Exploring the Impacts of Different Cropping Systems and Management Practices on Immature Oil Palm and Banana Plant Development

MSc Thesis Plant Production Systems

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Abstract

Oil palm plantations are expanding rapidly at the cost of natural forests. Homogenization of the landscape results in negative environmental and social impacts, prompting the exploration of more sustainable practices. Intercropping oil palm with banana offers economic value and optimises land use. Environmental, terrain-specific and management factors influence the development of oil palm and banana plants. This thesis investigates the impact of cropping systems, first-year management practices and planting distance on the development of immature unfertilised oil palms and irrigated and fertilised banana plants. Fieldwork conducted on an oil palm plantation in Sumatra, Indonesia, involved experimental plots with four treatments, including current and first-year intercropping and monoculture practices. Data analysis showed strong correlations between vegetative variables within oil palm and within banana plants. Positive significant effects were found of first-year watermelon intercropping on the oil palm development variables: height, frond number, leaflet width, and leaf area. Current intercropping showed a significant positive effect on the oil palm variables frond length and leaflet length, while planting distance had no effect on banana plant development. Nutrient partitioning, soil moisture level and light availability are suggested to be critical factors influencing oil palm development in intercropped systems. Further investigation into the long-term effects of these factors is necessary for better understanding of oil palm and banana plant development in intercropping systems, building further upon previous findings regarding the beneficial impacts of intercropping.

Keywords: oil palm, banana, growth, development, cropping systems, intercropping, management practices, planting distance, sustainable agriculture, Sumatra, Indonesia

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Introduction

The Problem with Monoculture Oil Palm

In numerous tropical regions monoculture oil palm cultivation grows in a rapid pace. This pace is inevitable as the world's population remains increasing resulting in a high demand for palm oil to use for fats and oils. As oil palm plantations expand, they contribute to changes in land use, primarily leading to the reduction of tropical rainforests, peatlands, and traditional land use systems (Burgess *et al.,* 2012; Corley and Tinker, 2016 p. 523-526; Tan *et al.,* 2009; Wicke *et al.,* 2011). The expansion of these monoculture plantations leads to homogenization of landscapes including negative environmental and social consequences as biodiversity loss, greenhouse gas emissions, wildfires, land tenure changes and conflicts about human rights (Corley & Tinker, 2016 p. 526-532; Koh & Wilcove, 2008; Wakker *et al.,* 2004; Wicke *et al*., 2008; Wicke *et al.,* 2011).
Worldwide, Indonesia is the leader of palm oil production and produces 45,500 thousand metric tons of palm oil in 2022/2023, compared to Malaysia, number 2 in the ranking, which produces 18,800 thousand metric tons (US Department of Agriculture & USDA Foreign Agricultural Service, January 12, 2023). The total land area of oil palm plantations in Indonesia expanded from 10.13 to 14.62 million hectares between 2012 and 2021 (*Statistics Indonesia*, November 30, 2022). The five provinces responsible for producing two-thirds of Indonesia's palm oil are situated on the islands of Kalimantan and Sumatra. These provinces include Riau, West Kalimantan, Central Kalimantan, East Kalimantan, and North Sumatra (*Statistics Indonesia,* December 1, 2022). The large and ever-expanding total area of oil palm cultivation, and the negative consequences, explain why campaigns have been set up calling for a ban on oil palm and why many organisations express their concerns about sustainability in oil palm monocultures (Corley & Tinker, 2016, p. 519-523).
However, oil palm is the most efficient oil producing crop far outreaching other vegetable oils as rapeseed, soybean, sunflower, coconut and olive looking at the average yield per hectare (Goh, 2016; Tan *et al.,* 2009; Figure 1). Expanding and producing the same amount of oil from these other crops will thus lead into more changes in land use. Besides that, producing oil palm is relatively cheap compared to the other crops. This makes it crucial to investigate how the sustainability of oil palm cultivation can be improved, as only palm oil can potentially provide the world population of sufficient fats and vegetable oil (Goh, 2016; Tan *et al.,* 2009).

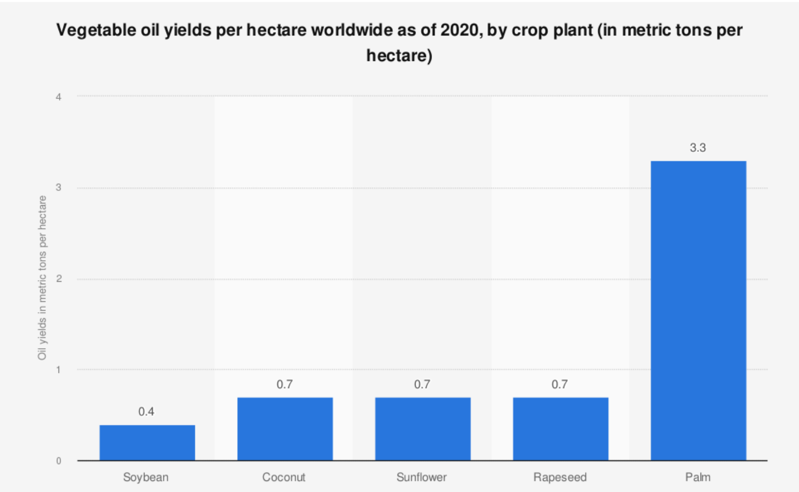

Figure 1 Vegetable oil yields per hectare worldwide as of 2020 by crop plant in metric tonnes per hectare, adapted from WWF (January 17, 2020).

Intercropping: A Promising Solution

A promising land management choice for a more sustainable way of producing oil palm is intercropping during the immature phase. This is easily explained as: using the unused area between the oil palm rows to plant other crops during the oil palm development stage (Namanji *et al.*, 2021). Intercropping in the immature phase can be practiced from the oil palm planting period until the onset of harvesting, primarily to utilize the unused space between the oil palm rows. By doing this, land use is maximized, decreasing the total land needed for agriculture compared to monocultures (Dissanayake & Palihakkara, 2019; Omar *et al.*, 2010). During the immature phase, the palm provides no fresh fruit bunches for oil production, making it economically beneficial to cultivate another crop since no income is generated from the oil palm at this stage. Growing the intercrop in the unused spaces can provide an early income, food security, weed suppression and an increase in nutrients in the soil, leading to improved soil fertility (Dissanayake & Palihakkara, 2019; Namanji *et al.*, 2021; Reddy *et al.,* 2004). Moreover, intercropping can improve biodiversity on the plantation as a result of growing different crops that can attract more and different (crop specific) species (Ashraf *et al.,* 2018). The intercrop can help with reducing the pressure of pests and diseases by disrupting the habitat of oil palm specific pests (Dissanayake & Palihakkara, 2019; Dissanayake & Palihakkara, 2023; Namanji *et al.,* 2021).

Challenges and Considerations in Intercropping

However, there are several reasons why intercropping with immature oil palm would not be beneficial. Management wise it can be more complex and labour-intensive to take care of two crops in an intercropping system compared to one in a monoculture as each crop may have specific requirements. If these requirements are not properly met, the crops may compete for resources which may cause a negative influence on their performance (Brainard & Bellinder, 2004; Dissanayake & Palihakkara, 2019). Also, there may be less space available between the crops making it harder to use mobile machinery (Amoah *et al.,* 1995; Dissanayake & Palihakkara, 2019). The closer distance between the crops may also make physical pest, disease and weed suppression harder and, if crops are not matched well, may serve as a host for transmitting pathogens to the other crop (Dissanayake & Palihakkara, 2019; Yu *et al.,* 2022). Another reason for not using intercropping practices is the lack of education and training for farmers on how to start and manage the system (Namanji *et al.,* 2021). These possible negative effects of intercropping emphasize the importance of the decision which intercrops to choose to create a successful intercropping system.

Intercropping Oil Palm with Banana

Banana is an herbaceous plant with a pseudo-stem and an underground stem with a shallow root system. The pseudo-stem consists of leaves rolled up over each other and forms an apparent trunk. Suckers grow next the pseudo-stem to replace the plant after it has produced fruits. Inside the stem a bud produces leaves and flowers. These flowers form a spike, which grows vertically downwards and bears both male and female flowers. Female flowers are pressed closely together and will develop into bananas, while the male flowers exist on the end of the spike and will die quickly. The spike creates only one bunch of bananas, consisting of several hands and fingers and then it will die (FAO, n.d., Figure 2).

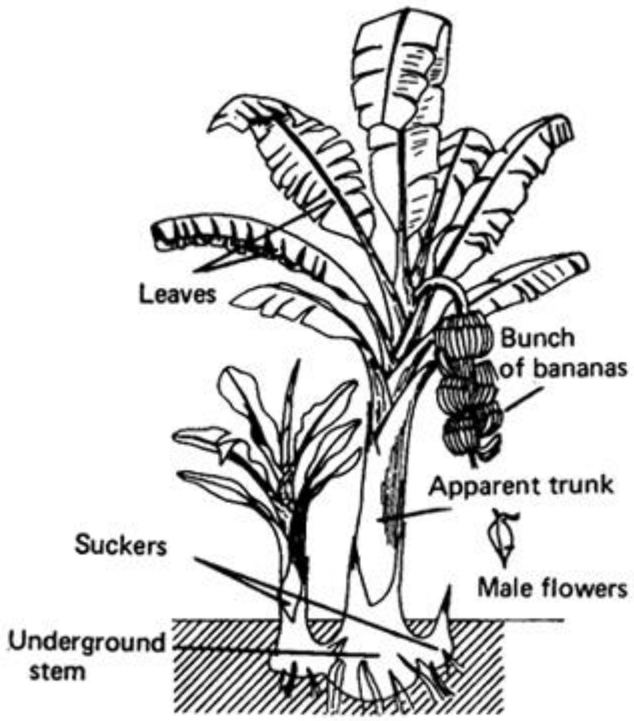

Figure 2 Banana plant, adapted from FAO (n.d).

In total, only a few studies have been published on the results and methods of intercropping oil palm with banana. Despite this general lack of results, choosing banana plants as an intercrop for oil palm can be especially an economically valuable decision without detrimental effects on oil palm growth. Banana was found the most profitable crop when intercropped with oil palm compared to turmeric and spider lily (Reddy & Suresh, 2009). In addition, no or minimal competition between banana and oil palm was found during the first 2 to 3 years for light, water and nutrients (Dissanayake & Palihakkara, 2023). It was also observed that intercropping banana in spaces between immature oil palm does not lead to competition between the two crops (Namanji *et al,* 2021). Further, no negative impact of the banana intercrop on the first harvest of the oil palm's fresh fruit bunches was found (Reddy *et al,* 2004). In addition, the highest banana yield was obtained in the first year of banana cultivation in a young oil palm plantation, compared to the banana yield of the following two years (Gawankar *et al.,* 2018), showing a positive performance result when intercropped with oil palm in the first year. However, management information on both oil palms and banana plants in these studies is lacking, making it difficult to confidently support these results in favour of oil palm-banana intercropping.

Complementarity and Competition between Oil Palm and Banana

Crops can compete for resources or improve and emphasize each other's resource needs. Intercropping becomes especially successful when resources are used in different ways. Partitioning of resources can be in space, in time or in other chemical forms, and happens above- and belowground. When complementation or facilitation occurs, the intercropping system is using resources better in combination, compared to separately in a monoculture. In this case the performance of one crop is increased by the presence of the other neighbouring crops. The other way around, when resources are used by both crops in time and space, competition can occur (Willey, 1990; Yu *et al.,* 2022).

Important resources of which competition and facilitation apply to are light, water and nutrients. At first, when oil palms grow to maturity, length and canopy size will increase and may overshadow the banana plants which can lead to competition by reducing enough access to sunlight or to complementarity by providing shadow during the hottest moments, preventing water loss and heat stress (Amoah *et al.,* 1995; Hidayat *et al.,* 2021). In this thesis, the oil palms are immature, meaning that both the canopy and the height are relatively small and that the banana leaf canopy can have a shading effect over the oil palm instead (Ntamwira *et al.,* 2013; Ocimati *et al.,* 2019; Ocimati *et al.,* 2021). While pruning can increase the yield of the smaller intercrop it may reduce the performance of the overlaying crop (Hidayat *et al.,* 2021; Ocimati *et al.,* 2019). The shading effect of either oil palm or banana may result in light competition and lower crop performance when not managed properly (Amoah *et al.,* 1995; Hidayat *et al.,* 2021; Ntamwira *et al.,* 2013; Ocimati *et al.,* 2019).

Moreover, water competition in an oil palm-banana intercropping system can occur if requirements for water and root depths overlap, while facilitation can take place if requirements and root systems differ. Oil palms generally have a deep rooting system, reaching depths exceeding 5 meter (Carr, 2011), whereas banana plant have more shallow roots, occasionally extending beyond 0.6 meters (Carr, 2009). This might reduce competition between both plants. However, the effective rooting depths of both plants does overlap. For banana this ranges falls between 0-0.4 meter (Carr, 2009) and most roots of oil palms are found between 0-0.6 meter (Carr, 2011). This overlap raises the possibility for water competition.

Further, both crops can compete for nutrients when having similar requirements resulting in a reduced nutrient availability and potentially a lower yield. Vice versa, if the nutrient requirements of both crops are different, facilitation can occur generating efficient nutrient utilisation and improved yield (Yu *et al.,* 2022). Oil palm takes up approximately 160 kg N, 52 kg P_2O_5, 459 kg K_2O and 74 kg MgO per hectare during the first three years after planting (Fairhurst *et* al., 2019, p. 311). Simultaneously, banana plants have higher nutrient requirements and take up on average 200-400 kg N, 45-60 kg P, 240-480 kg K, 150-180 kg Ca, 40-60 kg Mg and 14-20 kg S per hectare per year (TNUA, n.d.). To decrease the chance of competition, fertilizer applications need to be adjusted to provide sufficient and required nutrients for both crops (Fairhurst *et* al., 2019, p. 78-81; Ghaley *et al.,* 2005).

Factors Affecting Oil Palm Development

Oil palm cultivation ideally requires a mean annual temperature between 24 and 29 degrees Celsius and annual rainfall of 2000 mm or greater. The daily solar radiation should be around 15 MJ m^{-2}.day with windspeeds lower than 10 m s^{-1} (Corley & Tinker, 2016, p. 64). The climatic requirements for banana cultivation are similar, including temperatures between 25 and 30 degrees, annual rainfall of around 1700 mm and windspeeds preferably below 5 m s^{-1} (TNUA, n.d.).

The development of oil palm is affected by multiple factors influencing both monoculture and intercropping systems. First of all, there are environmental factors affecting the development of oil palm, as temperature, sunlight, carbon dioxide and rainfall. When the circumstances of these factors deviate from the required values, this may have consequences for the development of the oil palm (Corley & Tinker, 2016, p. 55-67, 112; Verheye, 2010). Second, terrain specific factors can influence oil palm development, including soil type, soil quality, slope, previous vegetation and land use. These factors may give an indication of the soil capability to support the oil palms. It is important to adjust to and base management practices on the terrain specific factors to prevent deficiencies (Corley & Tinker, 2016, p. 240-244; Verheye, 2010). Third, management practices are crucial factors that can

influence development. These management factors include among others planting density and pattern, irrigation, fertilizer and pesticide use, pruning, disbudding and pest and disease management. These factors are conducted to keep the health and yield of the oil palm as optimal as possible (Corley & Tinker, 2016, p. 105-111, 113-114, 302-306, 442; Verheye, 2010). Genetic variation may affect development, as some varieties are more suited for environmental and terrain specific conditions (Corley & Tinker, 2016, p. 114-116). Also, palm age is a factor, as the nitrogen, potassium and magnesium levels in the leaves decline with oil palm age and productivity will decrease around the age of 25 (Corley & Tinker, 2016, 112-113; Ismail & Mamat, 2002; Petri *et al*., 2023). Lastly, local and governmental factors are of great importance for development of oil palm plantations as (the change of) regulations can affect oil palm cultivation on both small and large scale. For example regulations about deforestation, use of chemical pesticides, labour practices, land tenure and rights, certification schemes and supply chain transparency (Bissonnette, 2016; Gardner *et al.,* 2019; Putri *et al.,* 2022; Schoneveld *et al.,* 2019).
The same factors affect the development of banana plants in the intercropped fields, although with varying optimal values and requirements. Identifying, working with, adjusting to and managing these factors is important to maintain optimal development of both crops.

Oil Palm and Banana Plant Development Indicators

The focus for measuring oil palm development is mainly on aboveground parameters as 96% of the oil palm's total annual dry matter is stored in aboveground biomass (Corley & Tinker, 2016, p. 93). For both oil palm and banana plants, the frond spans in both North-South and East-West direction are indicators for the canopy size and space occupation in the field. The height of the plants indicates vertical growth and biomass (Sheriza *et al*., 2020). Next, observing the number of banana leaves and oil palm fronds and leaflets provides further understanding of plant health, differences in growth rates and the yield potential (Aholoukpè *et al.,* 2013; Corley & Tinker, 2016, 93-95; Farjon *et al.,* 2021). The rachis, petiole and total length of the oil palm fronds offers insights about foliage characteristics, such as leaf morphology and the capability to photosynthesize (Aholoukpè *et al.,* 2013; Yahya *et al.,* 2017). In addition, the length and width of the banana leaves and oil palm leaflets provides information about photosynthetic efficiency, overall growth and adaption to environmental conditions (Yahya *et al.,* 2017; Wang *et al.,* 2021). Observing both male and female inflorescences is interesting as the inflorescence sex ratio is an indicator for oil palm performance as the female inflorescences develop into fruit bunches in contrast to male inflorescences (Corley & Tinker, 2016, p. 118-121). Measuring the SPAD values of leaves gives an indication of leaflet chlorophyll content and the evaluation of nitrogen and photosynthetic activity in the leaflets (Rendana *et al.,* 2015; Sim *et al.,* 2015).
Banana plant assessment focuses on the pseudo-stem diameter and the plant height which are closely related to banana plant development (García *et al*., 2020; Magalhães *et al*., 2020; Miao *et al*., 2022). Also, the number of suckers next to each banana plant can give an indication of proper field management and can affect development indicators of the main banana plant (Bhende & Kurien, 2016). The size of the fingers and weight of bananas can among others be influenced by removing the suckers (Borah *et al*., 2018). By analysing these parameters, oil palm and banana plant development can be researched.

Research Questions

This thesis aims to explore the impacts of different cropping systems, including intercropping and monoculture, and management practices on immature oil palm and banana plant development. One main research question guides this thesis:
Which impact do different cropping systems, including monoculture and intercropping, along with variations in planting distance and first-year management practices, have on the development of immature oil palms and banana plants?

