Here, total carbon stocks were also higher close to the oil palm trunk than in between lines, although differences were not significant (Figure 11). Under the frond pile, carbon stocks were as high as close to the trunk (w). The lowest values were found for the points of s1 and s2; they were significantly lower than in f and w. Thus, as hypothesized (hypothesis 7), topsoil SOC contents varied with management zones, which shows that accumulation and decomposition of SOC are affected by management zones. This heterogeneity can have two reasons: first, amount of carbon input might differ between zones, depending on root density and frond piles; second, type and amount of SOC input and management may influence the processes of carbon turnover.

Roots were a main factor for carbon input to soils; in zones with high root biomass (w and f), there were also higher SOC contents and net carbon stabilization rates compared to h and s3 (Figure 15 and Figure 12). This is in line with results from other studies (Frazao et al., 2013; Haron et al., 1998). Input from oil palm roots seems to come mainly through fine roots, as regression with carbon derived from oil palm was better than for total root biomass (Figure 13). However, this could also be due to the fact that fine root biomass may be more constant at a single point than coarse root biomass. Input through roots is due to turnover of roots and root exudates (Goodrick et al., 2016). The fact that correlations between root biomass and SOC contents or carbon stabilization rates were not very good, might be due to the fact that current root biomass does not necessarily reflect past root densities, as roots die and therefore distribution slightly changes. Additionally, fine roots which have high turn-over rates, also low C/N ratios of 62, making the carbon more easily decomposable than coarse roots with a C/N ratio of 116 (Table 6). However, the hypothesis 8, that roots are an important carbon source, can be confirmed.

Even though root biomass under the frond pile was slightly higher than in the weeding circle and there is additional carbon input from decomposing fronds, carbon stocks did not differ significantly between the two zones (Hypothesis 9)(Figure 15). This implies that decomposition of organic material is more complete under the frond pile than in the weeding circle. However, respiration per carbon as well as respiration per microbial biomass did not differ between the two zones, although they were higher than in h and s3 (Figure 15 and Figure 16). Thus, in both zones, microorganisms seem to be more efficient than in h and s3. It is possible, that decomposition of pruned fronds actually happens already on the surface, like proposed by others (Frazao et al., 2013; Haron et al., 1998). On the other hand, DOC was significantly higher under frond piles than in the weeding circle even after 31 days of incubation (Figure 17). Haron et al. (1998) proposed that carbon reaches the mineral soil under the frond pile only in form of dissolved or particulate organic carbon with low energy contents. This might be the reason for the high metabolic quotients in f, considering microorganisms would have to respire more to gain energy (Figure 16). A closer look at the development of respiration after rewetting of soils shows that it is possible that the frond pile samples respiration peaked even before the first measurement, which would indicate a high amount of highly labile carbon compared to the other zones whose emissions peak only 1 to 2 days after rewetting (Figure 14). The lowest layer of the frond piles was a sort of organic soil horizon, with well decomposed fibres from oil palm fronds. This mixture had a C/N
ratio of 29, thus, nitrogen seems not to be limiting for decomposition (Table 6). The fact that not only the amount of fine roots was highest in the frond pile zone, but oil palm primary roots were growing up into the described organic layer, while in other zones those were found mainly at a depth of 20-30 cm (see section 3.4), shows that frond piles are biologically highly active zones. There were also different invertebrates and fungi observed in that layer. An explanation for SOC not accumulating under the frond pile, could thus be, that there is a high turnover of labile carbon which keeps nutrients in a continuous cycle. The fact that microbial C/N ratios were as low as in w confirms, that decomposition was not limited by nitrogen. In fact, decomposing leaflets from palm fronds bring a low C/N ratio of 19 (Table 6) and should therefore be easily decomposed. On the other hand, weighing the frond pile in the field, alternating layers of frond petioles and rachis were found that could be associated with at least three full pruning events from three different years. These could be distinguished because full pruning is done once a year, while with harvesting only singular fronds are pruned. It suggests that those woody parts, with C/N ratios of 113 and 149 for rachis and petiole, respectively (Table 6), may remain on the surface for a long time and as the residues are not incorporated into the soil, they do not affect SOC contents. With the agronomists, it was discussed a lot whether distributing pruned fronds more on the surface would have more beneficial impacts than piling them up. Certainly, it would better protect bare soil against erosion. Spreading of fronds was also proposed as a solution in Guillaume et al. (2016), to increase SOC slightly and therefore maintaining microbial activity and protect against erosion. It would be interesting to compare the different effects of piling up vs. spreading fronds on SOC contents. However, in a system with cover crops, spreading becomes more difficult and may not be necessary. Haron et al. (1998) also found that roots were the main input for SOC in an oil palm plantation. They conclude that fronds could also be used for secondary product industries, as pruned fronds did not considerably increase SOC stocks under frond piles. However, in contrast to their findings, in our study root biomass was very high in the frond piles, suggesting that the zone may have agronomic importance in the context of the Llanos Orientales.

