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Assessing drivers of variation in understory vegetation in cocoa plantations in Côte d'Ivoire

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Assessing drivers of variation in understory vegetation in cocoa plantations in Côte d'Ivoire

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« Ceci aussi est pour le bien »

Talmud, Taanit 21a, Yerushalmi Shekalim

One of the most important lessons for me during the period that was spent slowly drafting this thesis, has been that in science it always will be important to accept the limitations that we are facing. Unfortunately I had to remind myself sometimes that there still could be value in these steps, despite being unhappy with the result on the table. It seems, looking back at all the people I had the privilege to meet during the period of research, that I slowly lost track of some of the essential observations of the field of study as a living reality. The traditional producing regions of cocoa in Côte d'Ivoire are at the brink of an important period of transition and transformation into a new production system and landscape. I'm very grateful having met so many young people and families that are engaged in society and community life, trying each day to make the best of it, trying to take along their families and friends on an upward trajectory. Students at universities such as the Universities of Daloa and Yamoussoukro with limited resources try to address and document challenges and formulate new ways of enabling the production system to adapt to the changes their country are facing.

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Abstract

In Côte d'Ivoire the majority of cocoa plantations are monocultures established on converted forest land. Over time these plantations have lost many of the species that were present in the forest, in part due to frequent removals during the year. In recent years cocoa cooperatives in Côte d'Ivoire have been increasingly stimulating cocoa farmers to maintain shade trees in their production fields. Amongst the continuously growing understory species that are found in the plantations are relevant forest species that could be used in restoring the desired shade cover.

Various studies have suggested that various environmental variables such as rainfall, light availability, presence of shade trees and soil affect species richness in the understory and its composition. On top of these also the impact of management should be accounted for. In order to assess the impact of these variables analysis of farm data in different regions is required. For this thesis field surveys were conducted in 49 cocoa plantations, in 12 of the most important production regions of the country. In each plantation four supervised treatment plots of 21*21m were established. Data was collected on species richness, non-cocoa tree species, shade level, litter depth and weeding frequency and management (farmer interviews) and combined with environmental data (rainfall). Using generalized linear mixed models and MANOVAs I assessed drivers of variation in species richness and composition.

Overall more than 226 plant species were encountered in the cocoa understory. Rainfall was the most important explanatory factor for species richness in the linear mixed model, species richness increasing with increased annual rainfall. By contrast, species composition was mostly determined by shade (for lianas) and litter (for grasses, herbs and shrubs), as obtained in a MANOVA test. The most species rich sites (based on Shannon index) were found in the more humid area. In terms of species composition, the drier transition zone stood out compared to both the more humid and the drier zones (based on Sørensen index). The most species rich plantations all had intermediate shade levels, with a presence of multiple shade trees in field. Another factor that could benefit species richness significantly is reducing the amount of weed removal events from three to two.

It would be recommendable that farmers not only implement tree species that are provided by cooperatives but also make use of natural regeneration to select useable species to complement shade cover. These seedlings have a proven better survival rate as their root system is developed from the start in the ground. Trainers from the cooperatives could be instrumental to train farmers in this selection process. In both recent and older plantations valuable forest species are still found that could be more successful in regeneration.

Page index

Contents

1. Introduction

1.1 Context cocoa production Côte d'Ivoire

In the production year 2022-2023 (summer to summer) over 2.23 million tonnes of cocoa beans (42% of the world production of cocoa) was sourced in Côte d'Ivoire (ICCO, 2023). To achieve this production an estimated thirty percent of the land surface of the country (ca. 2 million hectares) is in use for cocoa production (Tondoh et al., 2015), generally by smallholder farmers with farms of 1-4 ha on average (Boko et al., 2020). To obtain this production surface, a large part of the former forest cover, part of the Guinean rain forest, has been converted into plantations (Tondoh et al., 2015). Studies have estimated that between 1955 and 1993 the primary forest in the country has disappeared with approximately 7.6% per year on average (Kalischek et al., 2023; Koulibaly, 2019; Kpangui et al., 2018), decreasing from 12 before conversion to 2.2 million hectares of forest currently (Tondoh et al., 2015). This figure refers to the overall loss in forest cover, being linked to all different cultures that are cultivated nowadays such as cocoa, coffee, rubber, cashew, bananas (and plantain), oil palm and coconut palm (Kpangui et al., 2018; Sonwa et al., 2014; Sonwa et al., 2018).

One of the consequences of the conversion of forest into productive land is a reduction in biodiversity per hectare (Bisseleua et al., 2009; Esquivel et al., 2023; Maney et al., 2022; Marconi et al., 2022). In Côte d'Ivoire, along with spatial expansion of cocoa plantations, cocoa production was gradually intensified over time, leading to a higher density of cocoa trees per hectare and the removal of most covering forest vegetation and trees (Kpangui et al., 2018; Vroh et al., 2019). The change from a forest tree species dominated landscape with an extensive production system to an intensive full-sun monoculture with only fragments of remnant forest vegetation affected plant species richness and biodiversity in the landscape negatively (Kouakou, 2019; Kouman et al., 2022; Kpangui et al., 2018; Tondoh et al., 2015), which has been found in various studies elsewhere on the differences in biodiversity between full-sun monoculture plantations, cocoa agroforestry systems and natural forest (Andres et al., 2016; Cicuzza, Clough, et al., 2011; Marconi et al., 2022; Mattalia et al., 2022; Ofori-Frimpong et al., 2007).

The cocoa production zone of Côte d'Ivoire can be subdivided along two gradients: a climate gradient going from north to south and an historical one from east to west (Kouassi et al., 2023; Kpangui et al., 2018; Poorter et al., 2004). The climatical gradient goes from a drier region dominated by semi deciduous forest and around 1100mm/y to a region with rainfall over 1900mm /y and more evergreen semi tropical forest (Poorter, 2004; Tondoh et al., 2015). The historical gradient follows the gradual expansion of productive area since the introduction of cocoa in Côte d'Ivoire in 1950s from the East of the country towards the (South-)West, the south-west and south east being the last big areas to have been exploited since the 80s. Over the last 30 years the FAO (2017) has reported around 4.5 mln hectares of natural forest, originally 7.9 mln ha in the 1990s land were converted into productive land (Kouassi et al., 2021).

1.2 Importance of understory vegetation

The understory layer in forests plays an important role in succession in forest ecosystems. Cocoa (*Theobroma cacao L.*) is a forest species and once a plantation is fully grown the dynamics in the system are still linked to forest (Esquivel et al., 2023). It is the most species rich stratum in the ecosystem and thus relevant when studying biodiversity of systems (Gilliam, 2007; Thrippleton et al., 2016) and the composition of understory vegetation can have an impact on the potential for the regeneration of forest cover (Li et al., 2012).. In tropical forests over 45% of all vascular plant species in the understory are made up of herbaceous plants the rest being more ligneous (Linares-Palomino et al., 2009) or structurally dependent (27%) (Spicer et al., 2020; Spicer et al., 2022).

In undisturbed forest landscapes ground vegetation (understory vegetation) and spontaneous vegetation that grows in gaps between trees is comprised in majority with forest species. In cocoa plantations, intensification and reduction of shade tree canopy cover, reduce species richness and abundance of forest species (Cicuzza, Clough, et al., 2011; Maney et al., 2022; Marconi et al., 2022). Agronomic practices such as weeding and application of fertilizer cause further changes in species composition and make cocoa plantations more susceptible to invasive species (Davis et al., 2000; Herben & Goldberg, 2014; Marconi & Armengot, 2020; Marconi et al., 2022).

Research in Côte d'Ivoire documented negative trends in biodiversity in full-sun monoculture plantations (Koulibaly, 2019; Kouman et al., 2022; Tondoh et al., 2015). Some studies have been carried out focusing on the presence and use of shade trees or associated trees in plantations. Koulibaly et al. (2019) did such a study in the central regions of the country looking into species richness in the conventionally managed monoculture plantations where associated tree species were used. She found that in the understory a lot of potential for regeneration of useful tree species was found and that selective weeding might provide in a possible solution for farmers that look to diversify and include more shade species into their plantation. Others found distinct preferences in species used (Boko et al., 2020; Gyau et al., 2014; Kaba et al., 2021; Kouassi et al., 2021).

1.3 factors that affect species richness and composition

Some of the important ecological advantages of including shade trees in plantations are: (I) that they help ensure a longer productive period (Andres et al., 2016; Bisseleua et al., 2009), (II) that they improve soil fertility, maintenance and stability (Cissé et al., 2016; Tscharntke et al., 2011; Van Vliet & Giller, 2017).

1.3.1 Shade

Within the context of research into the differences between full-sun monocultures vs cocoa agroforestry systems (AFS) the impact of shade is one of the factors that is studied. More light should be positive for abundance herbs and negative for ligneous species(Marconi et al., 2022). Regional climatic differences should also be considered when taking into account growing conditions for vegetation. Different studies suggest that the more humid plantations are likely to harbour more species, as more forest species will be able to establish themselves (Koulibaly, 2019; Kpangui et al., 2018). Studies worldwide found that the optimal growing conditions for cocoa would be plantations with 20-40% shade, rather than full sun systems (Bisseleua et al., 2009; Konan et al., 2011; Steffan-Dewenter et al., 2007). Research has suggested that younger farmers are more willing to keep a recommended minimum of 15-18 shade trees/ha, especially specific ones (Cissé et al., 2016; Kaba et al., 2021; N'Zi et al., 2022; Smith Dumont et al., 2014; Vroh et al., 2019). Farmer attitudes change (Gyau et al., 2014).

1.3.2 Climate change

One of the problems related to climate change in the production regions with lower annual rainfall is the increase in the length of the dry season which impacts water availability to cocoa trees and understory vegetation. Shade cover is found to have a positive impact on the resilience of plantations in these drier regions to these increasing extremes (Dramane et al., 2021; Koulibaly, 2019; Kpangui et al., 2018). One of the ways of the Ivorian government and cocoa cooperatives to increase shade is the distribution of tree seedlings to their plantations via planting programs often coordinated by the national extension office for agriculture ANADER. Kouassi et al (2023) found that the effectiveness of these planting programs is deemed very poor, as only 9% of all trees they found in 150 plots had been originated from these programs. They found that seedlings from natural regeneration would have a much higher success rate, and that they subsequently play a much more important role in the current standing trees in plantations (Kouassi et al., 2023).