At first, it is possible that the oil palms will benefit from the fertilizer applied to the banana plants. Fertilizing banana plants increases the nutrient content in the soil and the oil palms close to the banana plants may benefit by taking up part of these nutrients (Fairhurst *et al.,* 2019, p.78; Ghaley *et al.,* 2005). In addition, when the bananas are harvested and the residue is left behind, the remaining nutrients can mix into the soil and may be taken up by the oil palms (Pariz *et al.,* 2020; Wairegi & Asten, 2010). This leads to the first research question.
Research question I: *Which effect do the presence and growth of banana plants have on the development of nearby immature oil palms?*

Second, the fields on which the oil palms are cultivated knows two different types of land management practices during the first year. The development of both banana plants and oil palms can be affected by the first-year management practices as a result of differences in soil health and fertility, organic matter, soil compaction, microbial biomass, weed control, nutrient management and pest and disease control (Kanianska, 2016; Ramankutty *et al.,* 2018). The second research question delves into whether land management practices in the previous year influence the development of the oil palms.
Research question II: *What is the effect of first-year oil palm-watermelon intercropping compared to oil palm monoculture, on the second-year development of immature oil palms?*

Third, the distance between the oil palms and the banana plants may be of influence for the growth of the banana plants. A closer or greater distance between the two crops can result in development impacts due to e.g. light availability, pests and diseases, windspeeds, nutrient competition or facilitation and access for management practices (Haque & Sakimin, 2022; Willey, 1990; Yu *et al.,* 2022). For example, the oil palms may take up nutrients that are needed by the banana plants, negatively affecting banana development (Dissanayake & Palihakkara, 2019; Willey, 1990). The possible effects of planting distance leads to the third research question.
Research question III: *Which effect does the distance between immature oil palms and banana plants have on the development of banana plants?*

Methodology

Study Area

Fieldwork was done from mid-October to mid-December 2023 on the Indonesian island Sumatra, in the province Bengkulu. Bengkulu is one of the seven provinces of Sumatra, located in the south-west and is adjacent to the Indian Ocean (Figure 3). The plantation on which the fieldwork was conducted is owned by the company Agricinal and consists of several thousands of hectares, of which the experimental oil palm-banana intercropped field consists of 15 hectares. The banana plants on the experimental field are maintained by the company Arconesia. The oil palms under study were replanted between November and December 2022. This replanted area is characterized by a relatively gentle slope.

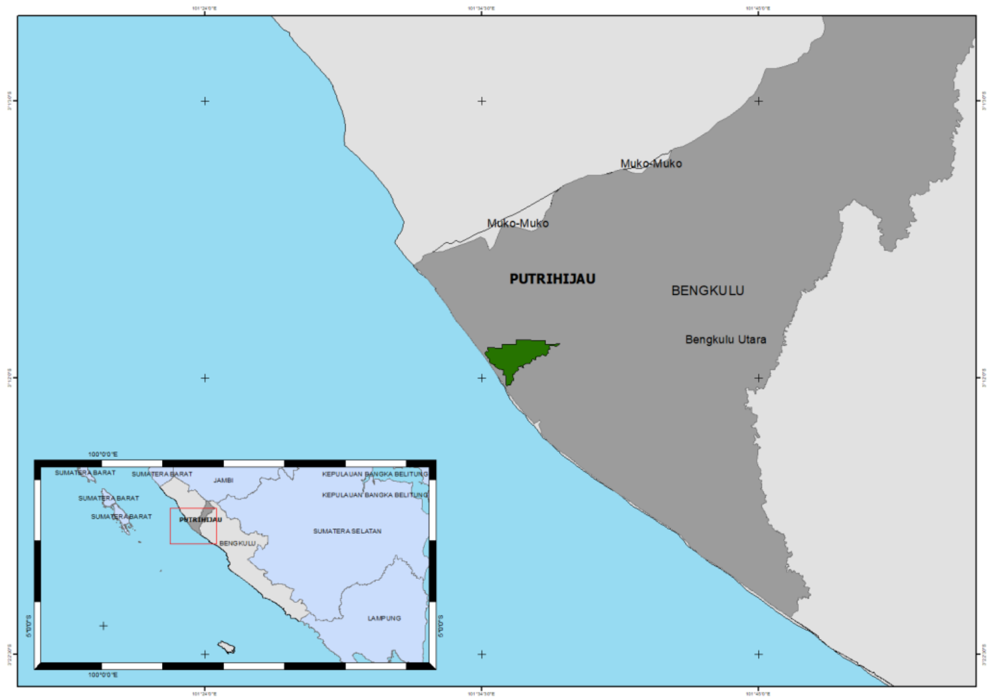

Figure 3 Map of the Bengkulu province and fieldwork area.

One of the major cultivated products in Bengkulu is palm oil due to the favourable environmental conditions for growing oil palm (*The Editors of Encyclopaedia Britannica*, 2023). The dominant climate according to the Köppen-Geiger classification is a tropical rainforest climate (Af) (Peel *et al.*, 2007). This regional climate includes consistent yearly temperatures between 24 and 31 degrees Celsius. The year consists of a wetter and a drier season in terms of precipitation, respectively around 300 mm in the wettest month and 125 mm in the driest month. In addition, windspeeds range between 2.2 and 3.2 m s^{-1} and the daily solar radiation ranges between 15 and 19 MJ (*Weather Spark*, n.d.). Considering these climatic conditions in the fieldwork area, the area can be considered suitable for growing both oil palm and banana plants. During the fieldwork period the precipitation was relatively low, resulting in overall drier conditions compared to previous years.

The soil type of the experimental field was defined as an Inceptisol, which generally has a low organic carbon content. To provide sufficient nutrients for the growth of oil palms and banana plants, fertilizer inputs, including nitrogen, phosphorus and potassium, are essential (Suryatmana *et al.*, 2021).

Data Collection

Experimental Design

The company Arconesia initiated intercropping activities within the replanted area. Initially, the entire site of Arconesia consisted of oil palms intercropped with watermelon. At the moment of writing, the area is used for banana intercropping. The plots are classified in four different treatment groups: oil palm-banana intercropping with first-year oil palm monoculture management (OPB-M), oil palm-banana intercropping with first-year oil palm-watermelon intercropping management (OPB-W), oil palm monoculture with first-year oil palm monoculture management (OPM-M) and oil palm monoculture with first-year oil palm-watermelon intercropping management (OPM-W) (Table 1). In total this research contains 138 oil palms and 120 banana plants.
The plots were established within the replanted area of the plantation. Specifically, the experimental oil palm-banana intercropped field was situated in the centre of this replanted area. The oil palm species that was planted on the plantation is *Elaeis guineensis var. tenera*. In the experimental field the banana species *Musa acuminata* was planted, including 1200 banana plants ha^{-1}. Consequently, the plots within the experimental field were considered pseudo replicates, as they originated from a single source but were treated as independent observations in this thesis.

Table 1 Overview of plots, cropping type, first-year management practice and treatment abbreviation.

Plots (Figure 5)	Cropping type	First-year management practice	Abbreviation
B 1,2,3,5,6	Oil palm-banana intercropping	Oil palm monoculture	OPB-M
BW 1,2,3,4	Oil palm-banana intercropping	Oil palm-watermelon intercropping	OPB-W
M 1,2,3,4,5,6,7,8,9	Monoculture	Oil palm monoculture	OPM-M
MW 1,2,3,4	Monoculture	Oil palm-watermelon intercropping	OPM-W

One monoculture plot included 6 oil palms in a triangular planting pattern with a distance of 9 meters between each palm. The set-up of one intercropped plot consisted of 6 oil palms and 12 banana plants (Figure 4). Prior to the fieldwork period from October to December 2023, the monoculture and intercropped plots were marked, and initial measurements were done in June and July 2023.

The map of the fieldwork area including the locations of plots is presented in Figure 5. Originating from 9 July 2022, the map shows a mature oil palm plantation as this date was before the area underwent replanting and oil palm intercropping started. Notably, from the BW plots, a gentle slope downwards was observed in all directions, with an incline observed between the M1,2,3 and B3,5 plots in the northern direction. The MW1,2,3 plots were situated at the lowest elevation, approximately 16 meters above sea level, while the BW1,2 and M1,2,3 plots were located at the highest elevation, around 25 meters above sea level. The fieldwork area shows a maximum slope of 12% and a mean slope of 4%. To the west lies the coastline, outside the map boundary. On the left side, the map features a yellow line indicating the paved road. The white line illustrates the unpaved pebble road through the plantation. The water source used by farmers for banana irrigation is situated to the east of the plots, marked by a blue arrow (Figure 5).

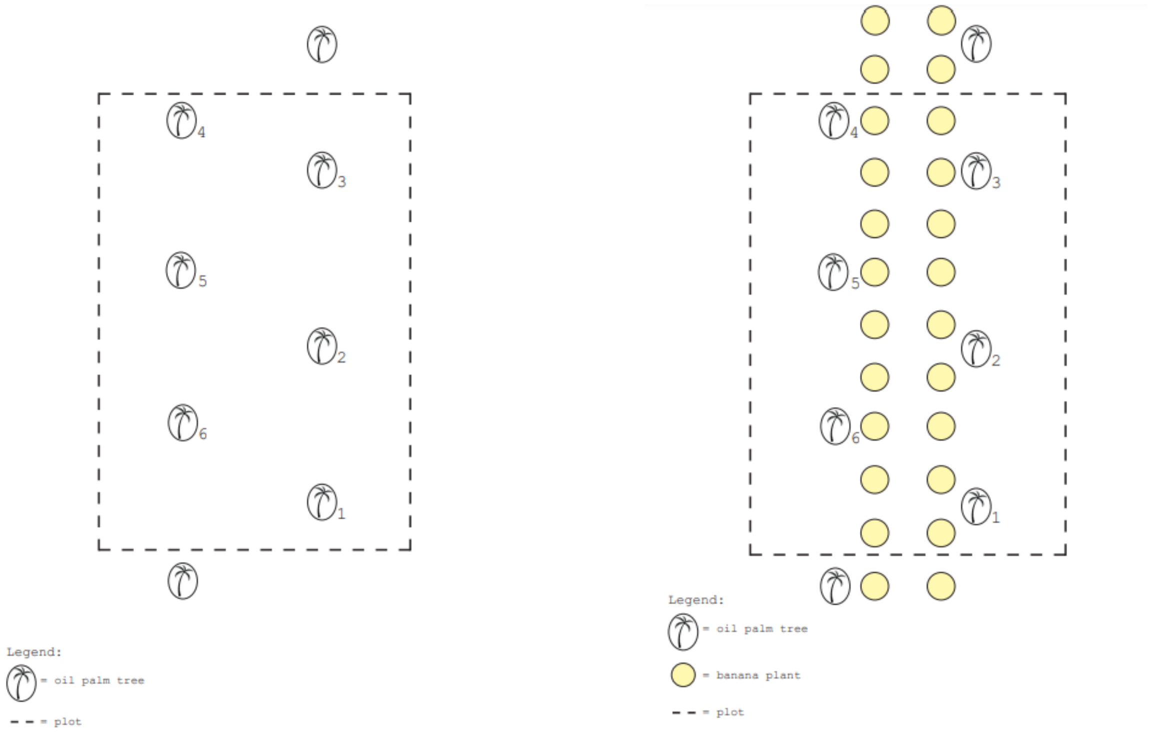

Figure 4 Set-up monoculture plots (left) and set-up intercropped plots (right).

Management Details

To observe similarities and differences between plots with the same or different treatments, details of each plot were noted. These details included, planting dates, fertilizer application, irrigation use, herbicide use, pruning, weeding, weed species, plant appearance, first-year management and soil type. These management details were asked to the maintenance manager of the field and were noted during fieldwork observations.

Multiple management practices were implemented across both the intercropped and monoculture plots. At the moment of measuring the oil palms were approximately two years old, of which one year in the nursery and one year planted on the plantation. For weeding a contact herbicide was used, mixed with water and applied by spraying (Figure 6). These weeding practices were mainly focused on the grasses and plants surrounding the oil palms using 13 cans per ha, including 12 litres of herbicide-water mixture per can, which equates to weeding approximately 10 oil palms per can of herbicide. Roughly four hours after application the result became visible. The timing to start weeding was primarily based on observations, when the grass grew to a height that obstructed palm development, typically occurring around once every three months. This weeding practice was used around the palms in both the intercropped and monoculture areas. Other than that, no pesticides were used on the entire plantation. Also, around once every three months the lower, (almost) dead oil palm fronds were removed and used as mulch around the oil palms in the monoculture area and between the oil palm and banana plant rows in the intercropped area.

Figure 5 Map of the plots in the fieldwork area.

Figure 6 Herbicide use around the immature oil palms.

For the banana plants the non-selective herbicide, Syngenta Touchdown, was used for weeding around the banana plants and in between the two banana plant rows when the banana plants grew older. A total of 2-3 litres of the herbicide per hectare (before mixing with water) was used and mixed with water up to 15 litres per can. The same as for the oil palms, the contact herbicide was sprayed on the weeds around the banana plants and the result became visible within a few hours. This application was repeated every seven weeks for each banana plant. Additionally, fertiliser types and applications differed per growth stage of the banana plants. The dose per banana plant was applied in the first week of each indicated month (Table 2). After the fertilizer was applied a handful of soil was put over and left to further soak into the soil. After eight months there was a shift in fertiliser type from stimulating plant growth to promoting productivity (Table 2).

Table 2 Fertiliser application scheme Banana Plants.

Months after planting	**Fertiliser type**	**Dose per banana plant**	**Nutrient composition (%)**	**Fertiliser type**	**Dose per banana plant**	**Nutrient composition (%)**
1 – 2	Yara Mila UNIK	100 grams	16 N – 16 P – 16 K			
3	-	-	-	-		
4	Yara Mila WINNER	250 grams	15 N – 9 P – 20 K – 0.7 Mg – 3.4 S	YaraLiva NITRABOR	250 grams	15 N – 26 Ca – 0.3 B
6	Yara Mila WINNER	250 grams	15 N – 9 P – 20 K – 0.7 Mg – 3.4 S	YaraLiva NITRABOR	250 grams	15 N – 26 Ca – 0.3 B

8	Yara Mila WINNER	250 grams	15 N – 9 P – 20 K – 0.7 Mg – 3.4 S	YaraLiva NITRABOR	250 grams	15 N – 26 Ca – 0.3 B
9 – 10	Yara Mila COMPLEX	25 grams	12 N – 11 P – 18 K – 2.7 Mg – 20 S – 0.015 B – 0.2 Fe – 0.02 Mn – 0.02 Zn	YaraLiva NITRABOR	250 grams	15 N – 26 Ca – 0.3 B

The lower banana leaves were removed when turning yellow and left in between the banana plant rows as mulch. Moreover, the banana plants were drip-irrigated when there was no precipitation and the soil was dry, which was the case for nearly the entire fieldwork period. The water for irrigation was pumped up from the nearest river through rubber pipes to a water tank and connected to rubber pipes in the field. The water dripped into the soil, out of the holes in the rubber pipes, next to banana plants (Figure 7). Furthermore, to ensure that subsequent banana plants would grow, the farmers maintained a sucker management of keeping three suckers and removing the extra ones. The banana plants were planted at different moments in time, in different blocks, so that the banana harvest was spread over a longer period. These planting dates range between 15 April and 26 June 2023 and are classified in age groups, with the higher the age group, the later the planting date (Table 3).

Figure 7 Irrigation pump (left) and irrigation tubes next to the banana plants (right).

On the plots with intercropping oil palm-watermelon as first-year management, the watermelon used to be managed by applying 90 kg ha^{-1} of fertilizer, having 2500-3000 watermelons ha^{-1}. Also, irrigation was applied in the same way as for the banana plants. As excessive precipitation last year resulted in fungal infections, fungicides were used to kill and prevent for fungi and their spores.

Table 3 Planting dates per plot and age group of the banana plants.

Planting date	Plot	Age group
15 April 2023	B 1, 2, 6; BW 4	1
18 May 2023	BW 1, 2, 3	2
11 June 2023	B 4	3
26 June 2023	B 3, 5	4

Oil Palm Measurements and Calculations

To answer the oil palm related research questions, various non-destructive measurements were manually undertaken of all oil palms per plot. The measured parameters are listed in Table 4. By using these parameters, the ground projection and leaf area were calculated. In Appendix V the measurements per oil palm development parameter are described in detail.

Table 4 Measured oil palm development parameters.

Oil palm number + plot number	
Parameter	**Unit**
Distance to the closest banana plant	cm
Frond span in North-South direction	cm
Frond span in East-West direction	cm
Height*	cm
Number of fronds	-
Length of the third frond	cm
Rachis length of the third frond	cm
Petiole length of the third frond	cm
Number of leaflets on the third frond	-
Length of 6 largest leaflets on the third frond	cm
Mid-width of 6 largest leaflets on the third frond	cm
Number of inflorescences	-
SPAD value of lower, middle and upper leaflets on the third frond**	-

*Measured from the ground surface to the tip of the tallest leaf

**From the tip to the base of the third frond

Combining the frond span measurements in North-South and East-West direction, the ground projection was calculated with Equation 1 (Maijer, 2023):

$$Ground\ projection\ (m2) = \frac{(0.5 *\ NS) * (0.5 * EW) *\ \pi}{10000}$$

- NS = North-South canopy projection (cm) (Eq. 1)
- EW = East-West canopy projection (cm)

During the initial measurements in June and July 2023, the rachis, petiole and total length of the frond, and the leaflet number, the length and width of the leaflets were measured on the third frond (Figure 8). Frond 3 was the best measurable frond at that moment. During the fieldwork between October and December 2023 the leaflets and frond related measurements were again measured on frond 3. The leaf area of the third frond was calculated by using the number of leaflets, mean length and mean mid-width of the six largest leaflets on the third frond. The leaf area was calculated according to Equation 2 (Corley & Tinker, 2016, p. 93-95):

$$Leaf\ area\ frond\ 3\ (m2) = 0.455 * (n * l * w) - 0.245$$

- n = number of leaflets on the third frond (Eq. 2)
- l = mean length of six of the largest leaflets on the third frond
- w = mean mid-width of six of the largest leaflets on the third frond

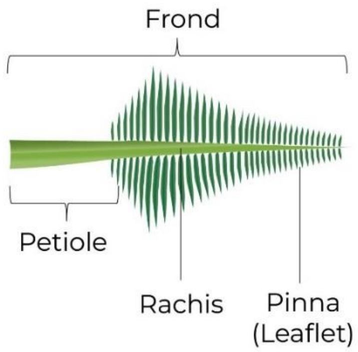

Figure 8 Parts of an oil palm frond, Figure adapted from Teng (2023).