SOC stocks are the result of a balance of carbon inputs and decomposition. While fertilization generally leads to higher biomass production and thus higher carbon inputs to soil (Batlle-Bayer et al., 2010), liming and fertilizer application may also lead to accelerated decomposition of SOC (Kuzyakov et al., 2000). As discussed above, roots are the source of most of the carbon that is stabilized in SOC. Without fertilization oil palm growth would evidently not be possible on these soils. However, in the mature plantation C4-derived carbon stocks were lower in the 0-10 cm layer than in the 10-20 cm (Figure 11). This shows that there has been actually a loss of original savanna-derived carbon, as it can be assumed, that the natural savanna soil before land-use change had decreasing SOC contents with depth. How SOC contents develop with the land-use change, depends thus on the capacity of oil palm carbon inputs to replace the lost savanna-derived carbon. The mechanism behind this decrease of C4-derived carbon could be the decomposition of previously recalcitrant SOC, due to fertilizer inputs. Mineral N fertilizer is applied on the weeding circle in the first 4 to 5 years and afterwards spread everywhere, except in the harvesting path. The slightly lower C4 stock under w compared to the other zones, show that fertilizer input from the beginning of plantation may have accelerated decomposition of savanna-derived SOC in this zone (Figure 11). Comeau et al. (2016) measured CO2-emissions in an oil palm plantation on peatland after fertilization and found that heterotrophic respiration was increased for some days after fertilizer application, indicating an accelerated decomposition of SOC if no roots were present. However, if roots are present, they assume that roots would take up the nitrogen. Additionally, input of external C and/or N to the soil through organic matter or mineral N fertilizer can lead to
acceleration (positive priming effect) or retardation (negative priming effect) of soil organic matter decomposition (Kuzyakov et al., 2000). Input of organic matter in the oil palm plantation can be the decomposing fronds in the frond pile, input from cover crop litter and input through the root system that changes in amount and distribution (see first part) compared to savanna. Root biomass and distribution affect C/N inputs both through decomposing dead roots as well as through rhizosphere deposition. Thus, if SOC stocks can stay constant or increase over time of oil palm cultivation depends on the capacity of the new, oil palm-derived carbon to substitute the savanna-derived SOC that is lost due to accelerated decomposition.

There were no significant differences between s3 and h for all measured parameters (Figure 15 - Figure 17), except for the C/N ratio in microbial biomass, where s3 is surprisingly high. The similar values imply that there is no influence of compaction through machinery in h, at least not in the centre of the harvesting path in between the wheel tracks, where samples were taken. Apart from compaction, also fertilization between the two "paths" differs, as harvesting paths in mature plantations do not receive fertilizer, while the rest of the surface does. Nevertheless, there was no difference in C/N ratios of soil, although they are lower than savannas in all zones except for f. A possible explanation for the low nutrient concentrations in s3, despite fertilization can be found in the strong rainfalls, which might have washed away fertilizer. Plantations were flooded normally after heavy rains and, as the paths are slightly lower than the palm lines; this might have led to washing away of nutrients.