1.3.3 Litter

The presence of shade trees not only affects spatial heterogeneity and differences in light availability, but also affect litter and soil dynamics which can help maintain a more diverse understory (Abada Mbolo et al., 2016; Asigbaase et al., 2019; Vanhove et al., 2016) . Trees can help improve in-field conditions in extreme climate events, and contribute to spatial heterogeneity and species richness (Tondoh et al., 2015; Waldron et al., 2012).

Nutrient uptake is dependent on decomposition and mineralization of organic material(Van Vliet & Giller, 2017; Wartenberg et al., 2020). The thickness and composition of the litter layer is determined by the canopy cover, age of the plantation, climatic conditions and soil conditions. Depending on composition of litter different functional groups will be able to establish themselves. Davis et al. (2000) found for instance that due to the poorer soil conditions in monocultures (Davis et al., 2000; Obeng & Aguilar, 2015) that more invasive and pioneer species would establish themselves in the system if fertilization would be applied in some periods of the year. Ofori-Frimpong et al (2007) found that litter decomposition in monoculture systems was three times slower than in agroforests, which is related to the composition of litter and presence of soil biota (Obeng & Aguilar, 2015; Ofori-Frimpong et al., 2007).

1.3.4 Management

Management plays an important role when it comes to species richness in plantations. In general farmers tend to maintain a low herb cover in their plantations to favour their cocoa (Kouassi et al., 2021; Zekeng et al., 2023). However in recent years more farmers value the presence of a herb layer. Marconi (2020) equally found that un-weeded plots had a higher species richness than weeded ones (Marconi & Armengot, 2020). Full sun monoculture plantations with frequent weed removal are therefore likely to have fewer species than those with higher shade (Konan et al., 2011). An example of such management is weeding. Various studies have suggested that increasing weeding frequency leads to a decrease in species richness (Cicuzza, Kessler, et al., 2011).

Another form of management is that of mineral fertilizer treatment, which is part of the treatments of CocoaSoils. Van Vliet et al (2017) found that mineral fertilization affects available N, which would favour some efficient species and reduce the chances for other species that are less efficient in uptake (Van Vliet & Giller, 2017). Cicuzza et al (2011) also tried to compare the impact of fertilization on herb groups and they found a clear relation with grasses(Cicuzza, Clough, et al., 2011). It would be possible if similar effects could be seen in monocultures such as in Côte d'Ivoire. This might result in less diversity in the fertilized treatments with higher abundance for some species (such as grasses) than others.

1.4 Restoring biodiversity

In recent years there has been an increased interest in restoring part of the tree cover in plantations in Côte d'Ivoire and improving biodiversity. So far, the focus of biodiversity studies in cocoa plantations in Côte d'Ivoire has been on the presence of forest species in different regions of the country, specifically tree species (Kouassi et al., 2023; Smith Dumont et al., 2014) or focused on only a small study area (Boko et al., 2020; Cissé et al., 2016; Dramane et al., 2023; Koulibaly, 2019; Kouman et al., 2022; N'Zi et al., 2022; Tondoh et al., 2015).

Different functional groups of plants react differently to environmental factors, as they have different preferences. Pioneer species are often light loving and efficient in nutrient uptake whereas shade loving species are often reproducing slower and could be more ligneous (Hawthorne & Jongkind, 2006; Poorter, 2004). Another way to group understory plants in forest vegetation is according to structural groups. Documenting their relative abundance can provide in information on the growing conditions in the plantation (Hawthorne & Jongkind, 2006; Ramadhanil et al., 2008).

1.5 Research gap

Up till now no known studies have assessed biodiversity and more specifically all understory vegetation in conventional full sun monocultures in the most important production regions throughout the country. Combining vegetation data with environmental factors can provide in an insight in possible factors that contribute to this diversity. A possible schematic model that could help study these dynamics is presented on page 8 in figure 1. It builds on the resource limited growth that affect all plants (light, water, nutrients) as described in e.g. Craine & Dybzinski (2013) (Craine & Dybzinski, 2013) .

Different factors likely interact to affect the species richness and composition of the understory in cocoa plantations. Figure 1 provides a simplified schematic representation of these factors . Plant growth and species composition are dependent in the first place on availability of the three main resources (beige group): Light, nutrients and water. These in turn are impacted by four groups of factors. I distinguished (in 4 colours): environmental conditions (blue – soil (litter layer), plantation age, annual rainfall), factors related to overstory, both cocoa and associated trees (yellow and green - shade cover (but also litter; not added with an arrow to the scheme) and management (purple – fertilizer treatments and pest control, removal of weeds). It is however unclear which of these factors are most important in driving understory species richness and composition in cocoa plantations.

Few studies have been conducted focusing on changes in composition of understory vegetation due to environmental conditions. Whilst some studies focus on comparisons over time since conversion, understanding these conditions can also inform farm managers to favour specific management.

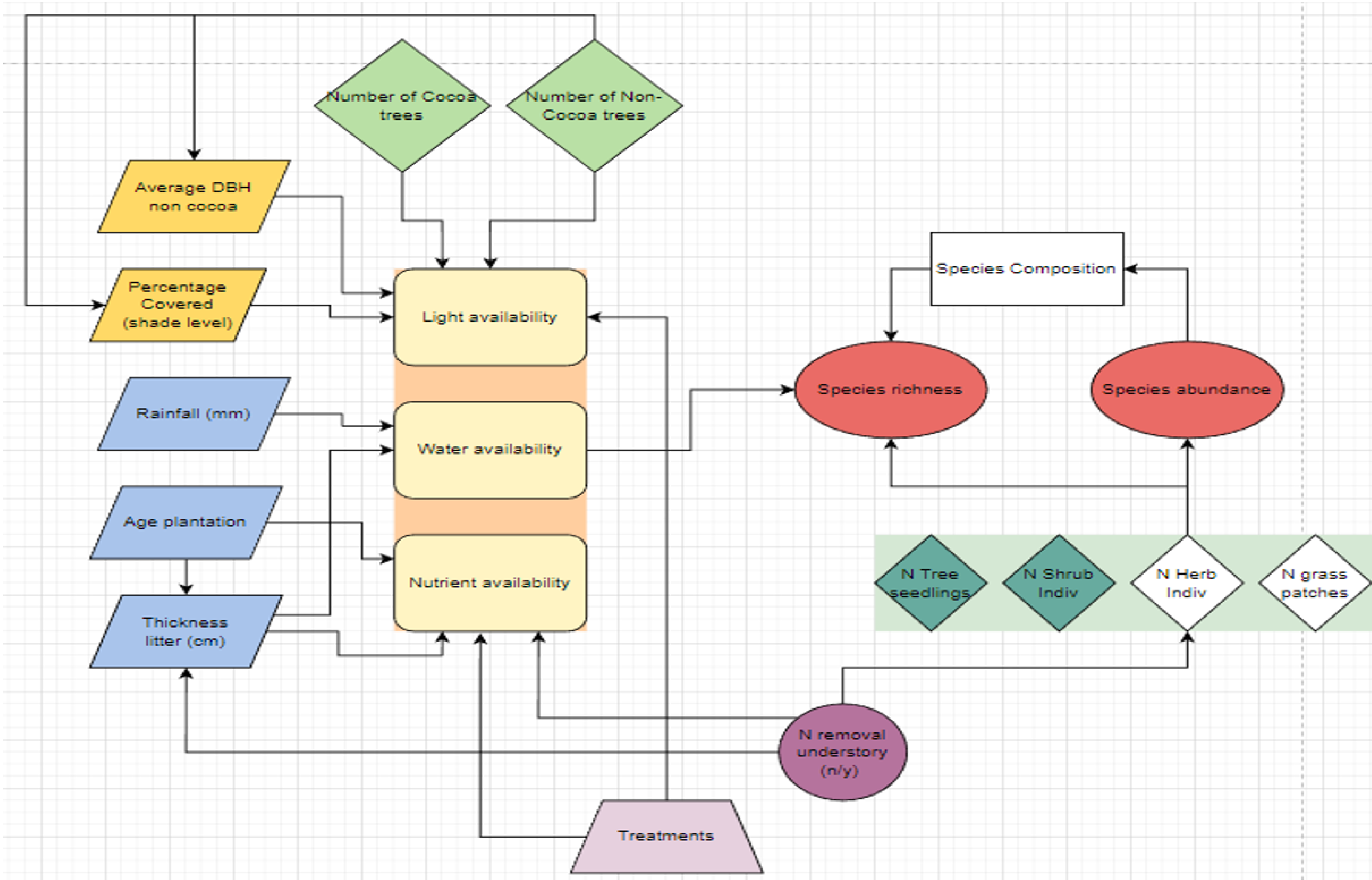


Figure 1: Schematic representation of interactions in a cocoa plantation. The functional groups of understory vegetation (green rectangular group on the right) all contribute to species richness an forming species composition. Their abundance is affected by weeding (N-removal) and their composition by the three environmental factors water, light and nutrient availability. Light and nutrien impacted by the rest of treatments of farmers (besides weeding; e.g. application of fertilizer, pruning, pesticides). number of trees (cocoa and shade) per plot and, for the latter, the kind of tree spe shade cover). Age of plantation and thickness of the litter layer both affect nutrient availability. Rainfall will affect the plant water availability directly and also indirectly through the characteristics

For this thesis I assessed plant biodiversity in plantations in most of the important regions of Côte d'Ivoire and to derive what factors affect species composition the most. Field work was done in these regions and plant surveys and other data was collected in order to document the factors.

A better understanding of the factors that explain differences in species richness in the understory vegetation in monoculture cocoa plantations can support the formulation of recommendations management towards better biodiversity and climate resilience outcomes. Therefore, the objective of this thesis is assess the differences in species richness in the understory vegetation in monoculture cocoa plantations within the main production regions of Côte d'Ivoire.

1.6 Research questions

To support the research objective of this thesis, I first seek to answer two introductory questions:

- How does species richness in the understory vegetation of cocoa plantations differ across regions in the country?

And:

- How does species composition differ across regions?

Then, following these introductory questions, the two main research questions are:

Q1: To what extent is the species richness of the understory vegetation in cocoa plantations in Côte d'Ivoire related to rainfall, shade, management, and thickness of the litter layer?

Q2: To what extent does species composition (functional groups) in understory vegetation under cocoa plantations change for different regions in Côte d'Ivoire, looking at the environmental factors?