In addition, during the fieldwork period the total number of inflorescences per oil palm was counted. Lastly, the SPAD values of three leaflets on the third frond were measured, around the tip, middle and base of the frond. The measurements were done in the mornings around the same time to avoid sunlight exposure, by using the SPAD-2000 device. Of these three measurements per third frond the average value was calculated.

In total, the oil palms were measured at three different moments in time, creating three time series: PT0, PT1, PT2. PT0 was measured between June and July 2023 and data of the oil palm monocultures with first-year oil palm-watermelon intercropping management was missing. PT1 has been measured in the end of October and begin of November 2023 and PT2 in the end of January 2024.

Furthermore, to assess the weed types present in each plot, the six most present weed species per plot were identified by using the application 'PictureThis' and noted down in descending order of presence.

Banana Plant Measurements and Calculations

Next to the oil palm measurements, parameters of development of all banana plants in the intercropped plots were also manually measured. These measured parameters are listed in Table 5. In Appendix V the measurements per banana plant development parameter are described in detail.

Table 5 Measured banana plant development parameters.

Banana plant number + plot number	
Parameter	**Unit**
Distance	close / far
Distance to oil palm (parallel)	cm
Age	months
Distance to other banana plant (parallel)	cm
Leave span North-South	cm

Leave span East-West	cm
Stem height*	
Plant height**	cm
Pseudo-stem circumference at base	cm
Pseudo-stem circumference at 1.3m	cm
Number of leaves	-
Length third leaf from the top	cm
Width third leaf from the top	cm
Number of suckers***	-
Number of hands	-
Number of fingers	-
SPAD value on left and right side of the third leaf	-

*Measured up until the start of the youngest (upstanding) leaf

**Measured up until the height of the highest horizontal growing leaf or halfway up the highest upright leaf

***Next to plant but also removed

To find out whether the distance between an oil palm and banana plant might influence the development of banana plants, the distances between each banana plant with its neighbouring banana plant and parallel oil palm were measured. Two banana plants were located parallel to one oil palm of which one was marked as close and one as far from the oil palm. Secondly, for calculating the ground projection the same equation was used as for oil palms (Equation 1). The plant height was measured up until the height of the highest horizontal growing leaf or halfway up the highest upright leaf. And the stem height was measured up until the start of the youngest (upstanding) leaf. The pseudo-stem circumference was measured at the stem base for all banana plants, as it was not possible to measure the diameter for all banana plants at breast height, which is usually used to measure the stem diameter. The pseudo-stem diameter was calculated by Equation 3 by using the stem base circumference.

$$Stem\ diameter\ base\ (cm) = \frac{stem\ base\ circumference\ (cm)}{\pi}$$

(Eq. 3)

For the number of leaves, only the full-grown leaves were counted. In addition, the length and width of the third leaf of each banana plant were measured. The third leaf was chosen as this leaf number is generally used to calculate the total leaf area (Kumar, *et al.,* 2002). The total leaf area of the banana plant was calculated by Equation 4 (Alvares *et al*., 2001; Guimarães *et al*., 2013):

$$Total\ leaf\ area\ (m2) = 0.0000901 * (L * W)^{1.2135}$$

- L = Leaf length of third leaf (cm) (Eq. 4)
- W = Leaf width of third leaf (cm)

Subsequently, the biomass of the banana plant was calculated by Equation 5 (Arifin, 2001):

$$Banana\ plant\ biomass\ (kg) = 0.030 * D^{2.13}$$

- D = Stem diameter at base level (m) (Eq. 5)

The number of suckers per banana plant was counted, including removed ones. Also, the number of fingers, single bananas, and hands, a group of attached fingers, were counted. Last, the SPAD values of the third leaf on the left and right side were measured following the same procedure as the SPAD measurements for oil palm.

In total, the banana plants were measured at four different moments in time, creating four time series: BT0, BT1, BT2, BT3. In BT0 data of some variables of banana plants was missing as these were too little to measure at that moment and was measured in the middle of June 2023. BT1 has been measured in the end of October 2023 and BT2 in the end of November 2023. BT3 has been measured in the middle and end of January 2024.

Data Analysis

During the fieldwork, I stored the data directly in Microsoft Excel sheets. Afterwards, I analysed the data using RStudio (R version 4.3.1).

For the analysis of the oil palm data, I took various steps. Firstly, I explored the data, checking for normal distributions and outliers. To address non-normal distributions, I performed log-transformation on the variables leaf number and leaf width, and sqrt-transformation on leaf area. After that, I performed a correlation analysis focusing on PT1 only which included the following variables: ground projection, height, frond number, frond length, leaflet number, leaflet length, leaflet width and SPAD. I created correlation coefficients, a correlation matrix, a correlation plot and a biplot of a principal component analysis (PCA), to examine the relationship between these variables. Then, I performed pairwise comparisons to check significant differences in correlations between oil palm development variables among the treatments.
After that I performed Linear Mixed Effect Models (LMM), focusing on PT1 only and on PT1 and PT2 together, considering each variable across fixed and random effects. The selected variables for these models included: ground projection, height, frond number, frond length, leaflet length, leaflet width and leaf area. I created a variety of different models, selecting the best model using the Akaike information criterion (AIC). I used the same LMM structure for all variables to evaluate the same effects and interactions for all variables. Equation 6 shows the LMM structure used for the variables for PT1 only and Equation 7 illustrates the structure of the LMM for PT1 and PT2. In the analysis over PT1 and PT2 together, I specifically tested the variables frond length and leaflet length as they showed a significant effect of current oil palm-banana intercropping compared to monoculture. Then, I calculated the mean difference per treatment between PT1 and PT2 for all variables.

$$OPvar \sim Intercrop + FirstYearLU + Intercrop * FirstYearLU + (1|Plot_{ID})$$

(Eq. 6)

Where OPvar = oil palm variable: ground projection, height, frond number, frond length, leaflet number, leaflet length, leaflet width and leaf area; Intercrop = 'oil palm-banana intercropping' and 'monoculture oil palm'; FirstYearLU = 'oil palm-watermelon intercropping' and 'monoculture oil palm'; (1|Plot_ID) = random effect 'plot number'

$$OPvar \sim Intercrop * Time + FirstYearLU * Time + Intercrop * FirstYearLU + Intercrop + FirstYearLU + Time + (1|Plot_{ID})$$

(Eq. 7)

Where OPvar = oil palm variable: ground projection, height, frond number, frond length, leaflet number, leaflet length, leaflet width and leaf area; Intercrop = 'oil palm-banana intercropping' and 'monoculture oil palm'; FirstYearLU = 'oil palm-watermelon intercropping' and 'monoculture oil palm'; Time = 'PT1' and 'PT2'; (1|Plot_ID) = random effect of 'plot number'

The analysis of the banana plant data is comparable to the oil palm data analysis. Simultaneously, I checked the data for normal distributions and outliers per age group.
After that, I performed a correlation analysis per age group of which I created correlation matrices, correlation plots and biplots for the four age groups of a principal component analysis (PCA), to examine the relationship between the variables per age group. This analysis included the following variables: ground projection, stem height, plant height, stem diameter base, leaf number, leaf length, leaf width and SPAD. Also, for the banana plant variables I performed pairwise comparisons to test significant differences between banana plant variables among the age groups.
Afterwards, I explored the relationships with stem diameter base of BT1 for the following variables: ground production, stem height, plant height, leaf length, leaf width and leaf area. I did this by obtaining logistic curves from non-linear least squares functions as the linearity assumption of the linear model data was not met and to provide a visual relationship between the two variables (Chen, 2014; Tian *et al.,* 2017; Tsoularis & Wallace, 2002). The logistic curve used is represented in Equation 8.

$$Stem\ diameter\ base\ (var, t1) = \frac{Asym}{1 + e^{(x0-x)/k}}$$

(Eq. 8)

Where Variable (var) = ground production, stem height, plant height, leaf length, leaf width and leaf area; Asym = Asymptote of stem diameter base; x0 = x value of the Sigmond's midpoint of the logistic curve of the variable; k = steepness of the logistic curve of the variable

Similar as for the oil palm data, I performed LMM for the banana plant variables and selected the best model by using the AIC. The selected variables for these models included plant height, stem diameter base, leaf number, leaf length, leaf width, leaf area and SPAD. Equation 9 shows the LMM structure for BT1 only and Equation 10 illustrates the structure of the LMM for BT1, BT2 and BT3.

$$Bvar \sim Distance * Age + Distance + Age + (1|Plot_{ID})$$

(Eq. 9)

Where Bvar = Banana variable: ground projection, stem height, plant height, stem diameter base, leaf number and leaf area; Distance = 'close' and 'far', distance from banana plant to parallel oil palm; Age = age groups '1','2','3','4'; (1|Plot_ID) = random effect of 'plot number'

$$Bvar \sim Distance * Time + Age * Time + Distance * Age + Distance + Age + Time + (1|Plot_{ID})$$

(Eq. 10)

Where Bvar = Banana variable: ground projection, stem height, plant height, stem diameter base, leaf number and leaf area; Distance = 'close' and 'far', distance from banana plant to parallel oil palm; Age = age groups '1', '2', '3', '4'; Time = 'BT1', 'BT2' and 'BT3'; (1|Plot_ID) = random effect of 'plot number'

Additionally, I checked the model assumptions, including linearity, normality, homogeneity and outliers. Further, I performed pairwise comparisons using the 'emmeans function', which calculates estimate marginal means, to assess significant differences between the treatments in the oil palm data and between the distance per age group in the banana plant data. In the oil palm treatments result section, I reported the least significant values when multiple comparisons were made between treatments.

Results

Correlations of Oil Palm Variables

Moderate-strong positive correlations were found between *ground projection, height, frond number, frond length, leaflet number* and *leaflet length* (Figure 9). Weaker correlations were found between *leaflet width* and the other variables, with the highest correlation between *leaflet width* and *frond length* (r=0.317). The same applies to *SPAD* and the other variables, with the highest correlation between *SPAD* and *frond number* (r=0.279) (Figure 9).
As visualised in the PCA plot (Figure 10) PC1 and PC2 collectively accounted for 61.6% of the total variance, with PC1 contributing 47.7% and PC2 contributing 13.9%. The PCA plot showed similar results as the variables *leaflet length, ground projection, leaflet number, height* and *frond number* are closely gouped together on the right side of the plot. On the other hand, *leaflet width* and *SPAD* showed more distinct positions in the top and bottom middle of the plots showing weaker correlations to the other parameters.
In general, lower correlations between the variables were found in the analysis per treatment compared to the correlation analysis including all treatments (Figure 11). Significant differences in oil palm development correlations were observed among the four treatments, notably between *ground projection* and *leaflet number* ($p < 0.001$), *ground projection* and *leaflet length* ($p < 0.001$) and *frond number* and *leaflet number* ($p < 0.001$).

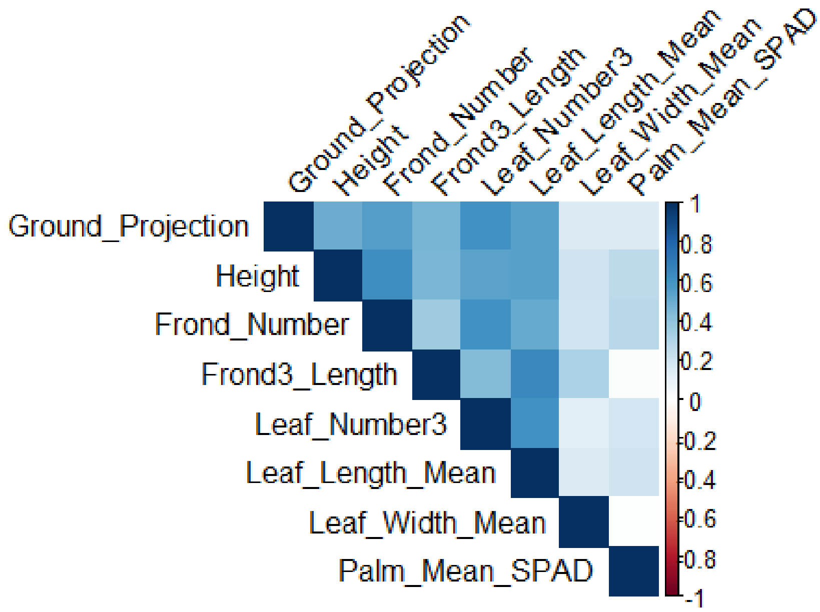

Figure 9 Correlation Plot of Oil Palm Variables including all treatments.
Complete correlation = 1 and -1; no correlation = 0. The colours represent the strength of the correlation.

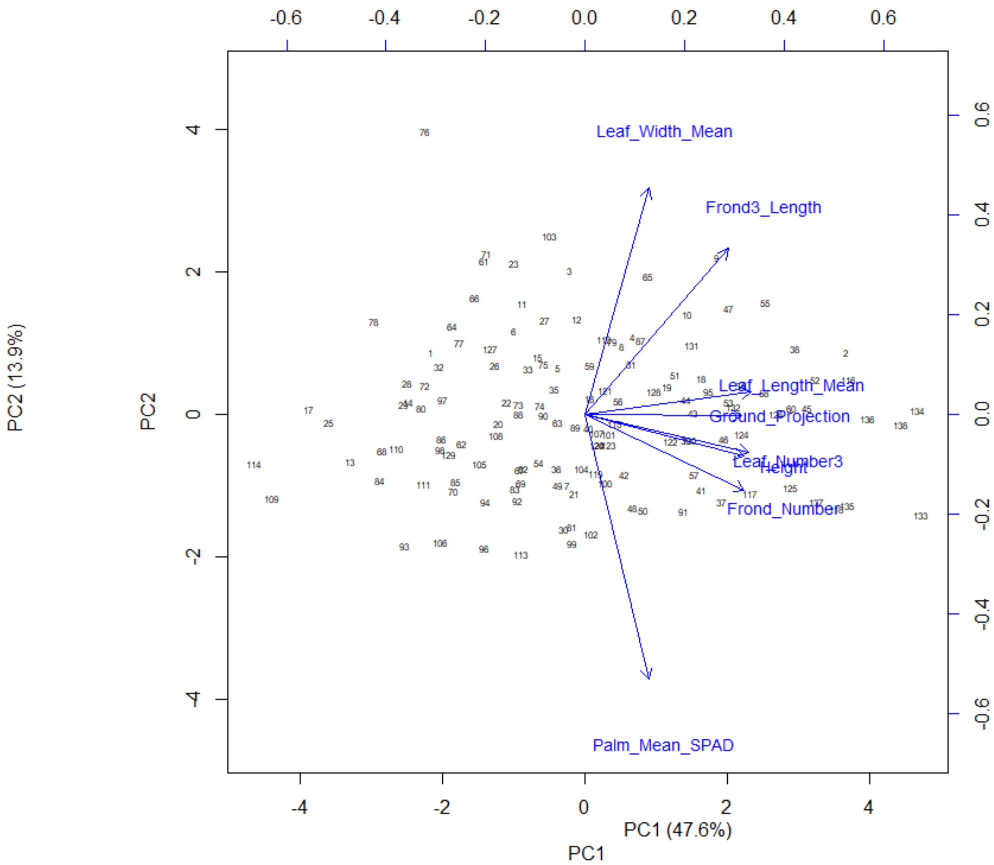

Figure 10 PCA Plot of Oil Palm Variables.

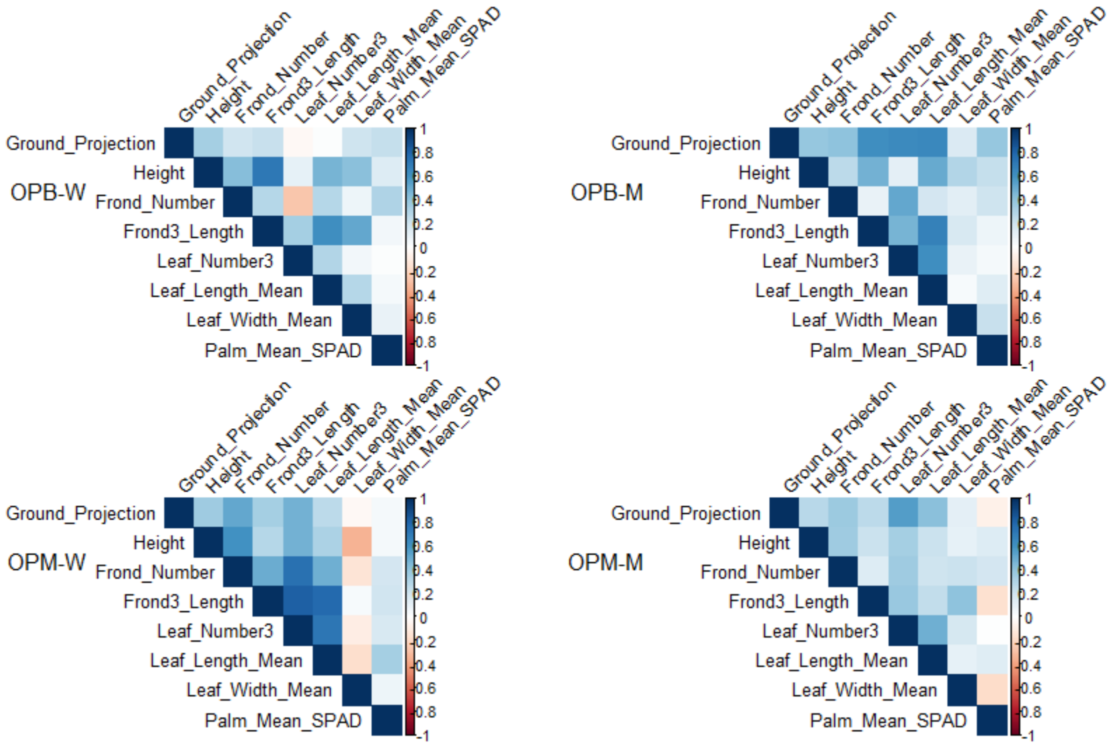

Figure 11 Correlation Plot of Oil Palm Variables within the treatments: OPB-W, OPB-M, OPM-W and OPM-M (top left to bottom right). Complete correlation = 1 and -1; no correlation = 0. The colours represent the strength of the correlation.