**Quality of Carbon Inputs and Microbial Activity in Management Zones**

In general, it seems the discussed differences in amount and quality of carbon and nutrients in the four management zones, had an effect on microbial communities and might therefore have implications for soil fertility. After metabolic quotients, also C/N ratios of microbial biomass and microbial biomass itself differed significantly between management zones (Figure 16). Unlike hypothesized, microbial biomass was lowest under frond piles and in the weeding circle (Hypothesis 10), even though carbon stocks and root biomass were high in these two zones (Figure 15). Haron et al. (1998) found that Cmic increased together with increasing SOC with oil palm plantation age, but also found that under frond piles the microbial biomass was not increasing at the same rate as SOC content. It has been shown that fertilizer type can affect microbial communities (Enwall et al., 2007). Organic fertilizer (manure) has been shown to promote microbial biomass and decomposer food webs under organic farming (Birkhofer et al., 2008). Frond piles could be considered as an organic fertilizer, but microbial biomass was found to be lower than in other zones (Figure 16). However, like discussed above, decomposition of frond pile derived carbon might mainly take place in the organic layer, thus microbial biomass might be higher in this layer than in the mineral soil that we incubated. Further investigations should, therefore, include this organic layer for measurements of biological activity.

However, respiration and also respiration per gram carbon was higher in f and w than in h and s3 (Figure 15)(Hypothesis 10). Looking at metabolic quotients, indicates that microorganisms were more active, as metabolic quotients in f and w are significantly higher than in s3 (Figure 16). With low values for Cmic in f and w, this indicates that there were less, but more active microorganisms, thus a more efficient microbial transformation in f and w than in between palm lines. While here microbial activity, measured as metabolic quotient, in between palm lines (s3 and h) was similar to values measured on savanna soils, there was an increase of microbial activity under frond piles and in the weeding circle. This is in contrasts to findings of constant metabolic quotients with land-
use change from forests to oil palm (Guillaume et al., 2016), but might be due to already low values of SOC under natural conditions. Under the frond pile the high microbial activity might be due to high amounts of DOC (Figure 17), thus labile carbon with concomitant nutrient input from the decomposing leaflets. The microbial C/N ratio was low under the frond pile showing no nitrogen limitation (Figure 16), while C/N ratio in soil was rather high (Figure 17). This might indicate that nitrogen is in fact demobilised/cycled in microbial biomass. In the weeding circle on the other hand, easily degradable carbon, that drives carbon turnover might be especially root exudates and dead fine roots, while coarse roots are more lignified and thus might produce more stable carbon. As expected from fertilization patterns, nutrients do not seem to be limiting in the weeding circle, as indicated by low C/N and C/P ratios both for soil and microbial biomass. This confirms Hypothesis 11 that nutrient contents depend on management zones. In a comparison of savannas to managed pastures it was found that litter quality as indicated by high C/N and C/P ratios controlled decomposition (Trujillo et al., 2006).

C/N ratios of microbial biomass were higher than 10 in all oil palm zones and savannas. This is higher than the average C/N ratio of 8.6 over biomass from many ecosystems given by (Cleveland & Liptzin, 2007). This suggests that there is a comparably high amount of fungi making up the microbial biomass, as C/N ratios of bacteria have been shown to have an average of 6.5 while fungi can have ratios from 5 to 17 (Cleveland & Liptzin, 2007). On the other hand, Haron et al. (1998) report microbial C/N ratios between 26 and 50 under oil palm, but they found no effect of management zones. High microbial C/N ratios might also show nitrogen limitation. Cleveland & Liptzin (2007) suggest that deviations from the average C/N or C/P ratio in microorganisms may show nutrient limitation. Thus, this would imply that in s3 nitrogen is very limiting, while phosphorous seems to be available. However, compared to h, s3 should be well fertilized, but we do not see a difference in the C/N ratio for soil for the two. The high C/N ratio in the inter zone remains an unsolved question. Dormant forms of bacteria might have higher C/N ratios and explain the high value in s3. Only 0.1 to 2 % of the total microbial biomass are active microorganisms (Blagodatskaya & Kuzyakov, 2013). However, results clearly show that microbial communities differ between the management zones.