2 Materials and methods

2.1.1 Study area

For this study, 49 research trial farms were visited in Côte d'Ivoire. These smallholder monoculture plantations have been connected to the CocoaSoils program (https://cocoasoils.org/), a research program focussed on the sustainable intensification of cocoa production, since the start of the project in 2018. In 2018 the team of IITA selected over 130 sites in all the main production regions of the country. The production zone of the country is divided into three agroecological zones that each have their specific soil characteristics. On top of this farms were selected in different climatic zones of the country, covering all the range of annual rainfall classes. The field work for this thesis was done as part of a larger research project focused on biodiversity in the CocoaSoils satellite trial sites that links similar field missions and inventories in the four main cocoa producing countries of Africa in the past two years: Cameroon (2022), Côte d'Ivoire (2023), Ghana (2022) and Nigeria (2023).

In the selection of the sites for this study, the intention was to have a representative selection of on-farm trial sites of CocoaSoils in 2023 . This selection (figure 2) was made based on geographic regions, annual rainfall, closeness to forest and tree cover per plot. Sites were selected in the 3 main production regions of the country. One of the objectives with the selected sites for this thesis was to represent this variability. In terms of pluviometry three main zones can be distinguished in the country, following a rough gradient from North to South: Dry zone, Moist zone and Wet zone. Generally all regions know two rainy seasons, only the length of the two periods differs between these zones. In the dry zone the onset of the rainy season is generally later, and the period shorter (Asante et al., 2021).

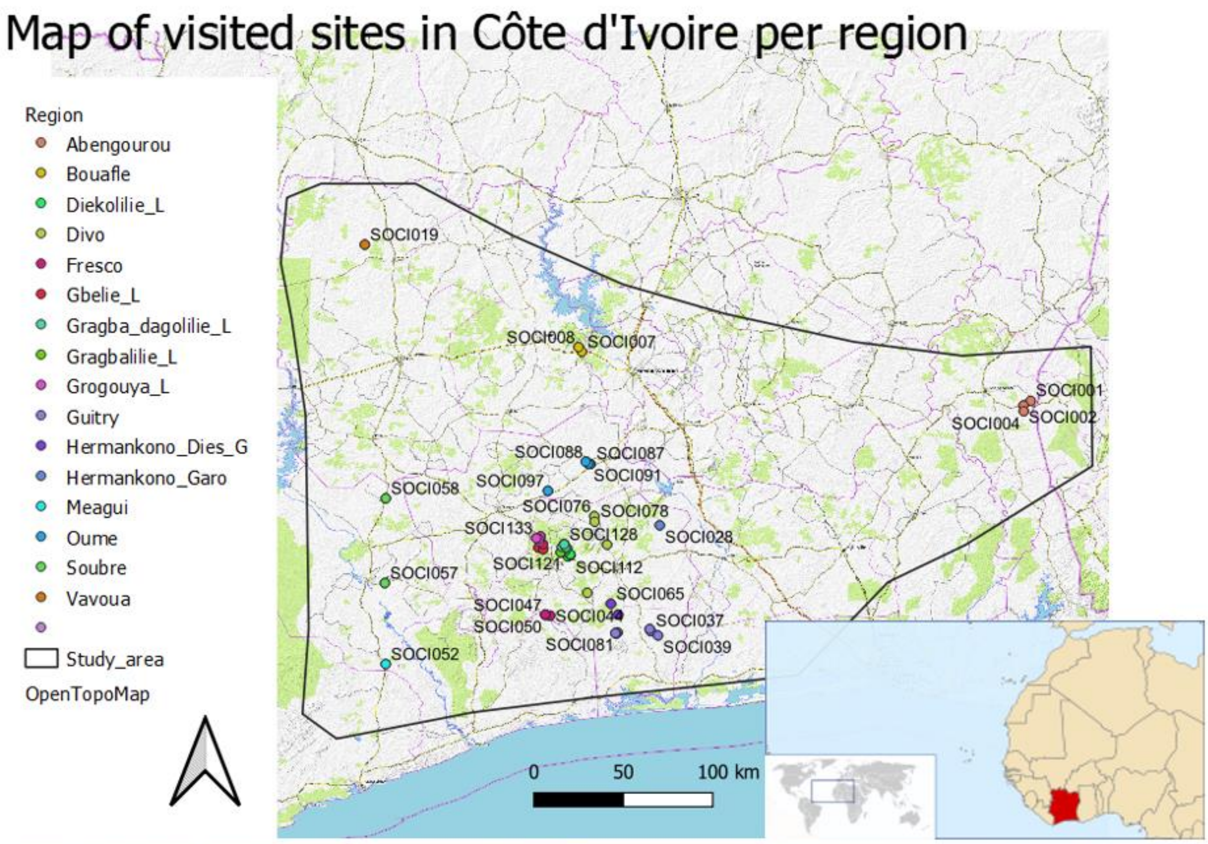


Figure 2: visited sites during field work, Map created with QGIS and open streetmap. Study area is in the southern part of the country. Smaller map of Africa with location Côte d'Ivoire. Source: Wikipedia commons

2.1.2 CocoaSoils study set-up

Each trial farm has four treatment plots of 21*21m with distinct management assigned. Two of the treatments include the application of mineral fertilizer, 1 following the national recommendations, the other using principles of integrated soil fertility management (CocoaSoils treatment).
All farms that are part of the CocoaSoils program were selected based on the criterion that they were planted between 8-22 years ago and that the total farm surface area would be larger than 0,6 ha. Each of the trial plots should have a minimum of 42 and a maximum of 56 cocoa trees.

The four treatments that are part of the program are:

- T1: The farmer is free to make his own management choices on this plot, no inputs from the side of CocoaSoils nor help with pruning
- T2: Regular pruning of the trees by technicians linked to the program to stimulate ventilation and light availability. Removal of understory vegetation minimum three times per calendar year. Use of pesticides and herbicides
- T3: comparable to T2 with application of the national fertiliser treatment[1]
- T4 comparable to t2 but with application of fertiliser treatment based on the off take model (CocoaSoils) on two moments in the year. Mix adapted to soil and the three agroecological zones[2].

2.2 Data and metrics

Data was collected that enables us to look at variation in species richness between study sites and regions, looking at the factors as represented in the scheme in figure 1. The following variables were assessed or calculated: Rainfall (mm), number of species, number of individuals, thickness of the litter layer in cm, percentage shade cover for understory vegetation, age of the plantation, number of weeding events per year, average DBH of non-cocoa trees.

In order to touch on all three resources required for plant growth, rainfall, shade and litter were measured following the relations as discussed in the introduction. In order to assess the impact of management only weeding was considered. Numbers of shade- and cocoa trees and the canopy diameter of shade trees were collected to be able to obtain shade data. DBH equally was used for this.

For each, a more detailed method is provided below.

Table 1: Model variables biodiversity assessment. Data was collected in the field of each farm within all 4 treatment plots. I distinguished predictors (independent variables) and response variables (dependent). The following categories were used: location dependent environmental factors, plantation characteristics and biodiversity related response variables.

Predictor	**Unit**
Resources	
Treatments	Ordinal (I-IV)
Location-dependent environmental factors	
Region	Geo-location /Farm ID
Rainfall	Mm/y
Depth litter layer	Cm
Plantation characteristics	
Plantation age	Years

[1] Application of NPK, Calcium oxide, Manganese oxide, Sulfur and Zinc on specific moments in the year.
[2] Application of NPK, Urea, MoP, Kieserite, Lime and ZnSO

Management frequency	Times/year
Nr hectares	Ha
Shade level	Percentage
Average DBH shade trees	DBH in M
Number cocoa	# trees
Number non-cocoa	# trees
Response variable	**Unit**
Biodiversity	
Species richness	No of species
Shannon diversity	Unitless
Sorensen Index	Unitless
Total Number of individuals	No of individuals
Number of individuals per lifeform	No of ind /groups
Proportional abundance (Rate of individuals/species)	unitless

2.2.1 Data collection

Field work was conducted during the months of February, March and April 2023 with a team consisting of a botanist from the university of Daloa, the extension officers of IITA and myself, supported by a driver from IITA that was familiar with the sites. In the field standardized protocols were used to obtain similar datasets as in the other countries. Data was collected on:

- floral composition of all understory plants along a transect on each of the four treatment plots
- thickness of the litter layer
- shade trees present within the plot and those outside the plot but with shade imprint and canopy cover overlapping the plot (species, DBH, estimated height and canopy diameter)

Lastly an interview was conducted with the farmer about:

- land use history (e.g. age of the plantation)
- the uses of all trees and herbs in the plots
- The origin of the trees and plants (planted, naturally regenerated, remnant)
- Fauna on and around the plantation (occurrence and frequency)
- Management (e.g. weeding frequency)
    - Management did not involve the treatments in this case, as they are caried out by the field technician of the cooperative

2.2.2 Biodiversity metrics

For the exploration of the sites first the Shannon index was calculated

Shannon-Wiener Index (H')

Index used to describe the diversity of an area in terms of species (Spellerberg & Fedor, 2003). It takes into account both number of species and abundance, which is what makes comparison easier.

Equation 1: Shannon index

$$H' = -\sum_{i=1}^{S}(p_i \ln p_i)$$

S=species number
P_i = proportion of the i-th species → N_i /N ; number of individuals i/total number of individuals

Sørensen Index

The Sørensen Index of similarity was calculated to compare regions (Chao et al., 2005). It is a statistic to measure similarity in species composition. A low number would imply dissimilarity. Numbers closer to 1 indicate higher similarity.

Equation 2: Sorensen index

SI = (2* SiC) / (SR1 + SR2)

SiC = total number of species in common between sites
SR1 = number of species in geographical unit 1
SR2 = number of species in geographical unit 2
*geographical unit could be either a farm, a region or a class. Generally both units should be comparable for a good comparison.

2.2.3 Potential factors affecting species richness

Farms in the same village or larger region often have higher similarity therefore farms were first regrouped in geographical region. Two other ways of grouping the farms that was done was based on rainfall class and understory shade level.

Shade impact – percentage of shade cover for understory vegetation

To estimate shade impact on understory vegetation, I calculated a shade estimate that combines shade originating from cocoa canopy and shade from canopy of associated trees. The resulting metric is derived from the counted cocoa density per treatment plot and the measured canopy per associated shade tree and its shade imprint onto the fields.