Correlations of Banana Plant Variables

The correlation plots of the banana variables show the correlations between the variables per age group (Figure 12). Many significant differences in banana plant development correlations were observed among the age groups, with the most prominent different between *stem diameter base* and *stem height* ($p < 0.001$). In age group 1 very strong positive correlations were observed between the height-related variables, *stem height, plant height, stem diameter base*, and *ground projection*. The age groups 2, 3 and 4 showed less strong correlations between these height-related variables. In age group 1 the correlations between *leaf number* and the other variables, except *SPAD* were low compared to the other age groups. *SPAD* was relatively poorly correlated with the other variables in the age groups 1 and 2, compared to age groups 3 and 4.
In the PCA plots the cumulative proportion of variance explained by the two axes in these plots are 81.6%, 81.6%, 86.9% and 92.9% respectively, for the age groups 1-4 (Figure 13 and Figures A1-A4 in Appendix I). In these PCA plots the clustering of the height-related variables, particularly in age group 1 is visualised. *Leaf number* and *SPAD* show more distinct positions in all PCA plots, most obvious in age group 1. A less clustered and more widespread pattern of the variables in the plot was observed when increasing in age group, from 1 to 4.

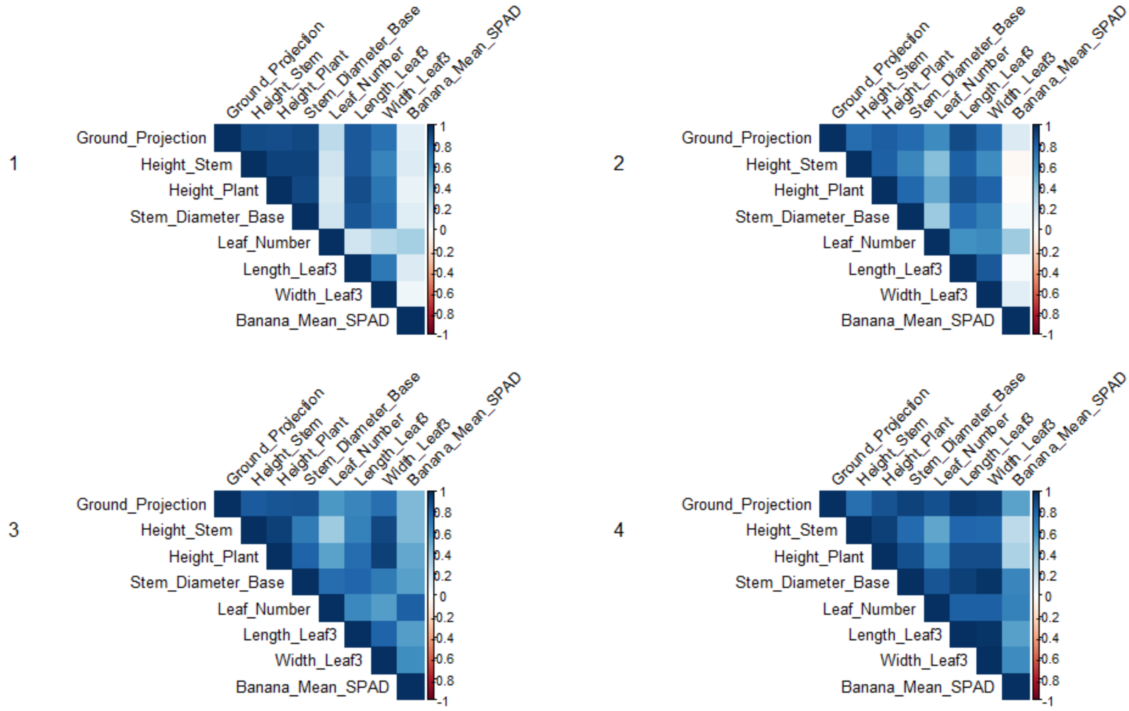

Figure 12 Correlation Plots of Banana Plant Variables for the Age Groups 1-4.
Complete correlation = 1 and -1; no correlation = 0. The colours represent the strength of the correlation.

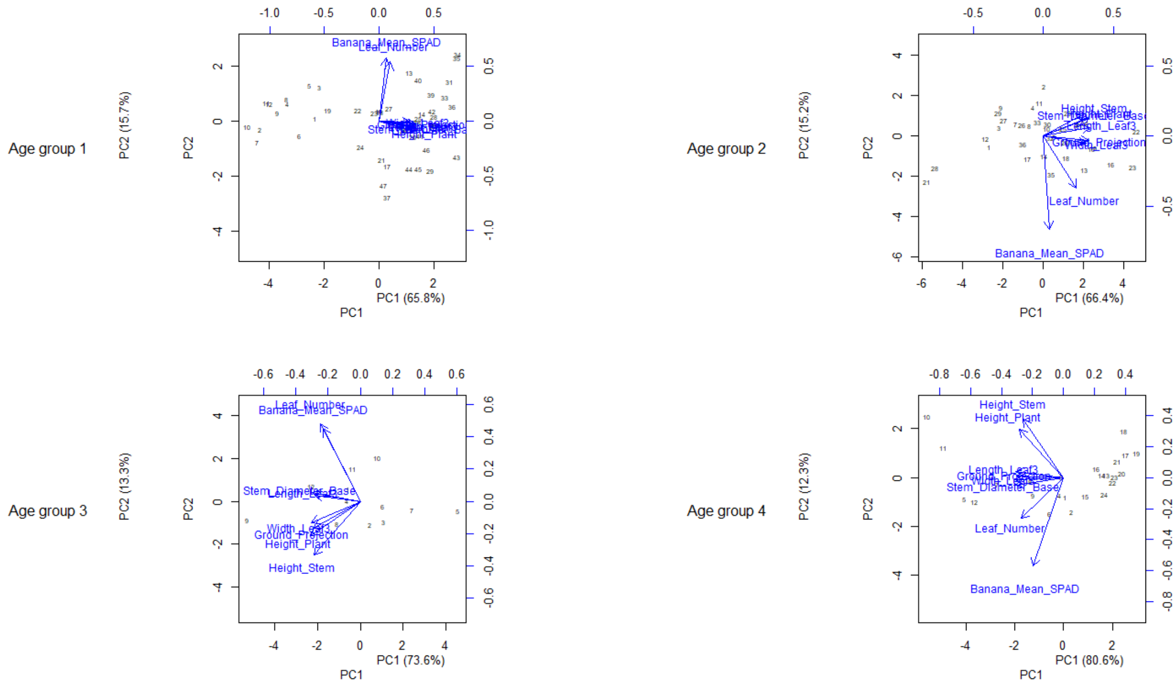

Figure 13 PCA Plot of Banana Plant Variables for the Age Groups 1-4.

Relationships with Banana Plant Stem Diameter at the Base

In Figure 14 the relationships between banana plant *stem diameter at the base* and *ground projection*, *plant height*, *stem height*, *leaf length*, *leaf width* and *leaf area* are visualised.

All logistic curves show that the increase of one variable corresponds with an increase in the other variable, and vice versa. In the plots of *ground projection* and *plant height* a decrease in the slope of the logistic curve around a *stem diameter base* of 16 cm and 13 cm, respectively was observed (Figure 14). The curves for *leaf length*, *leaf width* and *leaf area* showed a decline in the rate of increase at around 12 cm, 10 cm and 12 cm *stem diameter base*, respectively, approaching their asymptotes at roughly 198 cm for *leaf length,* 53 cm for *leaf width* and 6.7 m^2 for *leaf area* (Figure 14).

In all plots a faint pattern was observed, where age groups decreased (from 4 to 1) as the curve increased. Especially for *ground projection, plant height, leaf length* and *leaf area* the observations over all age groups were located closely around the curves, except for age group 1, indicating a better prediction of the logistic curves compared to *stem height* and *leaf width.* (Figure 14).

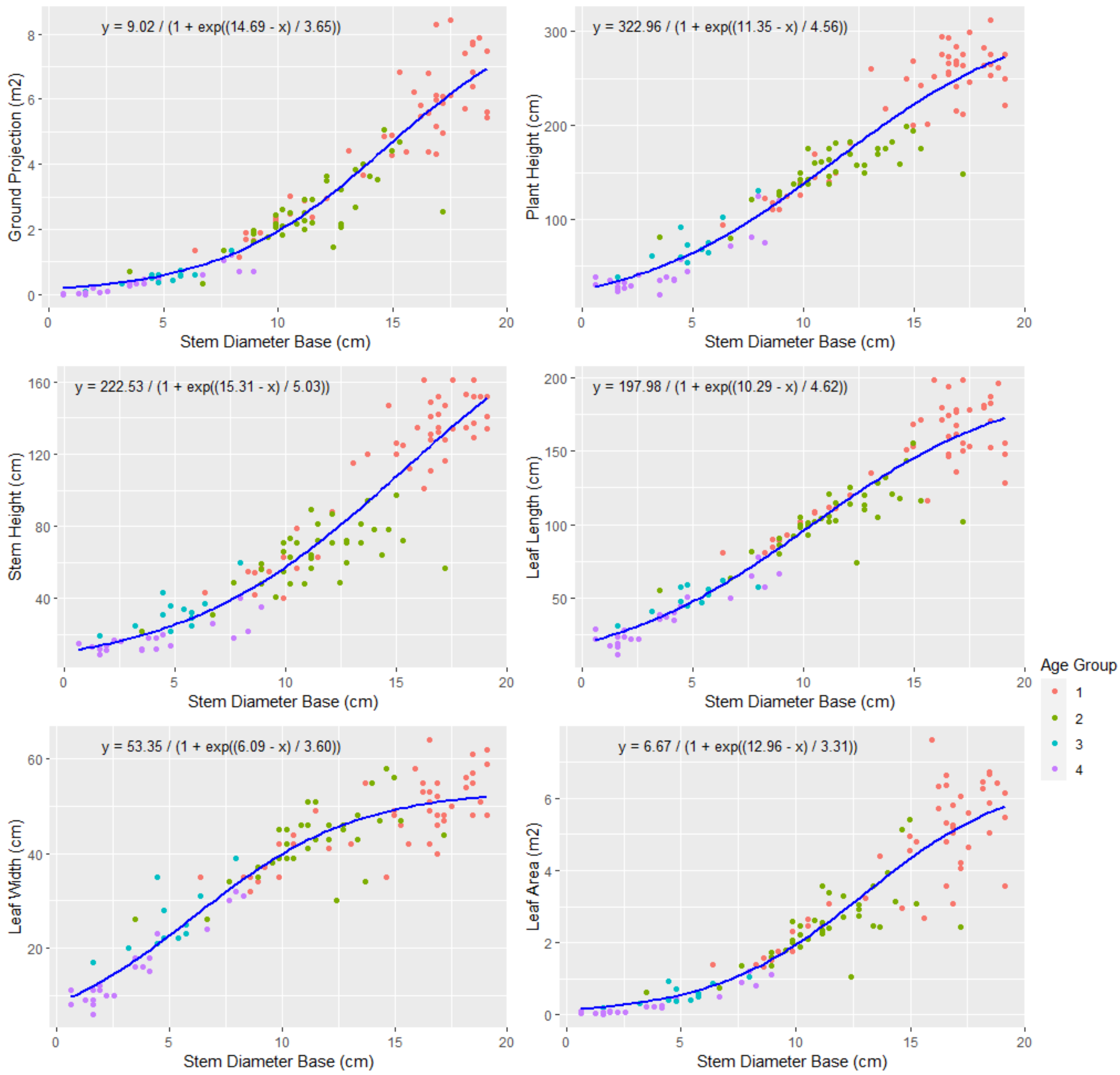

Figure 14 Relationships of Banana Plant Stem Diameter Base with Ground Projection, Plant Height, Stem Height, Leaf Length, Leaf Width and Leaf Area.

Oil Palm Treatments

Ground Projection and Height

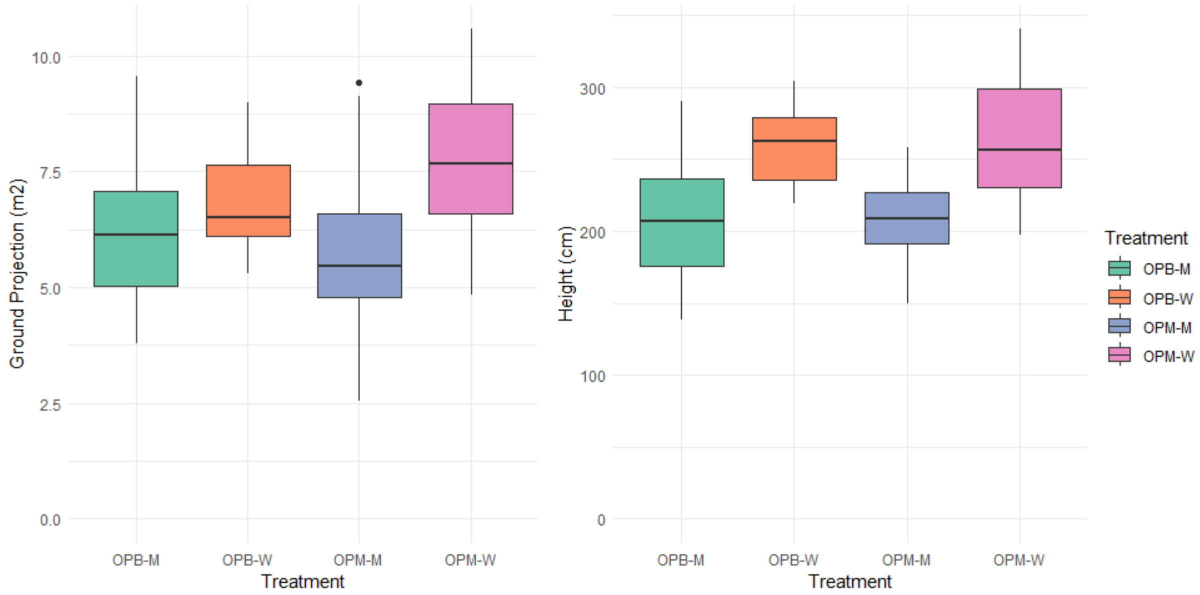

Figure 15 Oil Palm Ground Projection and Height per treatment for PT1.

In Figure 15 the oil palm *ground projection* and *height* per treatment are presented for PT1. Tables A1 and A2 in Appendix II show the output tables of the LMM including random and fixed effects for oil palm *ground projection* and *height* respectively.
Comparing the cropping systems intercropping and monoculture, slightly lower values of oil palm *ground projection* were found in the monoculture treatments ($t(19) = -1.45$, $p = 0.16$). First watermelon management practices showed slightly higher *ground projection* values compared to monoculture first-year management ($t(19) = 1.84$, $p = 0.08$). However, the effects in both the current and first-year management separately were not statistically significant (Table A1, Appendix II). The results showed a statistically significant positive coefficient for the interaction between cropping system and first-year management practices for *ground projection* ($t(19) = 2.38$, $p = 0.028$). This indicates that the effect of the cropping system on *ground projection* varied depending on the first-year management. The highest values of *ground projection* were found in the OPM-W treatment, compared to the treatments OPB-M ($t(19) = -3.92$, $p = 0.005$) and OPM-M ($t(19) = -5.46$, $p < 0.001$). The lowest values of *ground projection* were found for the OPM-M treatment, indicating that total monoculture management resulted in the lowest oil palm *ground projection* compared to the other treatments (Figure 15).

First-year watermelon intercropping management had a significant positive effect on *height* ($t(19) = 3.54$, $p = 0.002$) suggesting that oil palms planted in plots with watermelon intercropping during the first year were taller compared to oil palms planted in plots with monoculture oil palm management in the first year. This result is visualised in Figure 15, showing significantly higher values for *height* in the treatments OPB-W and OPM-W, compared to OPB-M ($t(19) = -3.54$, $p = 0.01$) and OPM-M ($t(19) = -3.65$, $p = 0.008$). The cropping system solely, and interaction between the cropping system and first-year management practices showed no significant effects on oil palm *height* (Table A2, Appendix II).

Frond Number and Frond Length

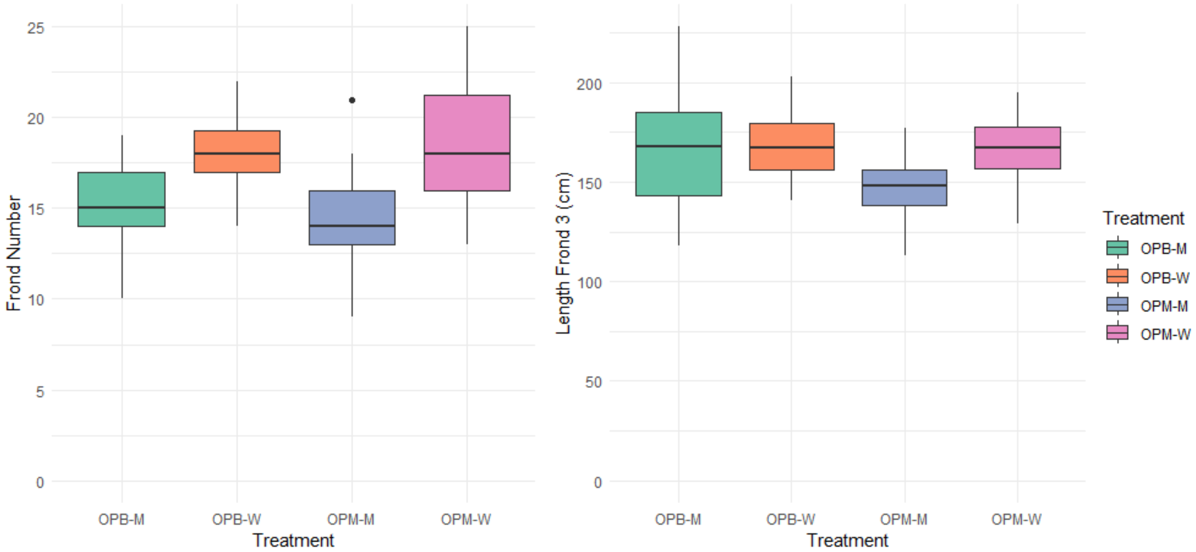

Figure 16 Oil Palm Frond Number and Frond Length per treatment for PT1.

Figure 16 shows the *frond number* and *frond length* of frond 3 per treatment for PT1. The variability among the plots for *frond number and frond length* is noted in the Tables A3 and A4 in Appendix II. Table A3 in Appendix II shows the LMM output for oil palm *frond number*. Similarly, as for the oil palm *height*, the *frond number* was positively significantly impacted by first-year watermelon intercropping management ($t(19) = 3.23$, $p = 0.004$). This indicates a higher frond number in previously oil palm-watermelon intercropped plots compared to previously monoculture oil palm plots. This can be observed in Figure 16, in which the treatments OPB-W and OPM-W show overall significantly higher *frond number* values compared to the treatments OPB-M ($t(19) = -3.23$, $p = 0.02$) and OPM-M ($t(19) = -4.56$, $p < 0.001$). The differences between the current cropping systems, and the interaction between cropping system and first-year management practices were not significant (Table A3, Appendix II).