**FIELD RESPIRATION AS INDICATOR FOR TURNOVER**

In-situ soil respiration decreased in the order weeding circle > frond pile > inter zone (Figure 18)(Hypothesis 12). The in-situ CO$_2$-flux consists of autotrophic root respiration as well as heterotrophic respiration of microorganisms. It can be seen as an integrated indicator of biological activity. It is not surprising, that the inter zone had the lowest values, as root densities and carbon contents were lowest in this zone. The fact that the weeding circle had higher fluxes than the frond pile, is surprising after the above discussed results, as it suggests a more active biology close to the oil palm trunk. As described above, under the frond pile there was a sort of organic horizon of small oil palm residues. This layer had been carefully pushed aside to measure soil respiration. As carbon turnover might be mainly taking place in this organic layer, this biologic activity may be missing in the field respiration measurement. Goodrick et al. (2016) measured CO$_2$-emissions in the frond pile area including oil palm litter and found rates to be twice as high as in the weeding circle. They calculated carbon inputs and found that those were predicting the found emissions better than quality of carbon input or environmental variables. Their results suggested that carbon from the fronds is more easily mineralised than from roots. Adachi et al. (2006) also found that spatial variation of in-situ respiration was explained by SOC content, followed by fine root biomass. Additionally, root respiration in the weeding circle might contribute more to CO2-fluxes than in the
frond pile, as there are more roots at further depth than under the frond piles (Corley, 2016). To have further insights, there are many methods to separate root respiration from heterotrophic respiration in field studies (Kuzyakov & Larionova, 2005). In this context, the most promising approach would be to use stable carbon isotopes ($^{13}$C), as it would allow distinguishing decomposition of savanna-derived and oil palm-derived and possibly even root-derived vs. frond-derived carbon.

**Incubation Experiment: MicroResp™ Method to Measure Basal Respiration**

Assessing basal respiration was a new use for the MicroResp™ kit. Usually, the kit is used to investigate respiration rates after addition of substrates. Incubating a small volume of soil for one month may lead to difficulties maintaining constant moisture. However, moving the small soil volume to the microwell plate might lead to disturbances and therefore higher fluxes of CO$_2$. To avoid this, the soils were left to incubate directly in the microwell, rather than sampling from the incubation batch for every measurement. Weight of the plate stayed constant over time, suggesting that with the wet paper on top, soil moisture was kept constant. Therefore, this method to measure basal respiration seems a feasible approach. Soil was transferred to the microplate and the first measurement was taken immediately afterwards. However, there is a high standard deviation for triplicates of samples for day one and two (Annex, Figure 20), which shows, that the legacy of transferring the soil samples might be quite high during this first phase.

The highest basal respiration was measured for frond piles and weeding circle, to be about 1.9 ug CO2-C/g*d (Figure 15). These values are much lower than the values of 6.6 ug Co2-C/g*d found by (Guillaume et al., 2016) for oil palm. However carbon contents here were around 1 mg C/g soil while in the study by (Guillaume et al., 2016) carbon contents were of 21 mg C/g soil, which might explain the differences. The fact that there is an increase in respiration from the first to the second day shows that the high fluxes are not the effect of soil disturbance but rather the effect of mineralization of the labile carbon pool, like described in (Guillaume et al., 2016).