For the cocoa shade I started from the principle that between cocoa trees normally three meter of space is reserved; each cocoa tree having on average a canopy diameter of three m (see Annexe 1-fig 6). Within plots of 21*21m there would be space for (7*7=)49 trees if the perfect grid is maintained (see fig 6). The maximum number of cocoa trees on a plot was 56, the minimum 42. Total available surface area per plot is 21*21m = 441m^2. Having 49 trees on the plot would result in π*(1.5)^2 *49 = 346.4m^2 of surface area shaded = 73% of total surface area.

For the associated shade the canopy diameter of each tree that either had its stem in the treatment plot and / or had part of its canopy above the treatment was measured. Subsequently the percentage of that shade surface area was noted and the effective covered surface area added to the total of associated shade tree shade surface area. This also led to a percentage of the 441m^2 as shade cover. Summing the percentage of the plot covered by shade of cocoa tree canopy and that of shade trees on the plot gives the total area of shade cover. Where the canopy of associated trees overlapped with cocoa shade cover, the percentage could 'exceed' 100%, which indicates that there are multiple layers of tree canopy (strata) above the herbs. In reality there is not more than 100% shade over the understory, but the light penetration is likely to be lower, which is why it seemed relevant to express this in the shade level registered at the treatment plot level. Of course this is a simplification of the real shade impact; and also tree height would have to be taken into consideration; but it does account for an element of density. The other parameter that is linked: average DBH could be used to verify if there might be deviating patterns.

Six shade classes were created: 40-60% (I), 60-80% (II), 80-100% (III), 100-120% (IV), 120-140%(V), 140-200% (VI)

Average DBH

Different studies found that basal area and thickness of the stem have a correlation with crown density and height of the tree (Dramane, 2021). For this metric I calculated an average diameter breast height (DBH) at 1m30 per treatment plot using the DBH measures for all associated trees in the plot. Logically only those plots with associated trees show any numbers. Elevated values in this metric therefore could reflect both presence of shade trees and their relative impact.

Rainfall data

Annual rainfall data (mm) for each site was retrieved from the UCSB CHG using an R script, a dataset called the CHIRPS precipitation data (Katsanos et al., 2016). Rainfall data was considered equal for all treatments, as the plots were close together, and the central coordinates per plot are reasonably central between all treatment plots.
Based on the CHIRPS data, I created 5 rainfall classes. These were: Very dry 1000-1200 mm/y, dry 1200-1400 mm/y, dry-humid 1400-1600mm/y, humid 1600-1800mm/y, humid-wet 1800-2000 mm/y

Litter

To collect the litter data, depth of the litter layer was measured at 5 positions in the plot. Near the base of the 4 numbered cocoa trees closest to the 4 corners of the plot and 1 at a cocoa tree in the center, close to the transect rope. On each of the 5 positions 4 measurements of depth were taken (see Annexe 1 - figure 5B). Litter depth for the plot was calculated as the average of the measurements at the 5 points.

2.2.4 Dividing understory species into structural classes

All identified species were classified into the categories trees, shrubs, herbs, lianas, grass, based on the flora of West Africa and Hawthorne (2006). Besides the chorology was specified in the database, which also was consistent with these categories.

2.2.5 Interview data: Age of plantation and number of weeding events

Data on the age of the plantation and weeding practices were collected through farmer interviews. In Annexe 1 some of the questions that were asked.

2.3 Analysis

For this thesis project all treatment plots were agglomerated for the comparison, and the observations listed in one list. Only in the regrouped shade classes the individual treatment plots were considered as singular entries.

There are two linked random effects that should be considered for a reliable picture of the most important factors for species richness. As already clear from the Linear models, Treatment seems not a very influential factor, but could still favour specific species. Site ID however, as a geographical factor linking every time 4 observations seems more important. I therefore included both in the general comparisons, but kept it to only Site ID in the others.

2.3.1 Biodiversity metrics

Within the floristic data collected in the field two separate datasets were created, 1 for adult tree species and 1 for all the understory vegetation. With the latter dataset it was possible to calculate for all farms and individual treatments mean Shannon values using equation 1. Then for beta-diversity between sites the Sørensen Index was calculated for the regions and the reclassed farms based on shade values and rainfall data.

First exploratory comparison

Building on these two datasets it was possible to compare regions in terms of species richness and composition. Using the genera and main families some quantifications were possible. The regroupings on Shade and Rain class were also used in comparisons.

2.3.2 Looking at relations between main predictors and response variables

To assess the influence of the different environmental predictors on understory species richness, I used linear mixed effect models (Zuur et al., 2009). Using such models is important as the sites are found in different regions, and to be able to assess the impacts of the other factors, we would have to correct for the effect of regions. Rainfall, shade cover, thickness of the litter layer, plantation age and number of removal events per year were included into the model as fixed effects, species richness as dependent variable and region and treatment as random effects.

Scaling was applied to the continuous variables rainfall, litter, average DBH and shade to be able to compare all variables and their relative importance (e.g. similar to Asante, 2021)(Asante et al., 2021). As the dependent variable consists of count data a Poisson distribution was used with a log link function in the LME4 package in R (Bates et al., 2014). Various models were run for all variables independently and with interaction between 2 or more. In the end the model with the lowest Akaike Information Criterion (AIC) was selected as the most explanatory. The most significant models were summarized in a table. As done by Asante (2021) random intercepts were also included for each farm to account for non-independence of data points from the same farm (the 4 treatments). The predictors were evaluated for collinearity by calculating the Variance Inflation Factor. Because weeding frequency was a numerical categorical parameter, it was transformed into a factor.

2.3.3 Relative impact of predictors on species composition

I tested relative differences in species composition of the five structural groups (trees, shrubs, herbs, lianas, grasses) using multivariate statistics: multivariate analyses of variance (MANOVA)(Scheiner, 2020). A one way MANOVA was used for all variables (and their interactions) except for rainfall as was correlated with regions. I looked at the differences in relative abundance of each of these groups to see whether some were more sensitive to changes in one of the main predictors than others.

On top of this MANOVA I wanted to do an extra check to see whether the percentage of the two contrasting groups in terms of plant characteristics: herbaceous and ligneous species would be regionally different using linear mixed models. By taking their relative importance in percentage of individuals in total of individuals, it is possible to see whether changes in one of the parameters affect both equally in a mixed effect model. Different model simulations for each of the two groups makes it possible to compare AIC and P value.

3. Results

3.1 Species richness

3.3.1 understory species

In the transects in total 21367 individual understory plants were identified, belonging to 225 species and 65 families (Table 2). The families with the highest number of species were Poaceae (23), Euphorbiaceae (16), Fabaceae (14), Asteraceae (11), Moraceae, Rubiaceae, Solanaceae, Sterculiaceae (9), Combretaceae and Convovulaceae (7). In terms of abundance however the order was different: Euphorbiaceae (16%), Poaceae(14%), Asteraceae (10%), Combretaceae (8%), Apocynaceae, Fabaceae (6%), Moraceae, Caesalpiniaceae (5%), Cyperaceae (4%). Equal proportions of growth forms were found.

Table 2: Species richness and abundance in the collected dataset during the field mission 2023

Group	N Species	Percentage	Individuals
Herbs	38	17%	2207
Shrubs	84	37%	5465
Trees	38	17%	1429
Grasses	28	12%	3923
Lianas	37	16%	3834
Total	**225**		**16858**

Table 3: Characterisation of the twelve regions. All values are averages from all farms in that region combined including all treatments. All regions with an L behind their name are in the region of Lakota. Similarly (G) means in the administrative Guitry region. We can see here that the Lakota region shows quite a high Shannon value, but reasonable differences in terms of composition. Numbers of species aggregated for total unique species in that region, individuals summed for all

								Sorensen	
Region	**N Farms**	**N Spec**	**N Ind**	**Rain (mm/y)**	**Litter (cm)**	**Shade %**	**Shannon**	**Mean**	**SD**
Abengourou / Niablé	3	59	1715	1110	9	98%	3.229756	0.494977	0.079249
Bouaflé	2	35	201	1076	8	63%	3.032561	0.416135	0.048539
Diékolilié (L)	3	56	351	1744	9	89%	3.491367	0.508859	0.075213
Divo	4	82	2267	1727	7	105%	3.446066	0.530529	0.111613
Fresco	3	84	2354	1932	6	102%	3.180073	0.424577	0.108618
Gbélié (L)	3	86	826	1765	9	97%	3.549933	0.489877	0.131681
Gragba Dagolilié (L)	5	107	2629	1713	11	104%	3.577998	0.526235	0.143524
Gragbalilié (L)	3	58	851	1730	10	92%	3.075113	0.480851	0.107678
Grogouya (L)	4	80	1783	1775	10	96%	3.193671	0.495556	0.125521
Guitry	6	101	2422	1823	5	92%	3.351608	0.476035	0.12092
Hermankono Diès (G)	2	67	1681	1858	6	115%	3.343992	0.48766	0.120092
Hermankono Garo	1	27	245	1495	8	108%	2.144079	0.355593	0.059216
Méagui	1	27	136	1845	7	100%	2.63421	0.39338	0.069185
Oumé	6	94	3358	1401	8	100%	3.254938	0.51773	0.096698
Soubré	2	42	440	1407	9	108%	2.782132	0.377019	0.088379
Vavoua	1	23	108	1053	9	74%	2.629616	0.315397	0.053765

When regrouping by region it is visible in table 3 that Shannon-Wiener diversity index also shows to be affected by region and rainfall. The highest diversity is found in sites in the central south and south west in the towns of Gragba Dagolilie and Gbelie with values of 3.5 with SD of 0.14 vs the lowest found in Hère Mankono Garo, Vavoua and Méagui, all singular farms in two extreme regions (values on average around 2.5 with an SD of only 0.05). Looking then at Sorensen by taking the average of the differences of one site with all we can see on average the dissimilarity.

Species richness differed quite substantially between sites (Fig 3). The mean species richness value across all regions was ‘H = 34.24 ± 6.3, with Gbélié as the most species rich (‘H = 48.3 ± 9) and Vavoua and Soubré the least with ‘H = 23 ± 7.5.