The fixed effects of *frond length* (Table A4, Appendix II) displayed a significantly positive effect in the current oil palm-banana intercropped plots when comparing to current monoculture plots ($t(19) = -2.80$, $p = 0.01$), indicating a higher *frond length* in intercropped plots compared to monoculture oil palm plots. As shown in Figure 16 the values for *frond length* are indeed significantly higher for the treatments including current oil palm-banana intercropping (OPB-M and OPB-W), compared to the current monoculture treatment OPM-M ($t(19) = -2.82$, $p = 0.049$). Although not significantly higher compared to OPM-W ($t(19) = -0.26$, $p = 0.99$). The other fixed effects, first-year management practice and the interaction between the two fixed effects, showed no significant effects on *frond length* (Table A4, Appendix II).

Leaflet Length, Leaflet Width and Leaf Area

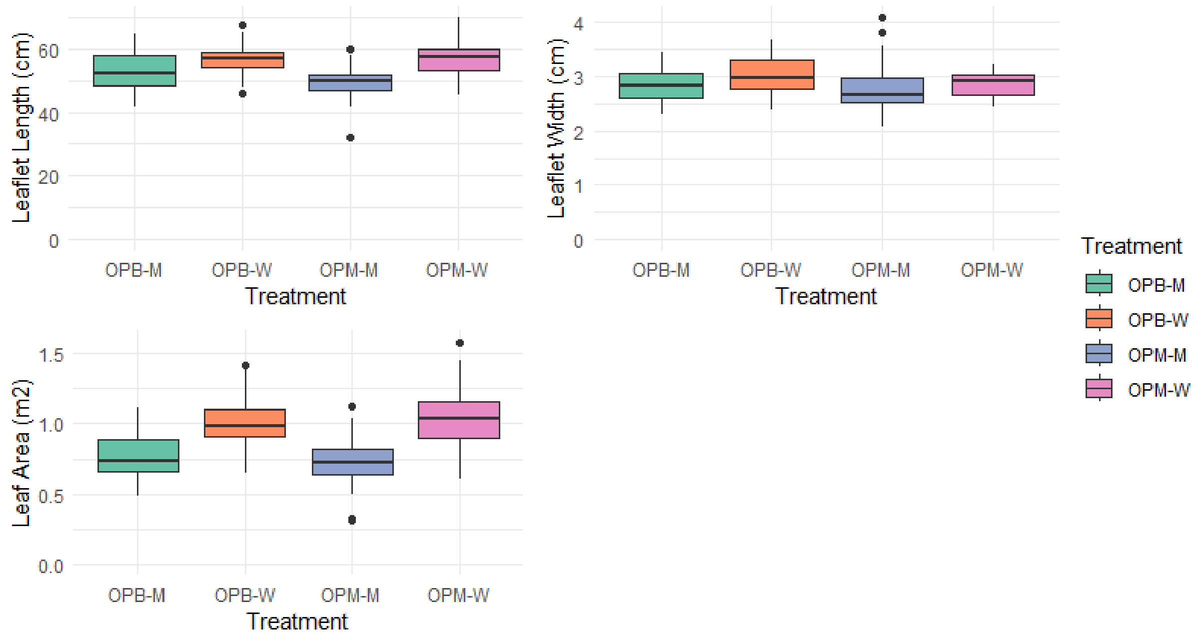

Figure 17 Oil Palm Leaflet Length, Leaflet Width and Leaf Area per treatment for PT1.

Figure 17 shows boxplots of the variables *leaflet length, leaflet width* and *leaf area* for the four treatments for PT1. The variability among the plots for *leaflet length, leaflet width* and *leaf area* is noted in the Tables A5, A6 and A7 in Appendix II.
The results for *leaflet length* showed a significant effect of intercropping on *leaflet length* ($t(19) = -2.79$, $p = 0.01$) (Table A5, Appendix II). This indicates that oil palms in the currently intercropped plots have longer leaflets compared to oil palms in monoculture plots. First-year management practices and the interaction between the two effects showed no significant effect on *leaflet length* (Table A5, Appendix II). As shown in Figure 17 the values for *leaflet length* are indeed significantly higher for the treatments including current oil palm-banana intercropping (OPB-M and OPB-W), compared to the current monoculture treatment OPM-M ($t(19) = 2.79$, $p = 0.05$), although not significantly higher compared to OPM-W ($t(19) = -2.50$, $p = 0.09$).

From the fixed effects of *leaflet width*, first-year watermelon intercropping management showed a statistically significant effect ($t(19) = 2.04$, $p = 0.04$), indicating a larger *leaflet width* in plots with first-year watermelon intercropping management compared to plots with first-year monoculture management. That the values of *leaflet width* are higher in first-year watermelon intercropped plots is minimally observable in Figure 17, with the pairwise comparison only showing a significant difference between OPM-M and OPB-W ($t(19) = -2.94$, $p = 0.04$). For cropping system and the interaction between the two effects, the LMM of *leaflet width* showed no statistically significant effects (Table A6, Appendix II).

The results of the linear mixed effect model for *leaf area* displayed a significant effect of first-year watermelon intercropped management (Table A7, Appendix II). Oil palms in plots with prior watermelon intercropped management practices show a larger *leaf area* than oil palms in plots with prior monoculture management practices ($t(19) = 4.26$, $p = 0.0004$). As can clearly be seen in Figure 17, the treatments OPB-W and OPM-W show these higher values in *leaf area* compared to OPB-M ($t(19) = -4.26$, $p = 0.002$) and OPM-M ($t(19) = -5.34$, $p < 0.001$). However, cropping system alone and the interaction between cropping system and first-year management did not significantly influence *leaf area*.

Frond Length and Leaflet Length over time

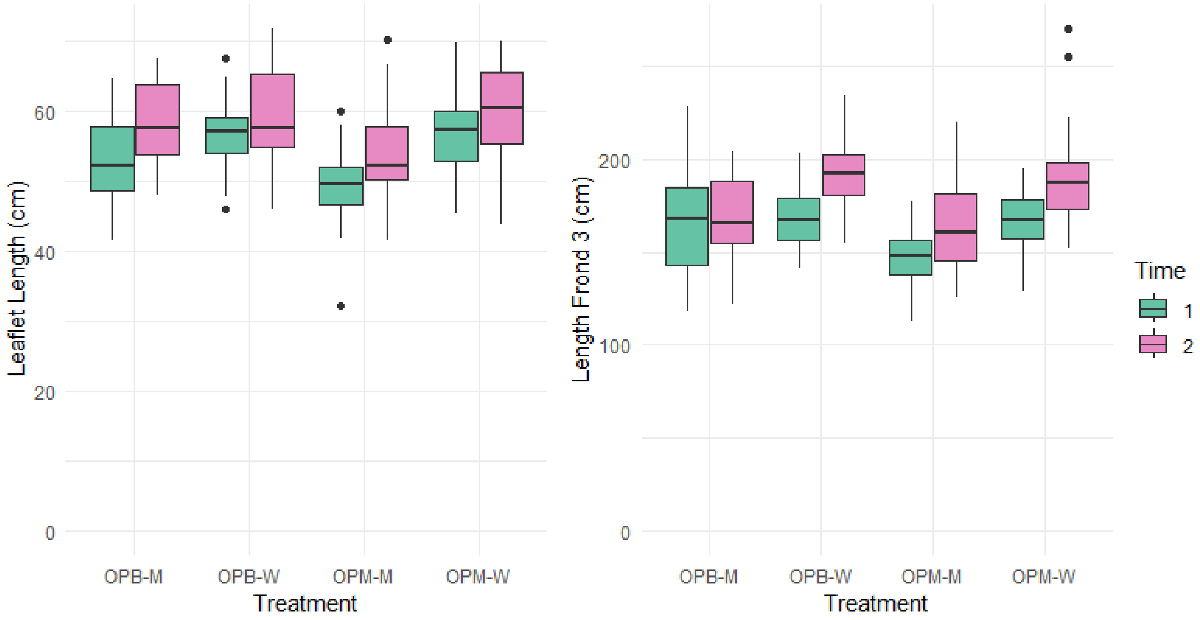

Figure 18 Oil Palm Leaflet Length and Frond Length per treatment for PT1 and PT2.

In Figure 18 the oil palm *leaflet length* and *frond length* are visualised for the four treatments and for PT1 and PT2. The time difference between the two time series was approximately 3 months. The analysis including PT1 and PT2 showed several significant effects on *leaflet length* (Table A8, Appendix II). As previously mentioned in the analysis only including PT1, intercropping had a significant effect on *leaflet length* (Table A5, Appendix II). Although when considering PT1 and PT2, *leaflet length* turned out even shorter in monoculture plots than in intercropped plots ($t(19) = -2.67$, $p = 0.01$), compared to the analysis of PT1 only. Time also had a significant effect ($t(19) = 4.09$, p-value < 0.001), indicating changes in *leaflet length* over time. Notably, the effect of first-year management became statistically significant ($t(19) = 2.299$, $p = 0.029$) compared to the analysis of PT1 only (Table A8, Appendix II). The highest increase over PT1 and PT2 for the mean of *leaflet length* was found in the treatments including first-year monoculture management practices OPB-M and OPM-M (Table 6). This increase can be seen in Figure 18.

Regarding the results of *frond length* development over time (Table A9, Appendix II), the LMM including PT1 and PT2 showed a higher significance in *frond length* in intercropped plots compared to considering only PT1 (p from 0.01 to 0.002). Time showed no significant effect on *frond length*. The interaction between time and first-year management practice was significant ($t(19) = 1.52$, $p = 0.02$), suggesting potential variations in the effect of time depending on the first-year management practice (Table A9, Appendix II). Notably, the highest increase in the mean *frond length* over PT1 and PT2 was found for oil palms having OPB-W and OPM-W treatments (Table 6). This increase is visualised in Figure 18, and is in line with the observed significant interaction between time and first-year management.

Table 6 Mean difference per treatment over PT1 and PT2 for Leaflet Length (left) and Frond Length (right).

Treatment	Mean Difference
OPB-M	4.63
OPB-W	2.83
OPM-M	4.86
OPM-W	1.97

Treatment	Mean Difference
OPB-M	2.92
OPB-W	23.6
OPM-M	16.9
OPM-W	22.7

Banana Plant Distance

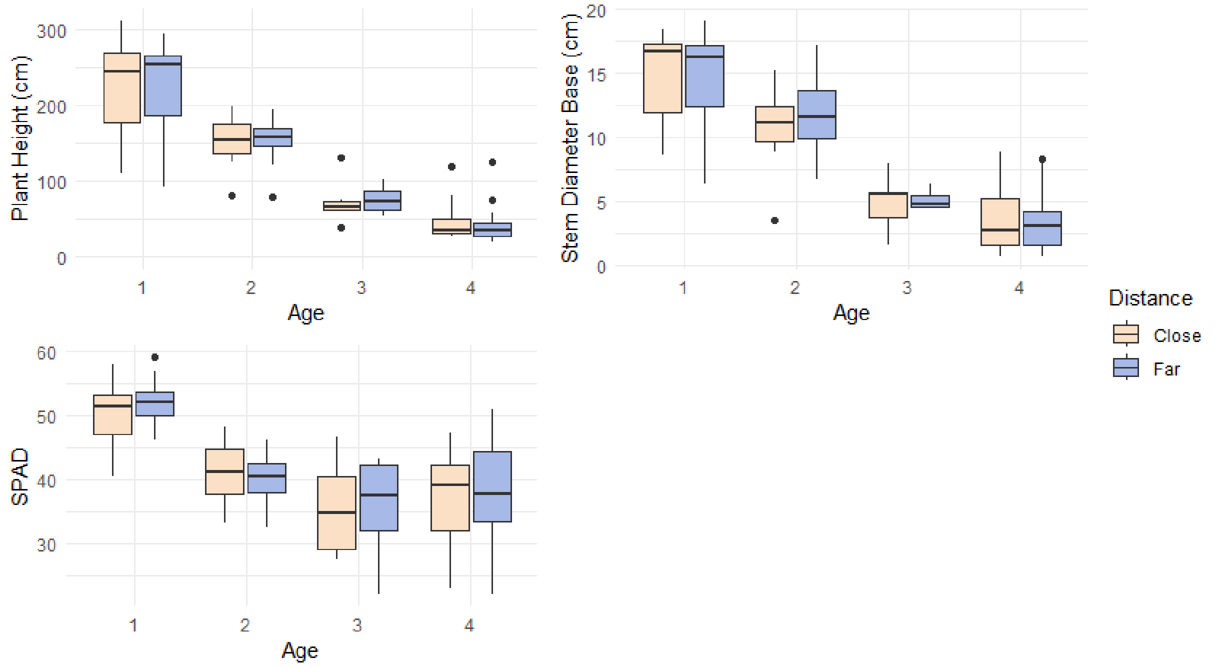

Figure 19 Banana Plant Height, Stem Diameter at the Base and SPAD by Distance and Age group for BT1.

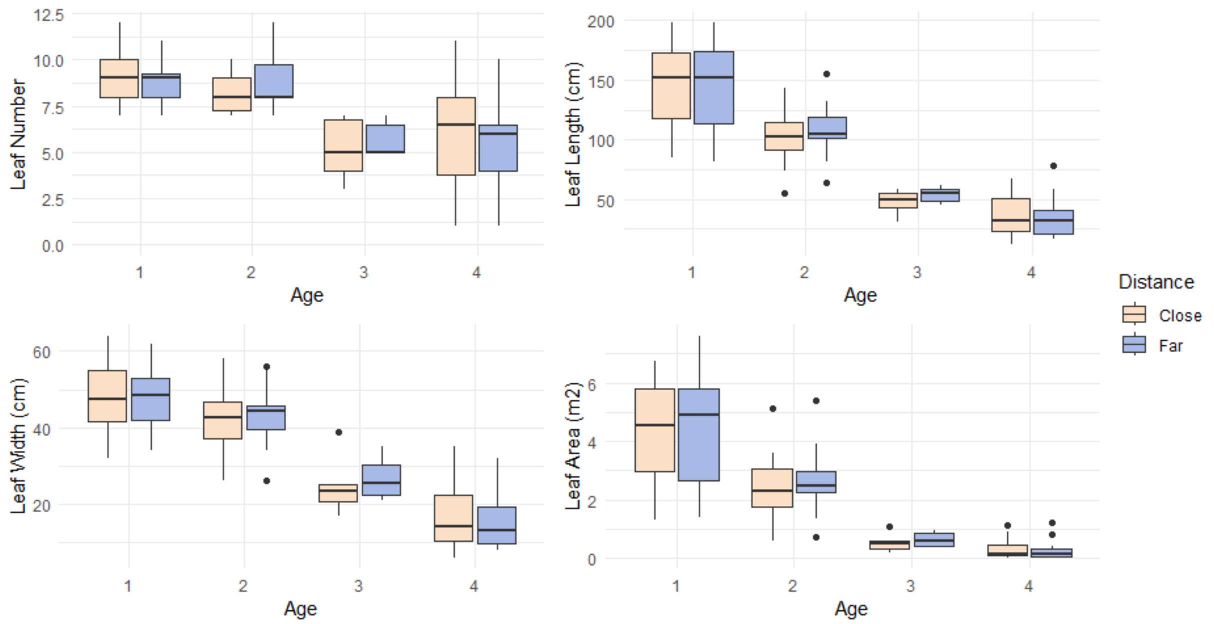

Figure 20 Banana Plant Leaf Number, Leaf Length, Leaf Width and Leaf Area by Distance and Age group for BT1.

In the Figures 19 and 20, the boxplots of banana plant development variables for the distance categories and per age group are visualised. The results of the LMM outputs are displayed in the Tables A10-A16 in Appendix III, including the variability among the plots. No significant differences were found between far and close distances to the closest parallel oil palm. This applies to all banana plant development variables. The LMM outputs of the banana plant development variables showed negative coefficients for the effect of the 'Distance Far', except for the variable *SPAD* (Appendix III). These negative values indicate that the banana plant the furthest away from the oil palm has slightly lower variable values compared to the banana plant the closest to the oil palm, however this was never significant (Appendix III). Some other findings showed significant differences between age group 4 and age group 1 and significant differences between age group 3 and age group 1 (Appendix III). Furthermore, no significant interactions between age and distance were observed (Appendix III).

In the Figures A5-A10 in Appendix IV the banana plant development variables over BT1, BT2 and BT3 are printed. Also, over time no differences between the banana plants far and close to the closest parallel oil palm per age group were observed. The LMM outputs of the banana plant development variables including BT1, BT2 and BT3 showed similar outcomes compared to the analysis of BT1 alone. Therefore, these LMM outputs are not included in this thesis.

Discussion

The main findings of this thesis showed significant impacts on oil palm development variables resulting from first-year watermelon intercropping and current banana intercropping practices. Additionally, close and far planting distance from oil palms had no effect on banana plant development variables. The correlations among the development variables in both oil palm and banana plants showed interdependence. In this section these key findings are discussed.

Oil Palm Treatments

Overall, it is important to interpret the results of this thesis with the understanding that these are pseudo replicates and therefore not completely independent observations. This concern will be elaborated in the limitations section.

Previous land use can give an indication about the ability of the soil to support the next plants and the short-term effects on plant development (Corley and Tinker, 2016, p.244). Plots with oil palm-watermelon intercropping in the first year showed higher oil palm development variables compared to first-year monoculture plots. This difference was statistically significant for height, frond number, leaflet width, and leaf area. These higher development variables in watermelon-intercropped plots suggest a positive impact on soil nutrient and water composition, potentially due to improved nutrient availability and microbial diversity from watermelon cropping systems (Tian *et al.,* 2023). The soil nutrient enrichment may be an effect of watermelon residues and excessive fertilisation as the amount of fertiliser applied to the watermelons during the first-year intercropping far exceeded the amount of fertiliser recommended by the FAO (Maijer, 2023). To give an indication, the lowest dose of fertiliser applied by the farmers contained 84 kg ha^{-1} N, 36 kg ha^{-1} P and 60 kg ha^{-1} K, while the recommended dose for the used planting density was 17.9 kg ha^{-1} N, 8.47 kg ha^{-1} P and 11.46 kg ha^{-1} K (Maijer, 2023). This could have resulted in the accumulation of substantial nutrients levels, around 1.3 kg N, 0.55 kg P and 0.97 kg K per plot, as a plot was approximately 200 m^2, that may have been left in the soil for uptake by the oil palms.
In addition, during the fieldwork measurements done in PT1, conditions were notably drier than in previous years. Intercropping with watermelon can enhance soil water retention and moisture maintenance (Kuvaini, 2022), particularly with the watermelon's irrigation, however specific irrigation amounts were not documented. This improvement in soil water holding capacity in first-year watermelon-intercropped plots compared to monoculture plots could further explain the significantly higher values observed in oil palm height, frond number, leaflet width, and leaf area.
So to conclude, following the completion of oil palm-watermelon intercropping, the oil palms in these plots could have continued to derive benefits from residual nutrients and enhanced soil water retention. This likely contributed to an increase in development variables compared to monoculture oil palm management in the first year.