**Implications of the Carbon Cycling Processes in View of the Land-Use Change**

Comparing the processes and carbon inputs of the four different zones, it can be thus concluded that differences in carbon stocks in the top ten centimetres are mainly due to changing input of carbon through fine roots. This results in lower carbon stocks in between palm lines (h and s3) than in weeding circle and frond pile. Differences in carbon cycling processes between weeding circle and frond pile can mainly be allocated to the differences in quality of carbon input and amount of fertilizer added, which leads to significantly different levels of DOC as well as C/P ratio in soil. The differences in decomposition seem also to affect stocks of savanna-derived carbon. Despite a slightly higher decomposition of savanna-derived carbon in w, the higher total SOC stocks compared to other zones imply that carbon input through oil palm roots and root exudates may be in fact able to balance and replace the lost savanna-derived SOC. Without knowing the initial SOC concentration, this cannot be finally answered. If carbon stock can increase with oil palm cultivation, depends in the end also on the stability of the newly fixed carbon. As quality of savanna biomass and oil palm biomass might differ and further inside the oil palm plantations carbon quality seem to differ, cultivation could change the long-time carbon storage capacity of the soil. In w and f, respiration per gram carbon is higher than in savannas, indicating that in these zones carbon is turned over faster, thus less stable (Figure 15). Thus, apart from decomposition of old carbon also oil-palm derived carbon seems to be cycled faster, enhanced by nutrient supply or carbon quality. These mechanisms could further be explored, by measuring isotopic signature of
the CO2 emissions from different zones to know which pools are actually decomposed. (Nottingham et al., 2015) suggest that mineralization of fresh carbon will be limited by phosphorous availability, while nitrogen limits old carbon. This might be the reason, why despite high inputs, carbon stocks do not differ significantly between management zones.

The equilibrium for SOC stocks that will be reached after the land-use change will depend on the remaining recalcitrant fraction of savanna-derived SOC (e.g. black carbon from fires, as proposed by Goodrick et al. (2014)) as well as the net carbon from oil palm stabilizing in the long-term. It will be therefore important for future research to look at development of SOC stocks under longer oil palm cultivation, as it is possible that changes in SOC stocks might have a different speed or direction than in the initial years. Additionally, it might be important to assess the whole rooting depth of oil palm, as (Goodrick et al., 2014) had found increasing SOC stocks in 0-2m for oil palm planted on grassland and oil palm roots are most dense under the trunk, where the grow deep. Management practices like cover crops and returning residues to plantations might affect those trends and should be further investigated.

Assuming that the agricultural frontier will move further into the Llanos in the future, oil palm, if well managed, might be a good choice compared to annual crops for maintaining or even building up SOC stocks and soil fertility. Other authors mention the advantage of oil palm because of no need for tillage, high return of residues, little compaction and continuous ground cover (if cover crops are implemented) (Frazao et al., 2013; Nelson et al., 2014).

4.6 CONCLUSION
There was a trend of SOC loss from savanna with the age of oil palm plantations until the 9th year. However, variability between sites was very high. Thus, more investigation is needed to see if this trend is due to site variability and if the effect remains over one or more lifecycles of oil palm cultivation. However, substantial stabilization of oil palm-derived carbon was found in a mature plantation, with 36% of the carbon in the topsoil being oil palm-derived after 9 years. Differences in net carbon stabilization rates led to significant differences in oil palm-derived carbon stocks between management zones and a heterogeneous distribution of SOC in mature plantations. Net carbon stabilization rates were high under the frond piles and close to the palm trunk. However, total SOC stocks did not fully reflect these inputs, as part of the new carbon has been replacing old, savanna-derived carbon. This can be attributed to changes in carbon cycling due to fertilization and priming effects, which were especially visible in the weeding circle.

Cover crops in young plantations were found to add considerable amounts of carbon to the soil, with high net carbon stabilization rates. This shows that management can have an impact on carbon sequestration, while the sole fact of planting oil palm in savannas might lead to decreases in SOC. However, it remains open, how good management practices as the implementation of cover crops or recycling of organic wastes with composting will influence the trend of SOC evolution with plantation age.