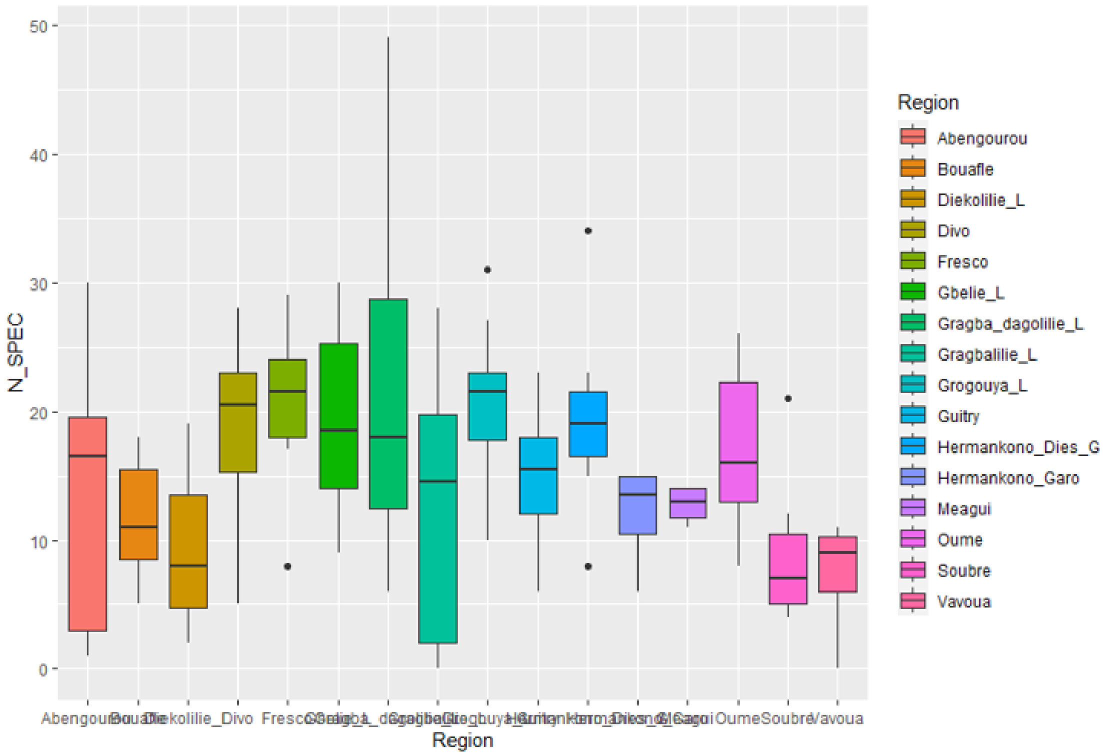


Figure 3: Number of species found in total in all farms in the geographic regions of the 49 farms. The additions L and G refer to the administrative region of Lakota (L) and Guitry (G)

3.1.2 Associated trees

Following the survey data on understory plants, the surveys on trees showed the following data. In total 676 associated shade trees were found in and around the plots distributed over 83 species. The most common species were all species that were of use to the farmers (fruits, medicinal or food) Persea americana (avocado, 77), Elaeis guineensis (wild/oil palm, 53), Citrus sinensis (Orange, 51), Coffea arabica (Coffee, 37), Mangifera indica (Mango, 36), Cola nitida (Cola, edible leaves, 28), Newbouldia laevis (Newbouldia, medicinal, 27). In terms of provenance, 25% were remnant forest trees, 26% were spontaneously regenerated trees and 43% were planted. In the region around Fresco we found the highest density of trees/field (11) or 236 trees /ha, whereas in Bouaflé and Vavoua we found 1 tree/field and 22 and 28/ha on average respectively. In Annexe 6 the numbers of trees per region and per hectare with standard deviation. In Annexe 7 a list with all species found and their frequency.

Per region the percentages amongst these groups differed (figure 4 a and b). In the drier and more exposed areas more trees seem to be planted than in the more humid and shaded plantations.

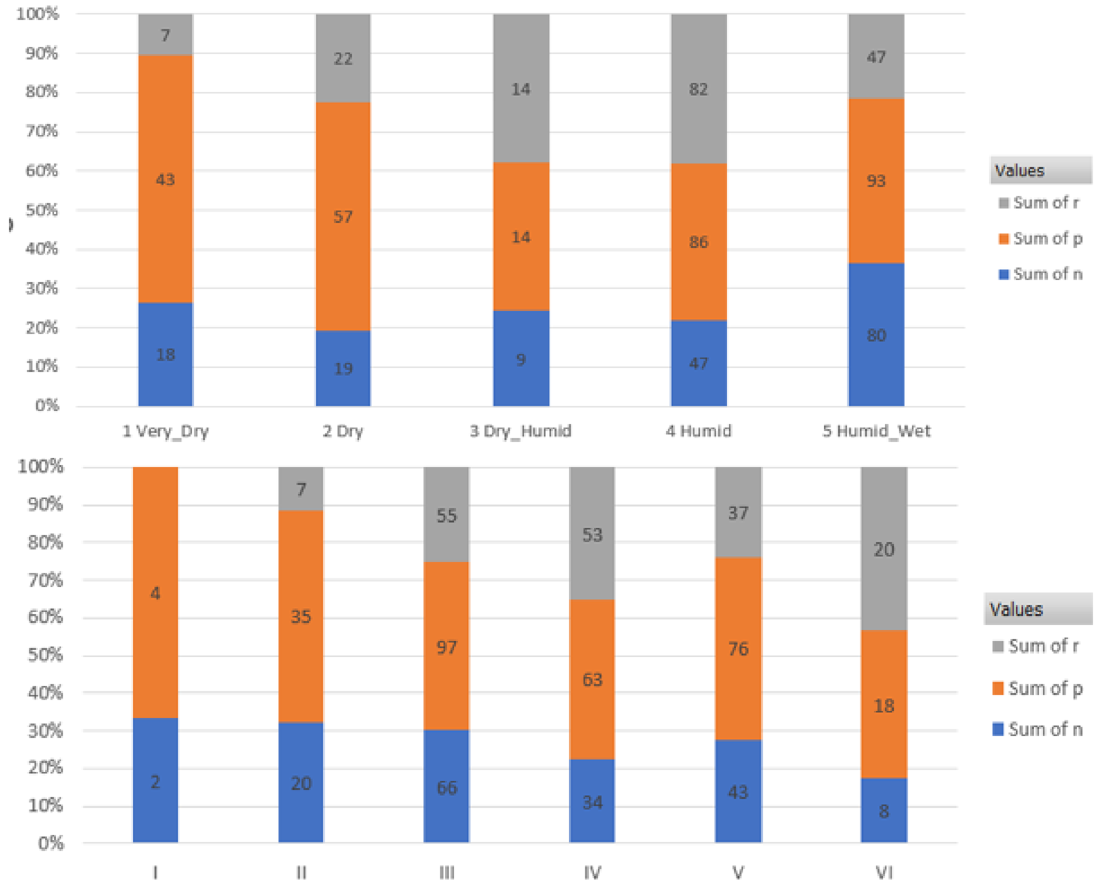


Figure 4a: Distribution of the origins of trees found in the treatment plots in the CocoaSoils farms, distributed over the region categories divided in rain classes (1000-1200mm/y, 1200-1400mm/y, 1400-1600mm/y, 1600-1800mm/y and 1800-2000mm/y. 4b distributed over the shade classes I-IV (40-60%, 60-80, 80-100, 100-120, 120-140, 140-highest%) Number of trees in the bar graph colour. R = remnant trees, P = planted trees, N =naturally regenerated trees.

3.1.3 Comparing the impact of predictors on response variables with different regroupings of the farms

Regrouping by rainfall and shade both show distinct differences in species richness.
In figure 5 a and b the different groups per class

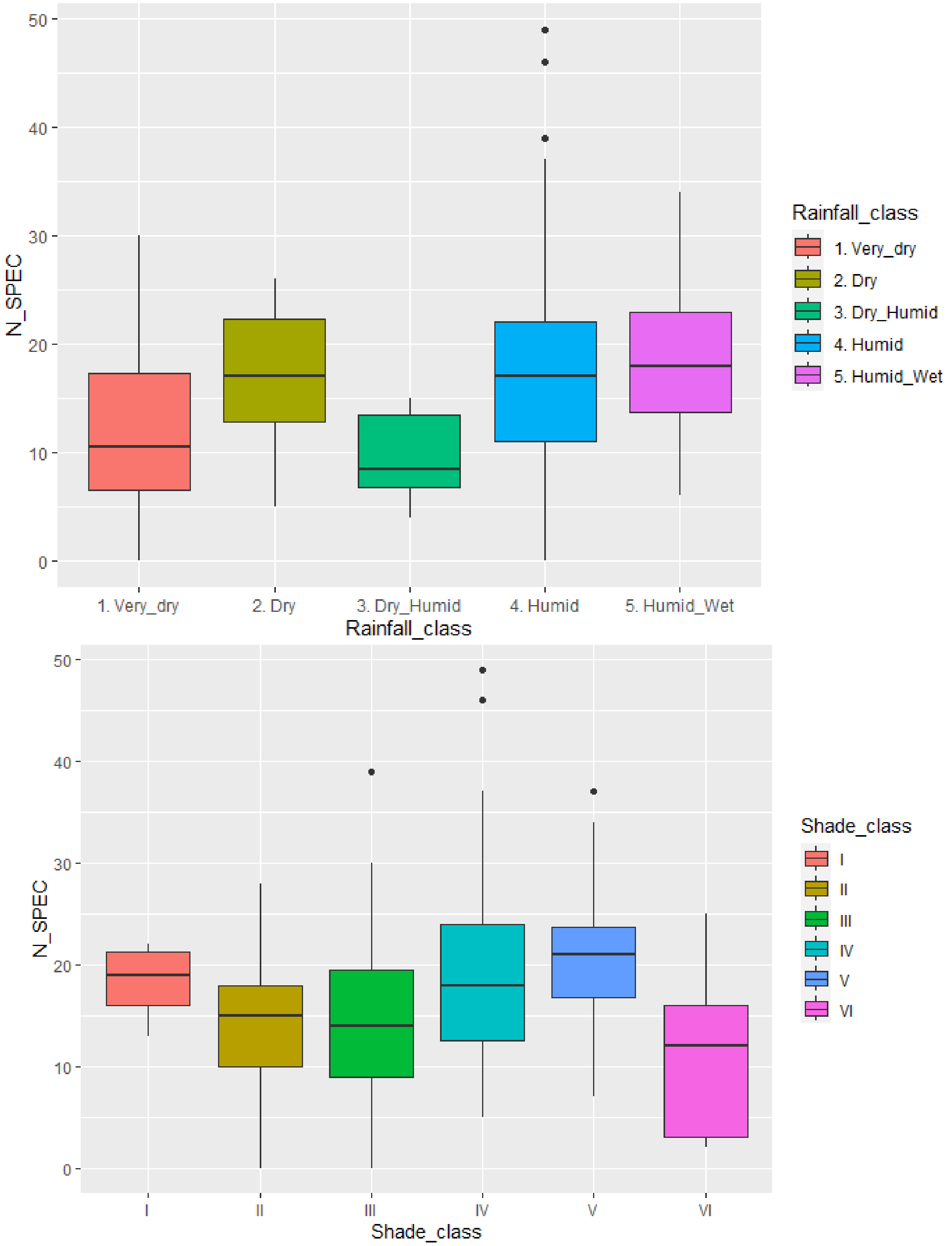


Figure 5a and 5b: Number of species per site for the regions reclassified on rainfall (mm/y) and percentage shade cover per plot. The effect of both factors shade and rainfall were found to be significant.