The results of current oil palm-banana intercropping practices in this thesis, although only significant for frond and leaflet length, suggest a positive influence on oil palm development in intercropped situations, hinting at potential benefits from the presence of banana plants. Intercropping irrigated oil palm with banana in India’s West Godavari district showed no adverse effects on oil palm growth until four years after planting and oil palm height increased significantly when intercropped with banana compared to without intercrop (Reddy *et al.,* 2004). Also, no to minimal competition for light, water and nutrients was observed between oil palm and banana plants during the first three years after planting in the Galle District, Sri Lanka (Dissanayake & Palihakkara, 2023). In Bengkulu, Indonesia no significant results on mature oil palm-banana intercropping on both one and two sides of the oil palms for the indicators, leaf area, ground projection and healthy frond number of immature oil palms were found (Oomen, 2023). Further, after three years of intercropping juvenile oil palm with okra, the oil palm variables frond length, leaflet number, leaflet length and width and leaf area increased compared to without intercrops in Bagalkot, India (Dissanayake & Palihakkara, 2019).

Oil palms without sufficient fertiliser application may suffer from nutrient deficiencies as the oil palms require substantial amounts of nutrients during the immature phase to support development (Fairhurst *et al.,* 2019, p.310-318). The nutrient supply in the soil by the fertiliser applied to the bananas, the mulch of the banana leaves and the removed suckers could have been beneficial for oil palm development in the intercropped plots. The height of immature oil palms three months after fertiliser treatment showed: the higher the dose of fertiliser was, the higher the increase in oil palm height, conducted in Peusangan Siblah Krueng, Indonesia (Satriawan & Fuady, 2019). Moreover, wheat-pea intercropping showed that when excessive fertilizer is applied to the main wheat crop, peas also benefit from this (Ghaley *et al.,* 2005). In the intercropped plots, it was found that there could be an excess of 31 g N, 42.5 g P, 122.5 g Ca and 15.8 g S remaining in the soil per banana plant. This was calculated by subtracting the uptake of a banana plant, as mentioned in the introduction, from the fertiliser application per banana plant (Table 2). These nutrients left in the soil could potentially benefit oil palm development by the uptake of these surplus amounts. However, there was a deficiency of 130 g K and 35.8 g Mg in the soil, which may cause competition for these nutrients in the soil between banana plants and oil palms. Specifically, potassium deficiency can lead to reduced banana leaf development and yellowing of leaves (TNUA, n.d.; (*YaraMila WINNER | YARA India*, 2018). Therefore, it is important to ensure sufficient potassium application for optimal banana plant growth in the intercropped plots.

Mulching with banana plant biomass is a common practice to protect and improve the health of the soil (Dorel *et al.,* 2010, Xavier *et al.,* 2020), and to increase water and fertiliser efficiency (Prakash *et al.,* 2019). Significantly higher banana growth, specifically plant heights and yields of banana plants itself, were observed when mulched with banana biomass compared to non-mulched circumstances (Dorel *et al.,* 2010; Prakash *et al.,* 2019). So, the larger oil palm frond and leaflet lengths observed in mulched intercropped plots, could have also been an effect of mulching. This effect must then only be observable in the intercropped plots with banana age group 1, as only in this age group mulching practices were applied.
Furthermore, unwanted suckers are removed to prevent nutrient withdraws from surrounding plants (Walmsley & Twyford, 1968). Suckers contain nutrients translocated from the mother banana plant during development (Kurien *et al.,* 2002; Walmsley & Twyford, 1968). Leaving the removed suckers as mulch could thus enrich the soil with nutrients and might potentially impacted banana plant and oil palm development in the intercropped plots. Since, the number of (removed) suckers varied per plot and banana plant, analysing the differences in amounts of suckers per plot and plant is essential to understand the effects of suckers on nutrient provision and plant development variables.
To conclude, the presence of banana plants in intercropped conditions may offer benefits to oil palm development through enhanced nutrient availability and soil health, by fertiliser applied to the bananas and the nutrients from the mulch of the banana leaves and removed suckers.

Incorporating both PT1 and PT2, compared to using PT1 alone, showed a statistically significant effect of leaflet length for first-year watermelon intercropping management. With approximately 3 months' time in between, no clear patterns could be observed in temporal effects. Long-term follow-up studies are interesting to analyse temporal treatment effects.

Intercropping can have unfavourable effects causing light, water or nutrient stress (Willey, 1990; Yu *et al.,* 2022). As the oil palms were still little, the ground projections of the banana plants, especially in a higher age group, sometimes overlapped the oil palm fronds which resulted in shade for the oil palms causing light stress. Larger fronds and leaves could capture light that would otherwise be blocked by the crown of the banana plants. In the Rainforest Zone of Nigeria, an increase in frond number and frond length was observed in irrigated oil palm seedlings under shade 2 to 20 weeks after planting, compared to unshaded seedlings (Agele *et al.,* 2017). Also, higher growth in oil palm seedling height and leaf area was recorded at 75% shade level compared to lower shade levels in the West Godavari district, India (Kummari *et al*., 2023). The increased growth of these oil palm variables may either indicate benefits or adaptation strategies when shaded.

Dry weather conditions during the fieldwork may have caused water stress resulting in changes in growth especially for the oil palms intercropped as both oil palms and banana plants require water for their development (Dissanayake & Palihakkara, 2019). A plant under stress generally directs its resources towards root growth (Hsiao & Xu, 2000) and allocates energy into water storage (Luo *et al.,* 2021) rather than focusing on leaf growth. This shift potentially reduces leaf area size due to the reduction in cell elongation and cell size (Boutraa *et al.,* 2010). No clear indications of water stress were found, as significantly larger frond lengths and leaflet lengths in current intercropped plots compared to monoculture plots were observed, likely caused by the irrigation of banana plants. Further research into root growth could give interesting insights if the oil palms are affected by water shortages, especially in the intercropped plots.

However, it is noteworthy that the mean leaf area of oil palms in all treatments in this thesis was approximately 1 m^2 or less, which is notably lower than typically observed leaf areas of around 2 m^2 one year after planting (Gerritsma & Soebagyo, 1999). Indicating that there are most likely factors inhibiting oil palm development.

In brief, an increase in a variable does not directly indicate a beneficial effect, it could also indicate competitive interactions. Further research is required to clarify this.

Banana Plant Distance

The analysis of banana development variables in relation to the distance between banana plants and oil palms showed consistent results: no significant differences between the banana plants far and close from the nearest parallel oil palm across all the time series. This suggests that the placement of the banana plants was not impacted by the presence of oil palms in terms of resource partitioning of light, water and nutrients. The size difference between the banana plants and the oil palms could plausibly explain sufficient light availability for the banana plants. Since the banana plants were larger compared to the oil palms light could be captured first by the banana plants (Ntamwira *et al.,* 2013; Ocimati *et al.,* 2021). Observing taller banana plants in intercropped situations compared to monoculture situations can be a result of light competition, to outgrow the oil palms (Dissanayake & Palihakkara, 2023; Sarrwy *et al.*, 2012). By the direct application of fertilizer around the stem likely both banana plants, close and far, received sufficient nutrients resulting in no development differences between close and far banana plants. Simultaneously, this fertiliser application around the stem may prevented the potential uptake of nutrients by the oil palms given the distance between the two plants, as the maximum growth rate theory explains that plants that grow the fastest tend to outcompete other plants in terms of resources (Grime, 1979, p.40). This may also apply to water uptake as the banana plants were irrigated close to their stem and therefore first taken up by the banana plants, minimizing uptake by the oil palms. This close irrigation to each banana plant may explain why no distinctions were observed between banana plants situated close or far from the oil palms.

The effect of planting distance on banana and rubber plant shows that an increase in planting density between both crops had no negative effect on banana plant growth in Sri Lanka (Rodrigo *et al.,* 1997). Additionally, in the highlands of Burundi the effect of tree species and legume intercrops on banana yield was researched and it was found that the banana yield was not affected by any of these tree species and legume intercrops (Akyeampong *et al.,* 1999). Further, no effect on banana yield after 3.5 years of intercropping with the *Grevilla robusta* tree was observed with different tree densities (Akyeampong *et al.,* 1999). These findings highlight comparable results as found in this thesis, showing no significant differences in banana development variables for different planting distances. In conclusion, no significant differences on banana development variables related to the distance between oil palms and banana plants was found. This suggests minimal impact of oil palm presence on banana plant development.

Variability among the Plots

The statistical variability found in both monoculture and intercropped plots suggests the presence of factors influencing differences between them. During the fieldwork measurements, differences between the plots were observed, such as weed types and weeding practices. Not every oil palm had been recently weeded around the stem and the types of weeds observed per plot varied. Although, the most common types were observed in almost all plots, their quantity differed between the plots. The top three most common weed species were *Camonea umbellata, Cyrtococcum oxyphyllum* and *Imperata cylindrica*, observed in 18, 16 and 15 plots, respectively. *Camonea umbellata* was the most observed weed type over all treatments. However, the three most common weed species differed in OPW-W, including *Bothriochloa ischaemum* in 3 of 4 plots and OPM-W, including *Clidemia hirta* in 4 of 4 plots (Figure 21). These differences could affect oil palms, as certain weed species can impact the formation of the oil palm's fresh fruit bunches (Satriawan & Fuady, 2019).

Figure 21 Most common weed species in all plots (from top left to bottom right): Camonea umbellata, Cyrtococcum oxyphyllum, Imperata cylindric, Bothriochloa ischaemum and Clidemia hirta.

Next to that, in some plots empty fruit bunches were found around the stem of the oil palms or between the banana plant rows (Figure 22), containing nitrogen, potassium, phosphorus, magnesium and calcium, which can benefit the growth of both plants (Budianta *et al.*, 2018; Menon *et al.*, 2020; Sari *et al.*, 2022).

As earlier discussed, in the intercropped plots with banana age group 1, banana leaves were used as mulch between banana and oil palm rows, a practice not observed in other plots, which may impact plant development (Dorel *et al.,* 2010; Prakash *et al.,* 2019). The quantity of banana leaves used as mulch varied between plots, as farmers did not precisely determine it. Additionally, the gentle slope that characterizes the plantation could influence the plant development outcomes in different plots. Different slope positions could affect soil physiochemical properties (Yasin & Yulnafatmawita, 2018), water and nutrient runoff which could result in a reduction in yield and nutrients in leaves (Balasundram *et al.,* 2006). Also as mentioned earlier, the number of (removed) banana plant suckers differed per plot and plant and could affect banana plant development (Bhende & Kurien, 2016) as well as the size and weight of bananas (Borah *et al*., 2018). In short, these factors could affect the variability between the plots and should be considered because of their possible impact on oil palm and banana plant development.

Figure 22 Intercropped plot with empty fruit bunches (left) and empty fruit bunches around an oil palm (right).

Correlations of Oil Palm Variables

In this thesis, high correlations between ground projection and height, frond number and frond length were found, which are also found in other studies. Canopy size was correlated with frond length (Gerritsma & Soebagyo, 1999) and frond number (Yahya & Manurung, 2002), and various oil palm hybrids showed high correlations of seedling height with frond length and frond number (Mathur *et al.,* 2022). However, correlations between ground projection and leaflet number, as well as between ground projection and leaflet length, differed significantly between the treatments, showing the importance of measuring these variables again in further research for comparisons between the treatments and underlying factors.

In literature focus of correlations is often between oil palm performance, especially FFB yield, and environmental factors, abiotic stress factors, pest and disease types or management factors as fertiliser use and planting density. Intercropping in this thesis may influence the correlations between the development variables due to resource complementarity or competition. For example, higher potassium levels in soils were found to be correlated with oil palm leaflet growth (Koussihouèdé et al., 2020). In this thesis, the correlation between frond number and leaflet number differed significantly between the treatments which may be a result of different soil nutrient levels, including potassium, among the different treatments.

Concentrating on one of the two highly correlated variables reduces fieldwork time while showing the same insights into treatment effects, as demonstrated in this thesis, which reveals significant impacts of current intercropping practices on both frond length and leaflet length. Similarly, given the high correlation between height and frond number and the same significant effect of first-year watermelon intercropping, measuring just one of these variables would be an option in further research of treatment effects.
In short, the correlations between the oil palm variables are likely influenced by shared underlying factors. However, the correlations vary between the treatments, suggesting the need for further

investigation into factors influencing this variation. Concentrating on one of two highly correlated variables could still capture treatment effects.

Correlations and Relationships in Banana Plant Variables

The banana plant stem diameter at base level was chosen for analysing allometric relationships. Especially growth status and vitality can be reflected by the banana plant's pseudo-stem diameter (García *et al*., 2020; Magalhães *et al*., 2020; Miao *et al*., 2022), as it serves as the plant's structure and support for other above-ground components as the leaves. In allometric relationships the girth at base was a better explanatory variable compared to plant height or girth at 1 meter for various banana plant variables (Nyombi *et al*., 2009).

Development stage-specific allometric relationships between banana variables were identified, with higher correlations between biomass of various banana plant components and plant girth in the early development phase compared to the later stage at flowering (Nyombi *et al*., 2009). This pattern is also observed in this thesis, showing less cohesive groupings and greater dispersion in the correlation plots and observations deviating further from the curve in the relationship plots as banana plants age.

Understanding the correlations and relationships between banana plant development variables could contribute to optimizing cultivation practices. Wider spacing between the banana plants resulted in a higher stem girth, number of suckers, number of functional leaves and leaf area. On the other hand, banana plants in more dense planting patterns were taller (Athani & Dharmatti, 2009), indicating that plant height grows higher in competition for resources (Dissanayake & Palihakkara, 2023; Sarrwy *et al.,* 2012). The high correlation between height-related banana plant variables found in this thesis, could be a result of the high planting density in the intercropping plots, which may have resulted in the need to grow larger development variables.
Overall, these findings emphasize the importance of studying age-related factors and the impact of management practices on banana plant development.

Limitations and further research

It is crucial to note that the results should be interpreted bearing in mind that these are pseudo-replicates and therefore not completely independent observations. Analysing pseudo-replicated results may lead to incorrect conclusions, as random effects or events affect in practice only one treatment. Besides that, treating pseudo-replicas as independent observations may increase the chance of finding statistically significant results (Hurlbert, 1984; Rogers *et al*., 2021).
The limited sample size per treatment, especially for banana plants per age group, and the short study duration for oil palms (only three months between the analysed measurements) limits the ability to find trends and fluctuations in plant development. Additionally, the fieldwork measurements were performed by different people, restricting the analysis over time to the variables frond and leaflet length only. This weakens the robustness and generalizability of the results regarding treatment effects and development over time.
Also, it is important to acknowledge that the banana plant distances 'far' and 'close' in this thesis are debatable and more complex. Given the plantation layout with banana rows between oil palm rows, distances are currently measured only on the line with the parallel oil palm next to the banana row and not from oil palms on other sides. This decreases the accuracy of defining close and far distances. Moreover, the absence of fertilizer application for oil palms limits the generalisability of the results

for fertilised oil palm plantations. The limited amount of precipitation compared to previous years may have influenced the development of both plants and ability to compare results to other situations. Last, the observations of PT0 and BT0 were excluded in the analysis for as measurements were missing, reducing the number of observations for both plants.
In brief, the limitations of this study emphasize the need for cautious interpretation of the findings.

Continuing the study so that the long-term effects of intercropping become visible is essential for understanding the impacts of intercropping on oil palm and banana plant development, productivity and the factors influencing this over time. Intercropping food crops with oil palm in the immature stage without sufficient fertiliser application, results in nitrogen and potassium deficiencies when the oil palms reach the mature stage (Nchanji *et* al., 2016; Rafflegeau *et al*., 2010) Fertilising additional plots can detect the differences in oil palm development between fertilised and non-fertilised circumstances. This increases the generalisability of the results for oil palm plantations that are fertilised and deepens the understanding of fertiliser effect on oil palm growth in monoculture and intercropped situations. In addition, the oil palms looked quite unhealthy and attacked. Assessing pest and disease prevalence in both oil palms and banana plants is crucial to understand potential cross-infections between the two. Weed identification, soil measurements and leaf nutrient analysis can provide better insight in the comparisons of weed dynamics, nutrients and water status between the treatments. Moreover, adding monoculture control groups enables direct comparison of banana plant development between monoculture and intercropped systems, and increasing the number of plots per banana age group allows analysis of the effect of first-year management practices on banana plant development. An alternative experimental design positioning banana plants at varying distances from oil palms on both sides could offer more precise insights into distance impacts.
On the whole, further exploration of these mentioned topics can enrich the understanding of management practices, oil palm and banana plant development and sustainable plantation dynamics.

Conclusion

Current oil palm-banana intercropping and first-year oil palm-watermelon intercropping showed significant impacts on the development of immature oil palms. The planting distance between banana plants and oil palms did not impact the development of banana plants. Resource complementarity and competition play a key role in cropping system dynamics. Soil nutrient composition, moisture levels and shading are central factors potentially affecting oil palm and banana plant development as they influence resource allocation, availability and plant physiology. This thesis provides new insight into the potential benefits and challenges of oil palm-banana intercropping, while it raises the question of long-term sustainability and optimal management practices. To create better understanding of plant growth, performance and management practices in oil palm intercropping systems it is essential to study the long-term effects of nutrient dynamics, water usage and the prevalence of weeds, pests and diseases. Maximising resource efficiency and minimizing environmental impacts can lead to more efficient and sustainable oil palm cultivation practices.