SOC stocks, net carbon stabilization rates and indicators of chemical and biological soil fertility differed between management zones, showing that different processes dominate nutrient and carbon cycling in the respective zones. Fine roots clearly were an important input of carbon to the soil, also leading to a high net stabilization rate in the weeding circle. Carbon input under the frond pile was lower than the high root biomass and amount of fronds would have suggested. This indicates that carbon derived from the frond pile was not accumulating in the soil. This seems to be
due to a quick decomposition of easily degradable parts of the fronds (leaflets), while the woody parts (petiole and rachis) seem to remain on the soil surface undecomposed. Nutrients seem to be taken up quickly by microorganisms, as shown by low microbial C/N ratios, or by the dense root mat, leading to average soil C/N and C/P ratios under the frond pile. Research could focus on finding an optimal solution to incorporate woody, less well degradable organic matter into soil, considering soil fertility but also the fact that the frond pile may be an important habitat in the otherwise empty plantations. Management zones had significant effects on microbial biomass, C/N ratios of microbial biomass and metabolic quotients. This indicates changes in microbial communities depending on management zones. Especially under frond piles and in the weeding circle, activity of microorganisms was found to be enhanced compared to the other zones and also compared to savanna. This might be due to easily available, labile carbon which is decomposed quickly and, thus, not accumulating in SOC stocks.

For long-term sustainability, it is clearly desirable to have increasing soil organic carbon stocks in an agroecosystem. SOC is important for soil fertility and thus directly affecting productivity of the land. On the other hand, also from an environmental point of view, carbon stored in SOC will remain in the system much longer than the one in biomass. This is especially important for the biofuel discussion. Under the assumption of a further expanding agriculture in the Llanos, it is also interesting to compare the effects on soil fertility of oil palm with those of cultivation of annual crops. No tillage as well as high inputs of residues under oil palm might be beneficial for SOC and with this, physical and chemical soil fertility. More research is needed to investigate management practises and their capacities to increase SOC and production sustainability with a reasonable amount of work and other inputs.

5 GENERAL CONCLUSIONS AND OUTLOOK

Our results suggest that oil palm aboveground biomass in the studied area is similar to other regions. However, comparably high root biomass was found. Results of carbon accumulation rates for above- and belowground biomass as well as high root to shoot ratios, suggest that under the given conditions, carbon allocation to the root system might be higher on these well-drained savanna soils than found in other biomass studies about oil palm. Direct quantification of biomass by uprooting some trees could verify this hypothesis. Quantification of the carbon storage function of savanna and oil palm biomass adds information for carbon budget estimates and could be used in life-cycle assessments. Here, the importance should lie in shifting from calculating C sequestration of plantations at the end of the lifecycle to time averaged values over the whole lifecycle of a plantation, which in our study, was at 15 years.

Higher carbon stocks in biomass compared to savannas, confirm that, in terms of carbon storage, expanding oil palm plantations in savannas is indeed more sustainable than expansion in forested areas. However, even with a positive carbon balance regarding biomass, lifecycle assessments including the land-use change, should take into account CO₂-intensive inputs like fertilizer and fuel use, as well as long-term effects on carbon storage in the soil. Therefore, it remains an open question if the energy and carbon balances can be positive for biofuel production in the Llanos Orientales of Colombia or on grasslands in general.

While carbon storage in biomass is only temporary for the time of the land-use, carbon sequestration into soils happens at a much longer time horizon. Here we found a slightly
decreasing trend of carbon stocks until the 9th year of oil palm plantation. Evidence for decomposition of savanna-derived SOC was found and was attributed to accelerated decomposition through fertilization and priming effects by input of labile carbon. On the other hand roots, especially fine roots of oil palm led to stabilization of “new” SOC. The balance between those two processes developing with plantation age will determine the equilibrium SOC content after savanna conversion to oil palm. To quantify this change and investigate the processes, SOC should be assessed over the whole rooting depth of oil palm and longer time periods. Changes might have different speeds or even different directions in early years after the land use change than in the long-term (whole cycle of oil palm or even more than one cycle). This is of a special concern, as SOC has a central role for soil fertility. Thus, it affects not only carbon storage in view of the climate change problematic, but also viability of the agricultural system. In the short term it influences costs associated with fertilizer and in the long term it defines if the newly cultivated land can be continued to be cultivated.