Composition

Looking then at comparability in composition we see the following in table 4 A and B

Table 4a, b and c: Sorensen index comparing regional classes. A divided into rainfall classes B divided into shade classes. Red cells are most dissimilar dark green most similar. Mean values in table 4a are calculated averaging the Sorensen values of one class for all other classes. Lower value implies more differences. Shade clearly has the lowest mean index, implying that the differences between these regions are most pronounced

Summary stats	Mean	SD	SE
Region	0.582045	0.071028	0.022461
Rain	0.613361	0.127909	0.033026
Shade	0.455651	0.116787	0.010661

Rain levels	N spec	Mean	SD	SE	Very Dry	Dry	Dry-Humid	Humid	Humid-Wet
Very Dry	84	0.596274	0.028478	0.014239	x	58	40	73	70
Dry	98	0.602176	0.031158	0.015579	0.63736	x	43	79	77
Dry-Humid	54	0.523806	0.057454	0.028727	0.57971	0.5657895	x	52	50
Humid	170	0.585732	0.102322	0.051161	0.5748	0.5895522	0.4642857	x	115
Humid-Wet	152	0.602236	0.093929	0.046964	0.59322	0.616	0.4854369	0.71428571	x

Shade levels	N spec	Mean	SD	SE	Class I (40-60%)	Class II (60-80%)	Class III (80-100%)	Class IV (100-120%)	Class V (120-140%)	Class VI (140-200%)
Class I (40-60%)	51	0.480151	0.044543	0.01992	x	47	47	50	48	27
Class II (60-80%)	124	0.674163	0.098036	0.043843	0.53714	x	111	106	95	58
Class III (80-100%)	171	0.648613	0.164828	0.073713	0.42342	0.7525424	x	133	113	63
Class IV (100-120%)	158	0.671025	0.141147	0.063123	0.47847	0.751773	0.8085106	x	111	64
Class V (120-140%)	138	0.659409	0.107901	0.048255	0.50794	0.7251908	0.7313916	0.75	x	60
Class VI (140-200%)	68	0.546808	0.059133	0.026445	0.45378	0.6041667	0.5271967	0.56637168	0.58252427	x

When averaging the numbers for comparability for regroupings on region (see annexe 7) rainfall class and shade class it is clear that the effect of shade seems to be the highest for separability in terms of species (average of 0.45 vs 0.58 for region and 0.61 for rainfall class). This means that different shade classes have a more distinct group of species that are found specifically there, whereas the rainfall region transitions seem to be more gradual finding more overlap in species composition between these big groups.

Species Richness

The sites in the transition zone had the lowest species richness with a mean richness of ‘H =24 (SD=7) followed by the driest (27 SD 12) where the richest site was found in the humid region, mean species richness ‘H 40 SD= 9.5. Also shade level showed to have an effect on some of the structural groups. In sites with shade levels between 40-60% for ground vegetation on average 18 species were found (SD 4), whereas in the highest shade level 15 species could be found (SD 7). The most species rich were sites with 80-120% shade. See tables in Annexe 5 Overall the site with the highest species richness was site SOCI126 in Gragba Dagolilié (Lakota, south west, humid), with 75 species (1076 ind), whereas the lowest diversity was found in SOCI122 in region Gragbalilie, with 5, however this seems an outlier as the other farms score much higher. On average the sites in the drier and sun exposed sites turned out to have lower richness. In annexe 5 a summary per region is given.

Looking at the difference between the treatments it was clear that the zero treatment (T1) showed in all comparisons the highest N spec (173 vs T2: 160, T3: 166,T4: 142), with an abundance of 6477 and also the Shannon proved slightly higher 'H 2.7 (sd 0.3).

3.2 Explaining variation in species richness

Using only linear regression rainfall appeared to be the most important factor determining species richness in plots (AIC -149.38, with a P of 0.0004), followed by a model combining Rainfall and shade level in the plot (AIC -149.28 but only a P of 0.0883).

Correcting for the random effect of region in the generalized mixed effect model only a P smaller than 0.05 was attained; whereas region proved to be highly significant (P<0.0001). Beside the random effect of region, overall rainfall and weeding had a significant impact on species richness (P < 0.0001, P<0.0386 and P<0.0482 respectively), rainfall still having the lowest AIC as visible in annexe 3 (1326 vs 1328). When we would take into account interactions between predictors however, also one of the combinations with litter showed highly significant. The combination Litter, Age of the plantation and the metric Avg_DBH, linked to the associated shade trees present in the plot also showed significant

Using a linear mixed effect model, comparison of AIC showed that not rainfall but shade, followed by frequency of weeding had a slightly better explanatory power; region having the highest significance, as predicted with the linear model and rainfall relation.

Table 5: Random effects for the individual predictors with regards to species richness. Shade level and management have a slightly lower AIC, which makes them more informative.

		ST_ID		Residuals			
	REML criterion at convergence	Variance	St Dev	Variance	Sd	%var expla	AIC
Rainfall	463.8	0.618	0.7861	0.3437	0.5862	64%	472.0558
Perc cover	453.1	0.6586	0.8115	0.3415	0.5844	66%	461.2761
Litter	456.9	0.6769	0.8228	0.3394	0.5826	67%	465.1292
N Remova	451.7	0.6356	0.7973	0.3437	0.5862	65%	461.9944
Avg DBH	458.4	0.6681	0.8174	0.3456	0.5879	66%	466.6119
Age	456.4	0.6756	0.822	0.3437	0.5862	66%	464.657

When looking at interaction effects, similarly the interaction shade and rainfall seems to have the strongest correlation. Both the combinations Rainfall + Percentage covered and Rainfall + Average DBH show significant p values (0.05 and 0.03 respectively) with the lowest AIC equally for percentage covered (485). In the tested threefold interactions similar patterns are shown, but these are harder to interpret.

Lastly in the added singular model with both random factors included only shade showed a significant p value (p=0.075) with an AIC of 494 and variance explained of 66%.

3.3 Species composition

Since species composition takes into account relative differences between groups of species, I used Multivariate Analysis of Variance. Before we found the biggest factor in regional differences was rainfall, but when we corrected for random effects it became clear that not rainfall but shade level, litter and weeding had more impact when we would compare between sites. As the intention will be to assess environmental variables mostly, and rainfall is linked to the random effect of site the decision was made not to use rainfall in the assessment.

Table 6: MANOVA table for the test Number Individuals all groups vs shade, litter, average DBH, Age and N removal. Three stars is highly significant (F<0.005), one star significant (P<0.05). For grasses Litter is highly significantly affecting the number of grass individuals, whereas for herbs and shrubs it is only significant. Shade is significantly affecting presence of Lianas in the understory.

Vegetatior	AOV stats	DF	Sum sq	Mean sq	F value	Pr (>F)	residuals	sum sq re	mean sq	Significance
Grasses	Perc covered	1	0	0.2	0.0001	0.990243	189	251007	1328.1	
Grasses	Litter	1	20536	20536.3	15.4632	0.000118	189	251007	1328.1	***
Grasses	Avg DBH	1	3	2.8	0.0021	0.96332	189	251007	1328.1	
Grasses	Perc covered	1	791	791.2	0.5957	0.44118	189	251007	1328.1	
Grasses	N Removal	2	2581	1290.7	0.9719	0.380259	189	251007	1328.1	
Herbs	Perc covered	1	630	630	0.8903	0.3466	189	133734	707.6	
Herbs	Litter	1	4661	4660.8	6.5869	0.01105	189	133734	707.6	*
Herbs	Avg DBH	1	48	48.4	0.0684	0.79399	189	133734	707.6	
Herbs	Perc covered	1	10	10.3	0.0146	0.90404	189	133734	707.6	
Herbs	N Removal	2	86	43	0.0607	0.94108	189	133734	707.6	
Shrubs	Perc covered	1	169	168.7	0.0914	0.7628	189	348906	1846.1	
Shrubs	Litter	1	8657	8657.1	4.6895	0.0316	189	348906	1846.1	*
Shrubs	Avg DBH	1	128	128	0.0693	0.7926	189	348906	1846.1	
Shrubs	Perc covered	1	1585	1584.9	0.8585	0.3553	189	348906	1846.1	
Shrubs	N Removal	2	6245	3122.7	1.6916	0.187	189	348906	1846.1	
Trees	Perc covered	1	65	64.993	0.6748	0.4124	189	18204.3	96.319	
Trees	Litter	1	55.5	55.469	0.5759	0.4489	189	18204.3	96.319	
Trees	Avg DBH	1	76.5	76.496	0.7942	0.374	189	18204.3	96.319	
Trees	Perc covered	1	73	73.005	0.7579	0.3851	189	18204.3	96.319	
Trees	N Removal	2	432.2	216.084	2.2434	0.1089	189	18204.3	96.319	
Lianas	Perc covered	1	6801	6801	6.5764	0.01111	189	195457	1034.2	*
Lianas	Litter	1	595	594.6	0.575	0.44924	189	195457	1034.2	
Lianas	Avg DBH	1	1587	1586.6	1.5342	0.21702	189	195457	1034.2	
Lianas	Perc covered	1	604	603.8	0.5838	0.44577	189	195457	1034.2	
Lianas	N Removal	2	2086	1042.8	1.0084	0.36676	189	195457	1034.2	

The dependent variable most relevant to composition is abundance, and then split into the 5 relevant groups: Grasses, Herbs, Shrubs, Trees, Lianas, grouped in de MANOVA.