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Appendix I: PCA Plots of Banana Plant Variables per Age Group

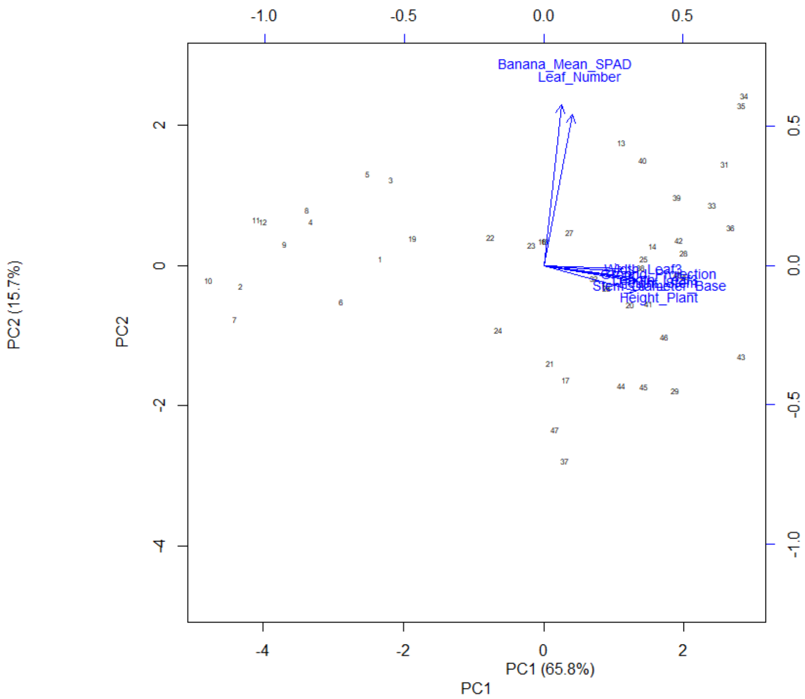

Figure A 1 PCA Plot of Banana Plant Variables for Age Group 1

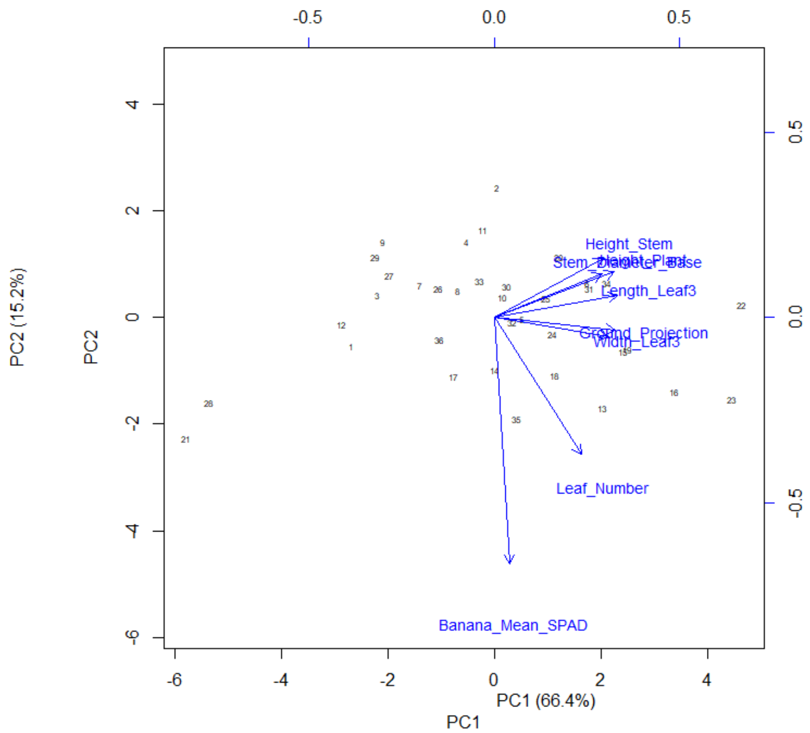

Figure A 2 PCA Plot of Banana Plant Variables for Age Group 2

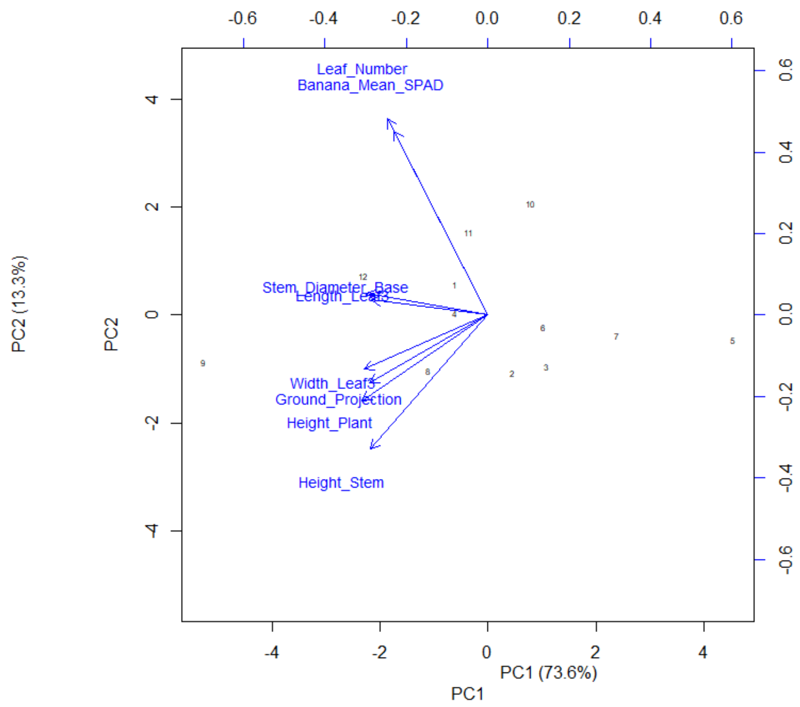

Figure A 3 PCA Plot of Banana Plant Variables for Age Group 3

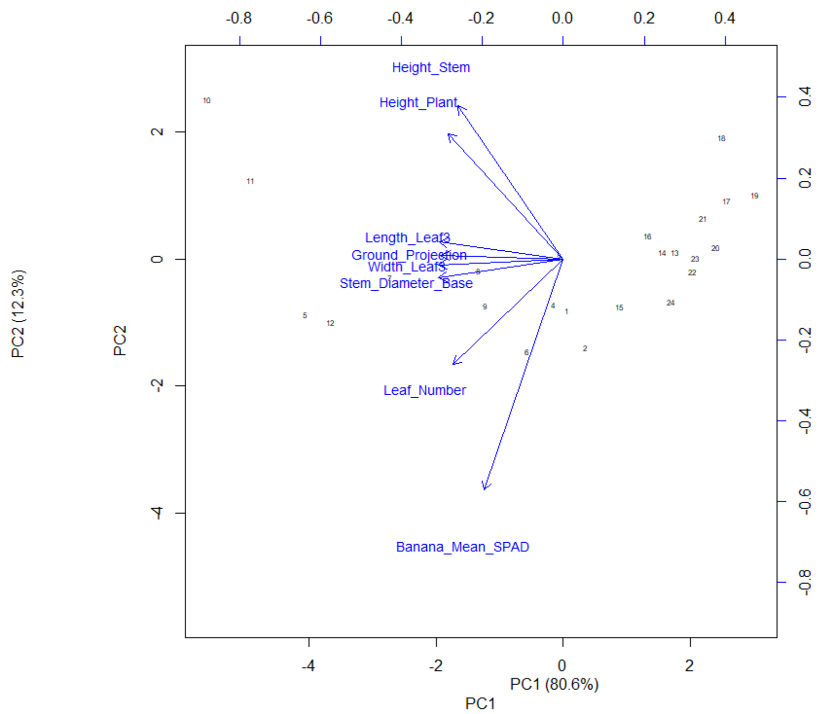

Figure A 4 PCA Plot of Banana Plant Variables for Age Group 4

Appendix II: LMM Results of Oil Palm Variables for PT1 and PT1,PT2

Table A 1 LMM Results for Oil Palm Ground Projection for PT1

Random Effect	**Variance**	**Std. Dev**		
Plot ID (Intercept)	0.067	0.259		
Residual	2.026	1.423		
Fixed Effect	**Estimate**	**Std. Error**	***t*-value**	***p*-value**
(Intercept)	6.082	0.260	23.425	< 0.001***
Intercrop Monoculture	-0.485	0.335	-1.447	0.1641
First Year LU Management Watermelon Intercrop	0.757	0.411	1.844	0.0808.
Intercrop Monoculture: First Year LU Management Watermelon Intercrop	1.339	0.561	2.388	0.0275*

The LMM R-squared values are 0.222 (marginal) and 0.247 (conditional)

Table A 2 LMM Results of Oil Palm Height for PT1

Random Effect	**Variance**	**Std. Dev**		
Plot ID (Intercept)	357.1	18.90		
Residual	776.7	27.87		
Fixed Effect	**Estimate**	**Std. Error**	***t*-value**	***p*-value**
(Intercept)	208.750	9.005	23.182	< 0.001***
Intercrop Monoculture	-0.194	11.625	-0.017	0.9868
First Year LU Management Watermelon Intercrop	50.458	14.238	3.544	0.0022**
Intercrop Monoculture: First Year LU Management Watermelon Intercrop	1.694	19.453	0.087	0.9315

The LMM R-squared values are 0.347 (marginal) and 0.553 (conditional)

Table A 3 LMM Results of Oil Palm Frond Number for PT1

Random Effect	**Variance**	**Std. Dev**		
Plot ID (Intercept)	1.212	1.101		
Residual	5.025	2.242		
Fixed Effect	**Estimate**	**Std. Error**	***t*-value**	***p*-value**
(Intercept)	15.139	0.585	25.900	< 0.001***
Intercrop Monoculture	-0.935	0.755	-1.239	0.2303
First Year LU Management Watermelon Intercrop	2.986	0.924	3.231	0.0044**
Intercrop Monoculture: First Year LU Management Watermelon Intercrop	1.227	1.263	0.972	0.3435

The LMM R-squared values are 0.343 (marginal) and 0.471 (conditional)

Table A 4 LMM Results of Oil Palm Frond Length for PT1

Random Effect	**Variance**	**Std. Dev**

Plot ID (Intercept)	103.4	10.17		
Residual	300.8	17.34		
Fixed Effect	**Estimate**	**Std. Error**	***t*-value**	***p*-value**
(Intercept)	165.333	5.058	32.689	< 0.001***
Intercrop Monoculture	-18.333	6.529	-2.808	0.0112*
First Year LU Management Watermelon Intercrop	2.625	7.997	0.328	0.7463
Intercrop Monoculture: First Year LU Management Watermelon Intercrop	17.792	10.926	1.628	0.1199

The LMM R-squared values are 0.188 (marginal) and 0.396 (conditional)

Table A 5 LMM Results of Oil Palm Leaflet Length for PT1

Random Effect	**Variance**	**Std. Dev**		
Plot ID (Intercept)	3.473	1.864		
Residual	24.486	4.948		
Fixed Effect	**Estimate**	**Std. Error**	***t*-value**	***p*-value**
(Intercept)	53.181	1.122	47.394	< 0.001***
Intercrop Monoculture	-4.042	1.449	-2.790	0.0117*
First Year LU Management Watermelon Intercrop	3.639	1.774	2.051	0.0543.
Intercrop Monoculture: First Year LU Management Watermelon Intercrop	4.840	2.424	1.997	0.0604.

The LMM R-squared values are 0.303 (marginal) and 0.390 (conditional)

Table A 6 LMM Results of Oil Palm log Leaflet Width for PT1

Random Effect	**Variance**	**Std. Dev**		
Plot ID (Intercept)	0.000	0.000		
Residual	0.014	0.120		
Fixed Effect	**Estimate**	**Std. Error**	***t*-value**	***p*-value**
(Intercept)	1.039	0.020	51.840	< 0.001***
Intercrop Monoculture	-0.022	0.02586	-0.852	0.3960
First Year LU Management Watermelon Intercrop	0.065	0.032	2.039	0.0434*
Intercrop Monoculture: First Year LU Management Watermelon Intercrop	-0.036	0.043	-0.820	0.4137

The LMM R-squared values are 0.059 (marginal) and 0.059 (conditional)

Table A 7 LMM Results of Oil Palm sqrt Leaf Area for PT1

Random Effect	**Variance**	**Std. Dev**		
Plot ID (Intercept)	0.0005	0.0229		
Residual	0.0094	0.0969		
Fixed Effect	**Estimate**	**Std. Error**	***t*-value**	***p*-value**

(Intercept)	0.087	0.019	46.711	< 0.001***
Intercrop Monoculture	-0.021	0.024	-0.869	0.3959
First Year LU Management Watermelon Intercrop	0.126	0.029	4.262	0.0004***
Intercrop Monoculture: First Year LU Management Watermelon Intercrop	0.041	0.040	1.008	0.3261

The LMM R-squared values are 0.340 (marginal) and 0.375 (conditional)

Table A 8 LMM Results of Oil Palm Leaflet Length for PT1 and PT2

Random Effect	**Variance**	**Std. Dev**		
Plot ID (Intercept)	3.473	1.864		
Residual	24.486	4.948		
Fixed Effect	**Estimate**	**Std. Error**	***t*-value**	***p*-value**
(Intercept)	53.064	1.146	46.299	< 0.001***
Intercrop Monoculture	-3.847	1.443	-2.666	0.0119*
Time2	4.867	1.189	4.093	< 0.001***
First Year LU Management Watermelon Intercrop	3.930	1.709	2.299	0.0292*
Intercrop Monoculture: Time 2	-0.162	1.389	-0.116	0.9074
First Year LU Management Watermelon Intercrop: Time2	-2.384	1.446	-1.649	0.1004
Intercrop Monoculture: First Year LU Management Watermelon Intercrop	4.296	2.117	2.030	0.0566.

The LMM R-squared values are 0.268 (marginal) and 0.332 (conditional)

Table A 9 LMM Results of Oil Palm Frond Length for PT1 and PT2

Random Effect	**Variance**	**Std. Dev**		
Plot ID (Intercept)	21.04	4.587		
Residual	456.81	21.373		
Fixed Effect	**Estimate**	**Std. Error**	***t*-value**	***p*-value**
(Intercept)	163.732	3.852	42.508	< 0.001***
Intercrop Monoculture	-15.665	4.818	-3.251	0.0024**
Time 2	6.119	4.465	1.370	0.1718
First Year LU Management Watermelon Intercrop	6.628	5.656	1.172	0.2499
Intercrop Monoculture: Time 2	8.690	5.215	1.667	0.0968.
First Year LU Management Watermelon Intercrop: Time2	12.702	5.427	1.522	0.0201*

Intercrop Monoculture: First Year LU Management Watermelon Intercrop	10.319	6.780	1.522	0.1444

The LMM R-squared values are 0.271 (marginal) and 0.303 (conditional)

Appendix III: LMM Results of Banana Plant Variables for BT1

Table A 10 LMM Results of Banana Plant Height for BT1

Random Effect	Variance	Std. Dev		
Plot ID (Intercept)	2233.8	47.26		
Residual	616.8	24.83		
Fixed Effect	**Estimate**	**Std. Error**	***t*-value**	***p*-value**
(Intercept)	224.792	24.169	9.301	< 0.001***
Distance Far	-0.792	7.169	-0.110	0.9123
Age 2	-72.792	36.919	-1.972	0.0941.
Age 3	-151.792	54.044	-2.809	0.0294*
Age 4	-176.708	41.862	-4.221	0.0050**
Distance Far: Age 2	3.236	10.951	0.296	0.7682
Distance Far: Age 3	3.792	16.031	0.237	0.8135
Distance Far: Age 4	-2.792	12.417	-0.225	0.8226

The LMM R-squared values are 0.636 (marginal) and 0.921 (conditional)

Table A 11 LMM Results of Banana Stem Diameter Base for BT1

Random Effect	Variance	Std. Dev		
Plot ID (Intercept)	8.352	2.890		
Residual	3.655	1.912		
Fixed Effect	**Estimate**	**Std. Error**	***t*-value**	***p*-value**
(Intercept)	14.974	1.497	10.004	< 0.001***
Distance Far	-0.119	0.552	-0.216	0.8292
Age 2	-4.063	2.286	-1.778	0.1226
Age 3	-10.040	3.347	-3.000	0.0221*
Age 4	-11.287	2.592	-4.354	0.0041**
Distance Far: Age 2	1.004	0.843	1.190	0.2365
Distance Far: Age 3	0.279	1.234	0.226	0.8219
Distance Far: Age 4	-0.013	0.956	-0.014	0.9889

The LMM R-squared values are 0.633 (marginal) and 0.888 (conditional)

Table A 12 LMM Results of Banana Plant SPAD for BT1

Random Effect	Variance	Std. Dev		
Plot ID (Intercept)	10.52	3.244		
Residual	21.45	4.632		
Fixed Effect	**Estimate**	**Std. Error**	***t*-value**	***p*-value**
(Intercept)	50.654	1.877	26.983	< 0.001***
Distance Far	1.425	1.337	1.066	0.2889

Age 2	-9.640	2.868	-3.362	0.0102*
Age 3	-15.079	4.198	-3.592	0.0073**
Age 4	-13.179	3.252	-4.053	0.00381**
Distance Far: Age 2	-2.512	2.043	-1.234	0.2201
Distance Far: Age 3	-1.183	2.989	-0.396	0.6931
Distance Far: Age 4	-0.417	2.316	-0.180	0.8576

The LMM R-squared values are 0.557 (marginal) and 0.703 (conditional)

Table A 13 LMM Results of Banana Plant Leaf Number for BT1

Random Effect	**Variance**	**Std. Dev**		
Plot ID (Intercept)	1.934	1.391		
Residual	1.510	1.229		
Fixed Effect	**Estimate**	**Std. Error**	***t*-value**	***p*-value**
(Intercept)	9.000	0.739	12.175	< 0.001***
Distance Far	-0.125	0.355	-0.352	0.725
Age 2	-0.611	1.129	-0.541	0.606
Age 3	-3.833	1.653	-2.319	0.0548.
Age 4	-3.250	1.280	-2.538	0.0399*
Distance Far: Age 2	0.292	0.542	0.538	0.5916
Distance Far: Age 3	0.625	0.793	0.788	0.4325
Distance Far: Age 4	0.042	0.615	0.068	0.9461

The LMM R-squared values are 0.381 (marginal) and 0.729 (conditional)

Table A 14 LMM Results of Banana Plant Leaf Length for BT1

Random Effect	**Variance**	**Std. Dev**		
Plot ID (Intercept)	677.4	26.03		
Residual	269.1	16.40		
Fixed Effect	**Estimate**	**Std. Error**	***t*-value**	***p*-value**
(Intercept)	146.375	13.437	10.893	< 0.001***
Distance Far	-0.833	4.736	-0.176	0.861
Age 2	-44.875	20.526	-2.186	0.0687.
Age 3	-98.708	30.047	-3.285	0.0153*
Age 4	-109.958	23.274	-4.724	0.0027**
Distance Far: Age 2	7.667	7.234	1.060	0.2916
Distance Far: Age 3	7.167	10.589	0.677	0.5000
Distance Far: Age 4	-0.667	8.202	-0.081	0.9354