Combining the two parts of this thesis, management practises can increase both carbon storage in biomass, as well as in SOC. To design oil palm production systems that are environmentally and economically sustainable, practises to improve carbon storage and nutrient cycling should be considered and investigated more. Frond piles were concluded to have an important role in nutrient cycling in oil palm plantations. High root densities and an active microbiology indicate the agronomic importance of this management zone. However, carbon is mostly decomposed on the soil surface; thus, this management practise does affect SOC stocks only indirectly via root input. It could be of interest to investigate possibilities of spreading pruned fronds instead of piling them up, without ignoring that frond piles might also represent an important habitat. Also, it could be tested if fertilizer application to the frond pile area can be beneficial, as fronds provide erosion protection and root densities are high for direct uptake of nutrients. Further, the implementation of cover crops seems likely to influence carbon storage in SOC positively. However, the high input of carbon and possibly nitrogen might also affect SOC dynamics. More research is needed to assess long-term effects on carbon and nutrient cycling by implementation of cover crops or addition of organic material like composts.

Thus, in the context of savannas in the Llanos Orientales, well managed oil palm plantations indeed seem to propose a sustainable development, not only in terms of biomass but also in terms of soil fertility. Still, it is clear, that replacing a natural ecosystem as the savannas always comes with environmental costs. Comparison with other, especially annual crops seems necessary, as agriculture is likely to expand further into the Llanos. Apart from ecological considerations, also socioeconomic sustainability should be of concern for decision makers. In this light, oil palm as a crop has the advantage that it is very manual labour intensive, thus, it provides much more employment than other crops that can be mechanized easily. However, there are clearly many social, economic and environmental benefits associated with a diversity of production systems compared to a single crop produced in a region.
REFERENCES


ANNEX

A.1 ROOT BIOMASS

Figure 19: Distribution of root classes in all sampled plantations. OP= oil palm roots, other roots = cover crop or understory roots.
Table 7: Up-scaled root mean dry biomass [t/ha] and standard error (n=5) for savannas and oil palm plantations.

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<th>Savanna</th>
<th>Oil palm plantations</th>
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<tbody>
<tr>
<td></td>
<td>NS1</td>
<td>NS2</td>
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<tr>
<td>OP all</td>
<td></td>
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</tr>
<tr>
<td>OP fine</td>
<td>0.4 ± 0.09</td>
<td>1.75 ± 0.25</td>
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<tr>
<td>other roots</td>
<td>2.24 ± 0.33</td>
<td>2.31 ± 0.78</td>
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A.2 Measuring basal respiration with MicroResp™ (method development)

Figure 20: Respiration during incubation showing the 5 replicates for zone w in oil palm and one savanna site.

Each sample was incubated in triplicates. Means and standard deviation for those triplicates are shown. The high variability for the first two days suggests that the effect of soil disturbance during the transfer is indeed quite high. Afterwards, however the standard deviation diminishes considerably. Therefore, the method seems to be suitable to determine basal respiration (here taken as the mean of day 8 and 15). Other samples had lower standard deviations, which might be due to lower SOC contents.
A.3 **In-situ Respiration**

![Graph of fluxes during the day (N=3)](image)

Figure 21: Daily variation of in-situ respiration.

Average CO₂-fluxes varied between 3.5 and 4.5 umol/m²*s (Figure 21). Daily variability resulted to be small, with higher differences decreasing in the order inter zone > weeding circle > frond pile. This might reflect temperature and moisture changes.