Using a model with all variables (shade cover, thickness of the litter layer, plantation age and number of removal events) added it becomes clear that Litter is the most important factor affecting differences in species composition for grasses (P 0.00012), herbs (P 0.01105) and shrubs (P 0.0313) (See table 6 above). Only for lianas the factor shade is significant (P 0.0111). Trees are not strongly affected by any of the variables taken into consideration.
The analysis on relative importance of each group in the total of individuals per field that was done based on the shade level parameter (perc covered) per field showed that with increasing shade lianas

increased in relative abundance whereas herbs and grasses (light loving species) reduced. Woody species seem less affected by the change in light conditions and only reduce slightly. The relation Is depicted in figure 6.

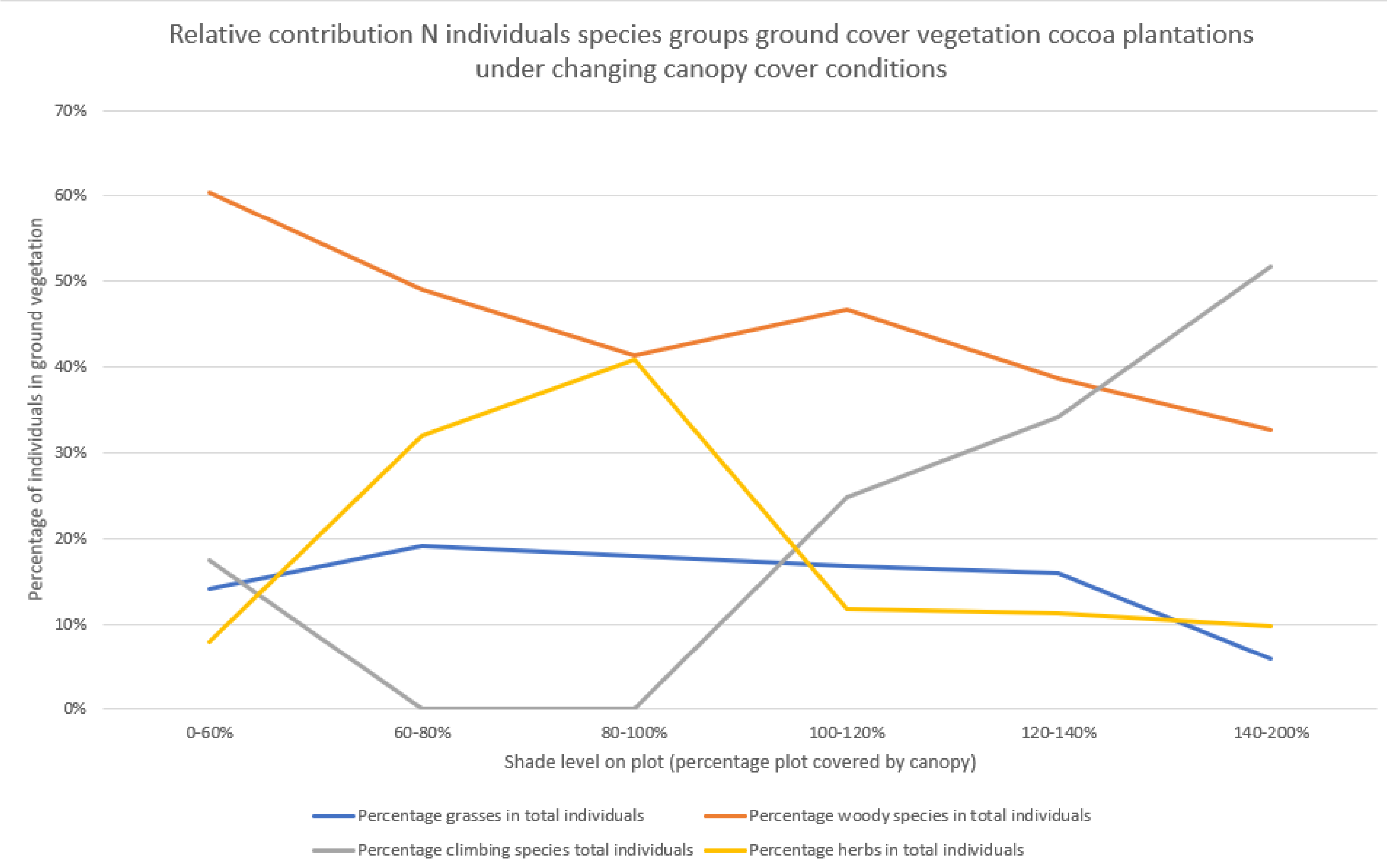


Figure 6: Changes in species composition with increasing shade density. As visible lianas are shade loving species that increase whereas the herbs (and to lesser extent grasses) seem to benefit more from lighter conditions.

3.4 Effects on relative abundance of ligneous and non-ligneous species

In order to correct for the random effects also here a linear mixed model is used to compare the species groups. Building on the results from the MANOVA a first test was done with interaction between litter and light availability. Looking at the random effects for the lower vegetation only a small part of the variation is explained by these two predictors. Only that of trees surpasses 50% with an AIC of 1390. Looking at the fixed effects however we can see in table 7 that site ID and Litter prove to be significant for the group of more light loving species, the grasses and the herbs, as also seen in figure 6. There were less grasses with thicker litter layer. Interestingly shrub cover seems to react as well to the interaction (P 0.07). Both trees and lianas, more shade loving species don't seem to be affected by litter, as visualized in figures 7 a and b

Table 7: Fixed effects interaction Shade level - Litter

Fixed effects							
Species	Predictor	Estimate	St Error	Df	t value	p	significance
Grass	Intercept (ST_ID)	102.957	51.129	180.376	2.014	0.0455	*
Grass	Perc covered	-48.939	50.781	186.416	-0.964	0.3364	
Grass	Litter	-9.968	6.039	185.781	-1.651	0.1005	
Grass	Perc covered : Litter	5.774	6.011	190.458	0.961	0.3379	
Herbs	Intercept (ST_ID)	73.698	36.032	132.13	2.045	0.0428	*
Herbs	Perc covered	-43.203	36.206	141.373	-1.193	0.2348	
Herbs	Litter	-8.603	4.31	144.473	-1.996	0.0478	*
Herbs	Perc covered : Litter	6.266	4.349	155.348	1.441	0.1516	
Shrubs	Intercept (ST_ID)	148.07	60.007	174.284	2.468	0.0146	*
Shrubs	Perc covered	-97.841	59.727	181.658	-1.638	0.1031	
Shrubs	Litter	-15.303	7.101	181.303	-2.155	0.0325	*
Shrubs	Perc covered : Litter	12.583	7.086	187.784	1.776	0.0774	.
Trees	Intercept (ST_ID)	7.8655	12.4978	190.952	0.629	0.53	
Trees	Perc covered	-2.6181	12.2448	187.58	-0.214	0.831	
Trees	Litter	-0.3792	1.4618	189.18	-0.259	0.796	
Trees	Perc covered : Litter	0.6415	1.4333	184.349	0.448	0.655	
Lianas	Intercept (ST_ID)	4.5052	43.8194	191.13	0.103	0.918	
Lianas	Perc covered	5.76	43.2113	191.962	0.133	0.894	
Lianas	Litter	0.1328	5.1467	191.979	0.026	0.979	
Lianas	Perc covered : Litter	1.0658	5.0814	190.792	0.21	0.834	

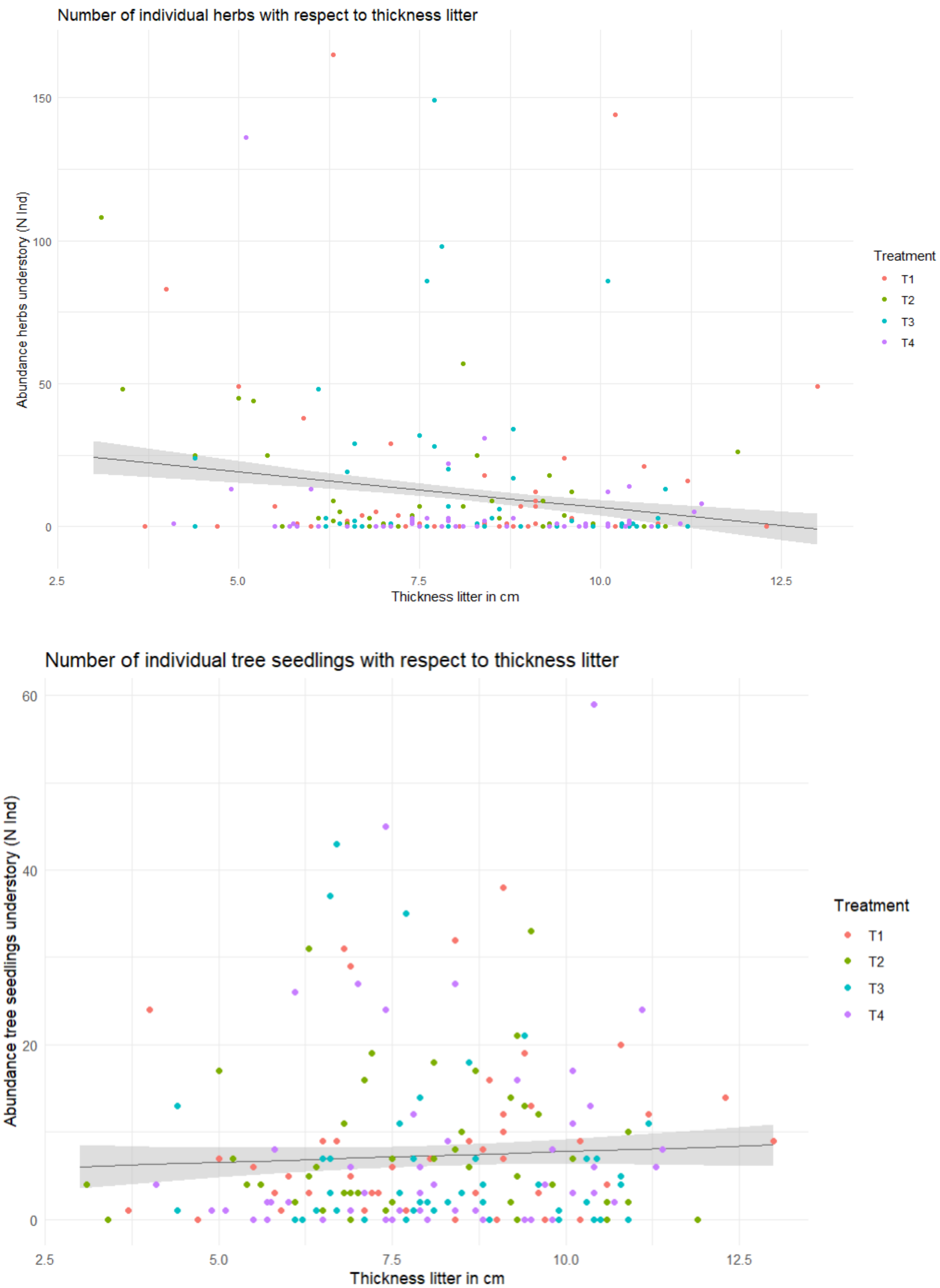


Figure 7a and b: Relation thickness of the litter layer and abundance of herbs (light loving) and tree seedlings (shade loving) Tree seedlings show no change, whereas abundance herbs decreases significantly.