The LMM R-squared values are 0.672 (marginal) and 0.907 (conditional)

Table A 15 LMM Results of Banana Plant log Leaf Width for BT1

Random Effect	**Variance**	**Std. Dev**		
Plot ID (Intercept)	0.075	0.273		
Residual	0.035	0.186		
Fixed Effect	**Estimate**	**Std. Error**	***t*-value**	***p*-value**
(Intercept)	3.849	0.142	27.174	< 0.001***
Distance Far	-0.011	0.054	-0.207	0.8361
Age 2	-0.129	0.216	-0.596	0.5715
Age 3	-0.679	0.317	-2.144	0.0726.
Age 4	-1.173	0.245	-4.779	0.0025**
Distance Far: Age 2	0.034	0.082	0.416	0.6785
Distance Far: Age 3	0.106	0.120	0.886	0.3778
Distance Far: Age 4	0.001	0.093	0.013	0.9895

The LMM R-squared values are 0.659 (marginal) and 0.892 (conditional)

Table A 16 LMM Results of Banana Plant sqrt Leaf Area for BT1

Random Effect	**Variance**	**Std. Dev**		
Plot ID (Intercept)	0.129	0.359		
Residual	0.060	0.245		
Fixed Effect	**Estimate**	**Std. Error**	***t*-value**	***p*-value**
(Intercept)	2.038	0.186	10.944	< 0.001***
Distance Far	-0.017	0.071	-0.235	0.8150
Age 2	-0.519	0.285	-1.926	0.1141
Age 3	-1.344	0.416	-3.227	0.0162*
Age 4	-1.561	0.323	-4.838	0.0024**
Distance Far: Age 2	0.092	0.108	0.846	0.3995
Distance Far: Age 3	0.106	0.158	0.669	0.5051
Distance Far: Age 4	-0.005	0.123	-0.040	0.9685

The LMM R-squared values are 0.671 (marginal) and 0.895 (conditional)

Appendix IV: Boxplots of Banana Plant Variables by Distance and Age Group for BT1, BT2 and BT3

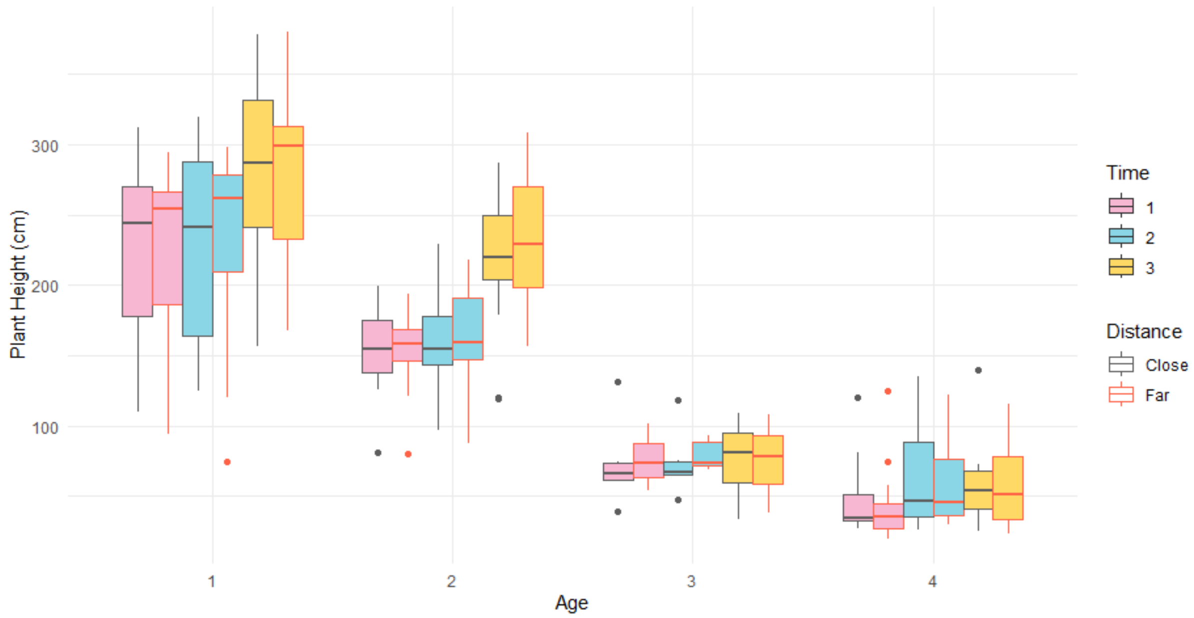

Figure A 5 Banana Plant height by distance and age group for BT1, BT2 and BT3

Figure A 6 Banana Plant stem diameter base by distance and age group for BT1, BT2 and BT3

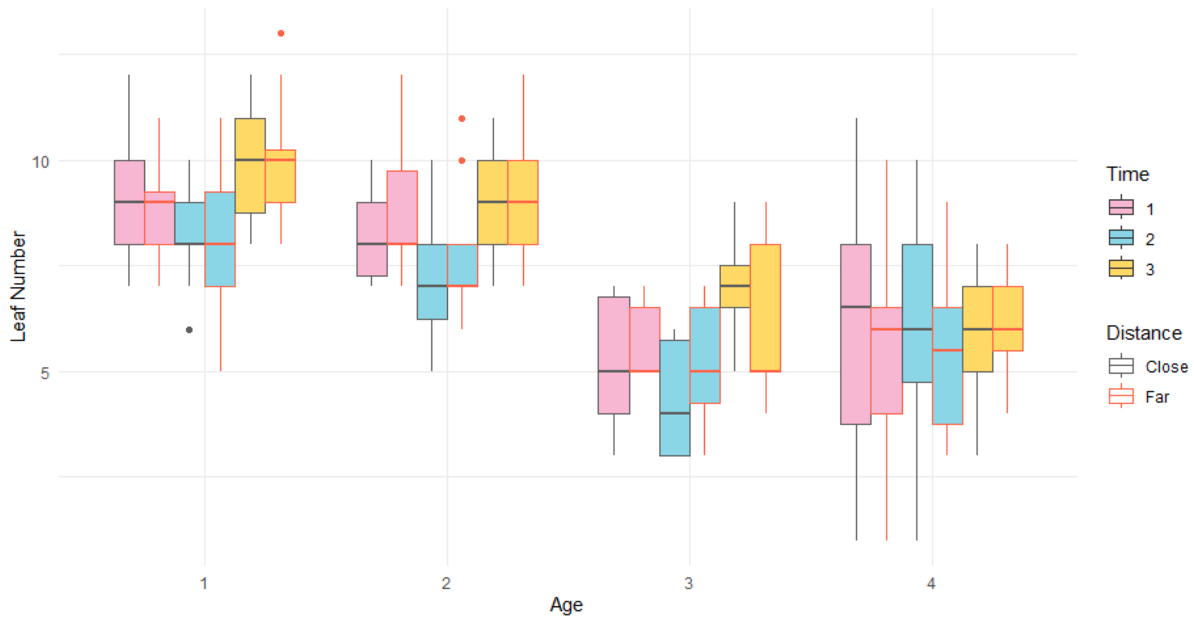

Figure A 7 Banana Plant leaf number by distance and age group for BT1, BT2 and BT3

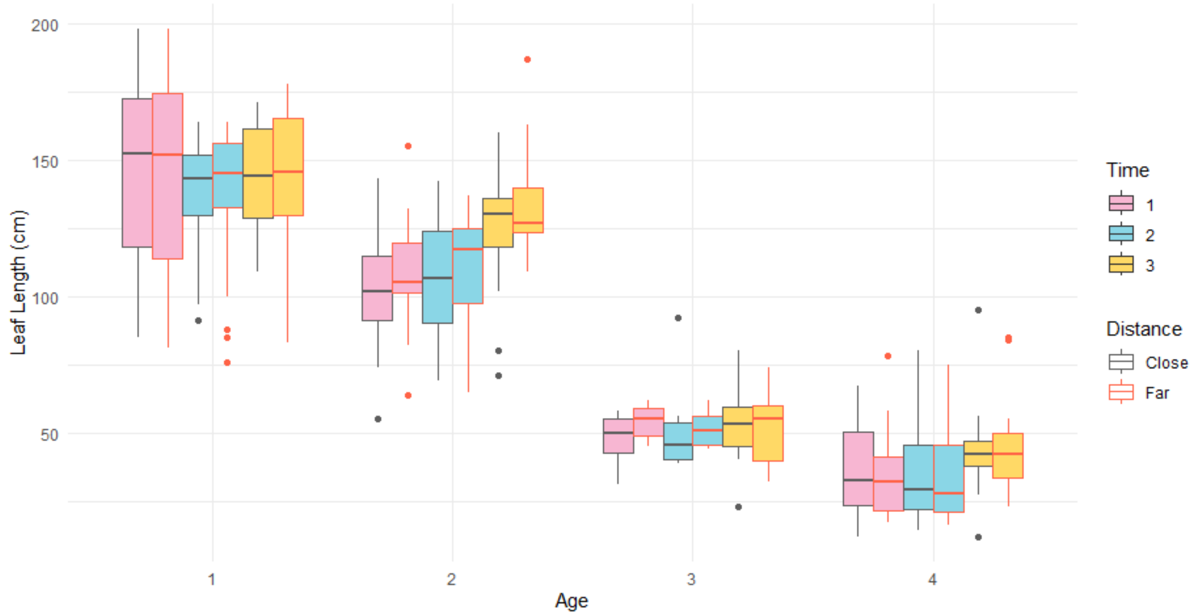

Figure A 8 Banana Plant leaf length by distance and age group for BT1, BT2 and BT3

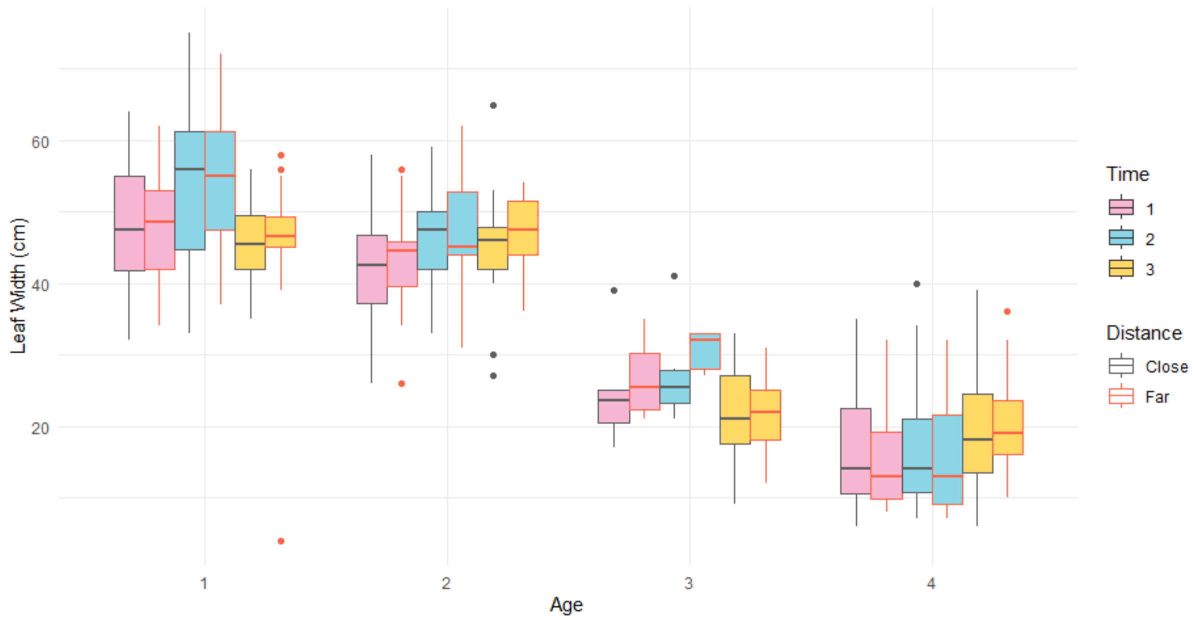

Figure A 9 Banana Plant leaf width by distance and age group for BT1, BT2 and BT3

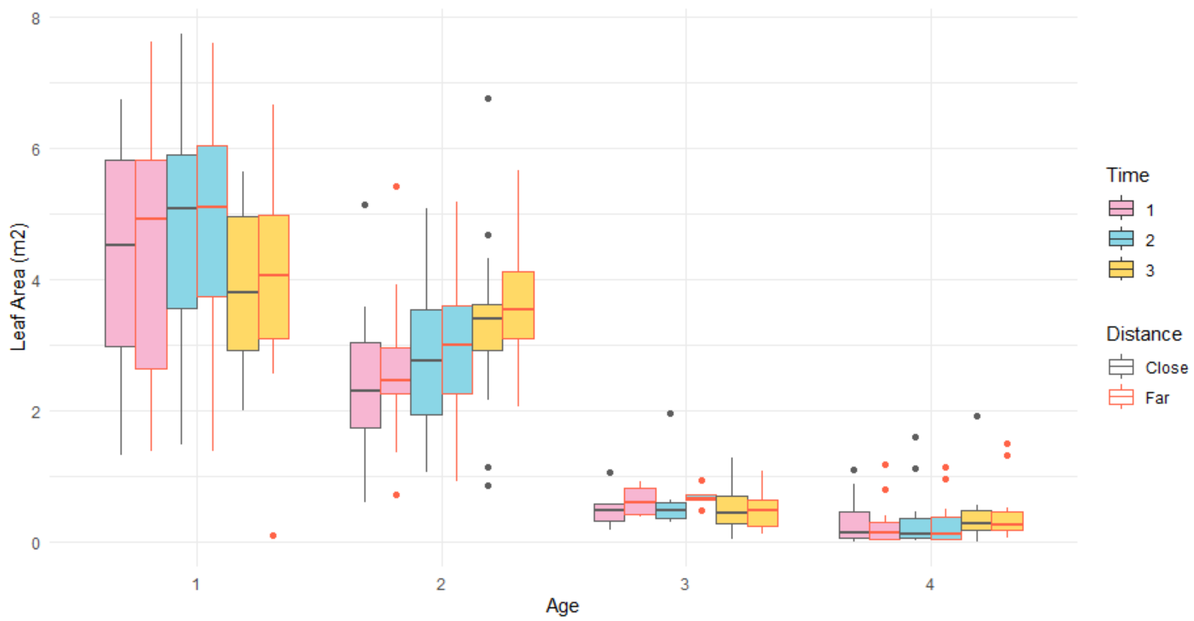

Figure A 10 Banana Plant leaf area by distance and age group for BT1, BT2 and BT3

Appendix V: Measurements of Oil Palm and Banana Plant Parameters

In this Appendix the measurements done during the fieldwork are described per development parameter for both oil palms and banana plants.

Oil palms

Frond span North-South and East-West directions

The frond span in North-South direction was measured by one person holding the measuring tape at the end of the longest frond in the northerly direction and the other person at the end of the longest frond in a southerly direction. This was repeated the same way in East-West direction.

Height

The height of the oil palm was measured from the ground surface to the tip of the vertically tallest frond. This was done by tying the measuring tape to a stick and holding it above my head and adding it to my own body height while standing as close as possible to the trunk of the oil palm.

Number of fronds

The number of fronds was counted beginning from the first totally opened up frond following the spiral until the last one alive. A frond was classified alive when more than half of the frond looked green and when more than half of the leaflets were still attached.

Total, rachis and petiole length of the third frond

The third frond was found by counting in the direction of the spiral, with the counting starting from the first totally opened up frond. The total length of the frond was measured from the closest possible point at the beginning of the spiral/trunk until the end of the midrib of the frond, which is the point where the last two leaflets divided. The petiole length was measured from this same beginning at the spiral/trunk until the first tips of leaflets started to appear at the frond. The rachis length was measured from the point where the petiole measurement stopped until the same end as for the total frond length. These measurements were done by using a soft measuring tape.

Number of leaflets on the third frond

The number of leaflets on the third frond was determined by counting all leaflets on one side of this frond and multiplying that by two.

Length and mid-width of the 6 largest leaflets on the third frons

The six longest leaflets were determined on the third frond, usually around the middle of the frond. The length of these six leaflets was measured from where it attached to the base of the frond towards the tip of the leaflet. The mid-width of these six leaflets was measured at the maximum width in the middle of these leaflets.

Number of inflorescences

The number of inflorescences observed per palm were noted. The distinction between male and female inflorescences was not made as that was hardly noticeable.

SPAD value of lower, middle and upper leaflets on the third frond

The SPAD values were measured by using the SPAD-2000 device. The SPAD values were measured on the third frond on: a leaflet close to the spiral/trunk, a leaflet halfway and on a leaflet at the end of the frond.

Banana plants

Distance to oil palm (parallel)

The distance between each oil palm and its parallel close and far banana plant was measured with a measuring tape, close to the ground.

Distance between banana plants (parallel)

The distance between the close and far banana plants, parallel to each oil palm, was measured with a measuring tape, close to the ground.

Leave span North-South and East-West

The frond span in North-South direction was measured by one person holding the measuring tape at the end of the longest leaf in the northerly direction and the other person at the end of the longest leaf in a southerly direction. This was repeated the same way in East-West direction.

Stem and plant height

The stem height was measured from the ground at the start of the pseudo-stem up until the start of the youngest (upstanding) leaf. The plant height was measured from the ground at the start of the pseudo-stem up until the height of the highest horizontal growing leaf or halfway up the highest upright leaf. This was done by tying the measuring tape to a stick and holding it above my head and adding it to my own body height while standing as close as possible to the pseudo-stem of the banana plant.

Pseudo-stem circumference at base and at 1.3 meter

The pseudo-stem circumference at the base was measured as close as possible to the soil with a soft measuring tape. The circumference at 1.3 meters was measured when possible.

Number of leaves

The number of banana plant leaves was determined by counting all full grown leaves.

Length and width of third leaf from the top

The third leaf from the top was determined and the maximum length and width of this leaf was measured with a soft measuring tape.

Number of suckers

The number of suckers was determined by counting the all suckers per banana plant, including removed ones.

Number of hands and fingers

When applicable, the number of hands and total number of fingers per banana plant was counted.

SPAD value on the left and right side of the third leaf from the top

The SPAD values were measured by using the SPAD-2000 device. The SPAD values was measured on the left and right side of the third leaf from the top.