In the model with all parameters, without interaction only grass and herbs respond to changes in the thickness of the litter layer (fixed effect for litter (P 0.03 and 0.04 respectively).

3.6 Comparing the relative abundance of grasses and woody species (shrubs and trees)

One of the questions we looked at was To what extent does species composition (functional groups) in understory vegetation under cocoa plantations change?
Of course an important part of the question is focused on the shift in composition between grasses and woody species. Another way to study this is by focusing on the relative abundance of one species compared to another and not the abundance numbers themselves.

Table 8: Random effects on mixed model on relative abundance grasses vs relative abundance woody species tested against shade level and Litter

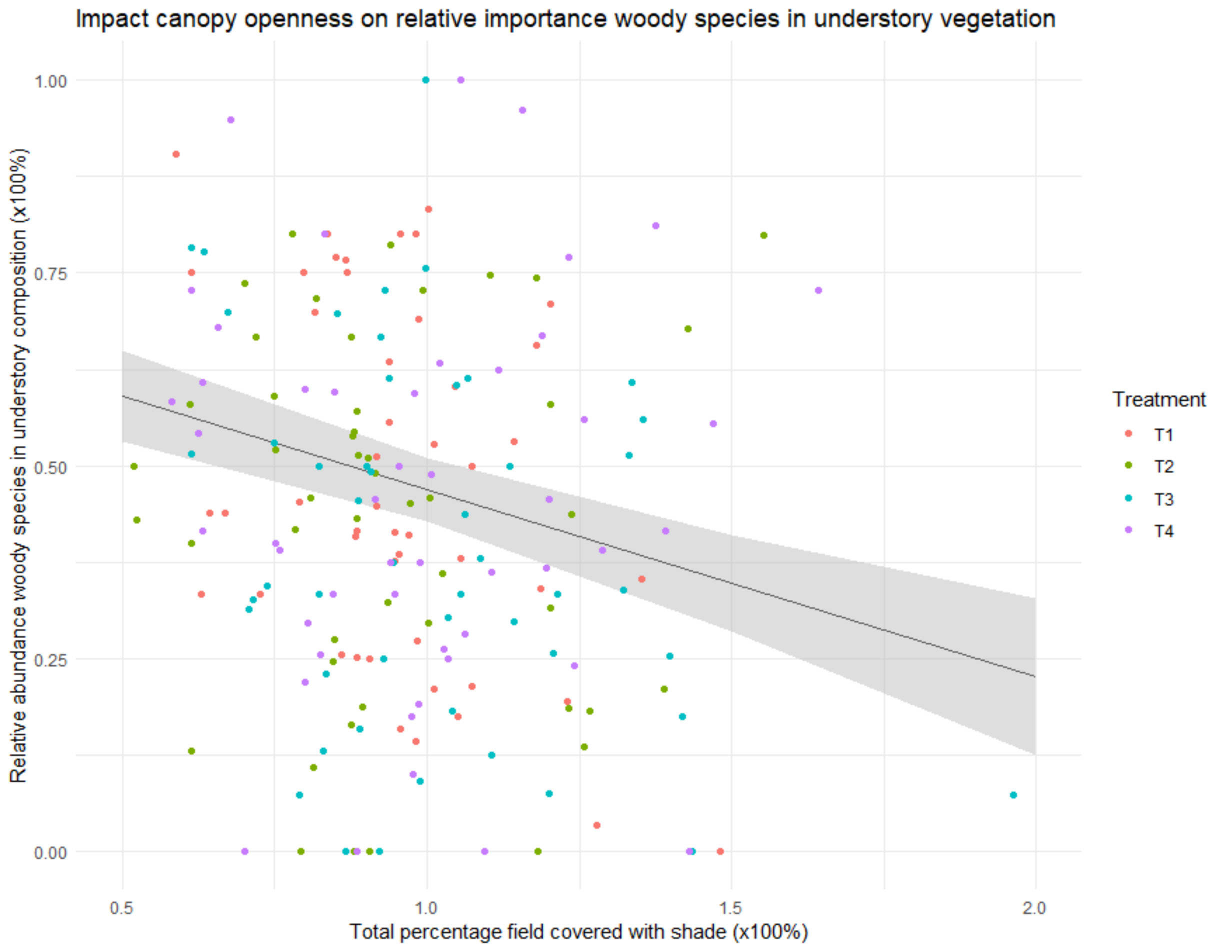
Perc Covered		ST_ID		Residuals			
	REML crit	Variance	St Dev	Variance	Sd	%var expl	AIC
Perc grass	-57.2	0.01011	0.1006	0.03468	0.1862	23%	-48.9516
Perc woody	-2.5	0.0102	0.101	0.04777	0.2186	18%	5.74692
Litter		ST_ID		Residuals			
	REML crit	Variance	St Dev	Variance	Sd	%var expl	AIC
Perc grass	-58.1	0.00798	0.08934	0.034835	0.18664	19%	-49.9377
Perc woody	2.7	0.01151	0.1073	0.04733	0.2176	20%	10.9128

The model only with shade cover shows that grass is relatively more accurately described than woody species (AIC -48 vs 5 respectively). The same applies to the model with only Litter.

Interestingly however in the fixed effects it is visible that shade only has a lightly significant (P 0.09) effect on woody species (more light leads to a small increase), whereas for grass only the site ID (P 0.0002) is strongly significant. For Litter depth however the inverse is true: grass species have a strongly significant (P 0.009) relationship to litter, whereas woody species don't, except for the Site ID (P 0.0003)

Looking then at the model with all parameters and the two random factors added it becomes clear that the relative abundance of grass is clearly described the best by the model with an AIC of -11 and 22% of the variance explained vs 13% for the woody species (AIC 42). With regards to the fixed effects only litter is descriptive for grass (P 0.02), whereas woody species are correlated with both of the shade related parameters perc covered and Avg DBH (P 0.007 and 0.04 respectively)

We can illustrate this as well as in figure 7, figure 8 a and b.
We can see that a higher shade level has a stronger negative impact on the woody species, whereas grasses don't change very much.



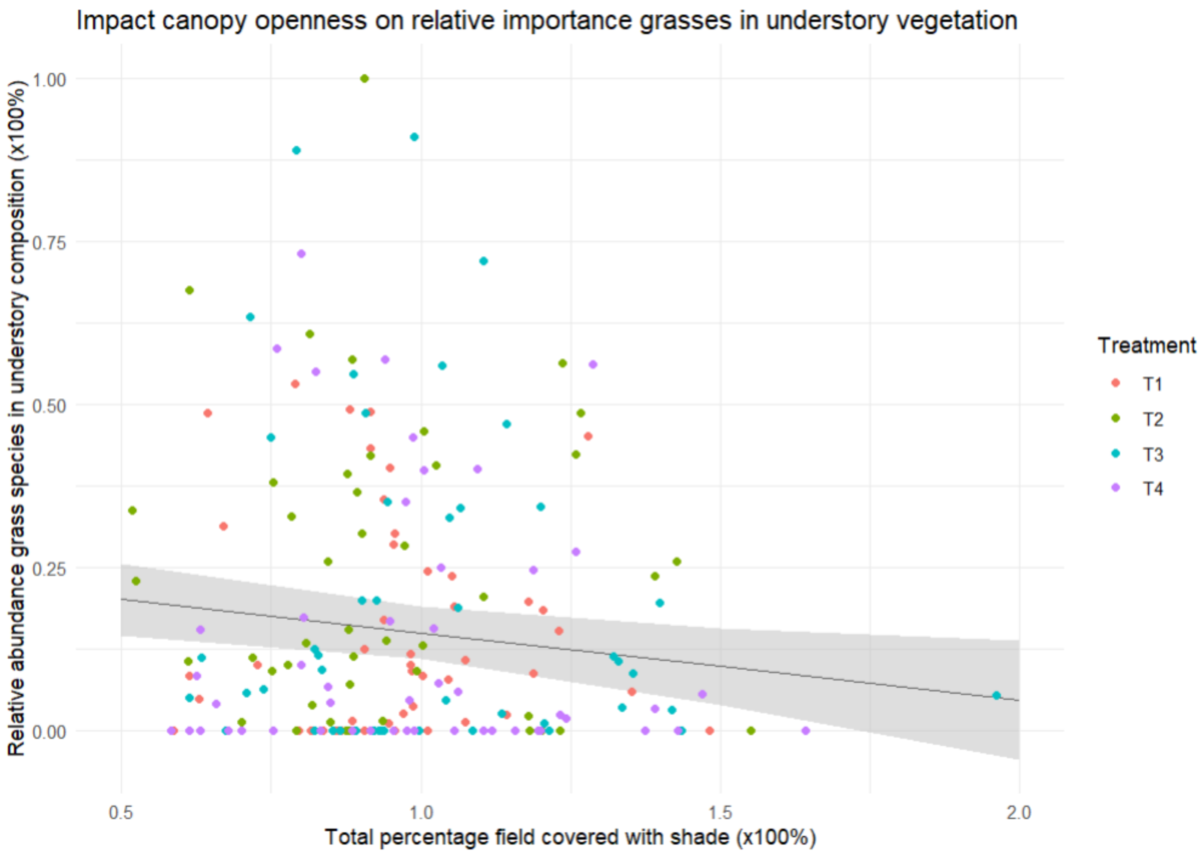


Figure 8a and b: differences in impact canopy openness on relative importance grasses and woody species in species composition understory. Woody species in this case are two groups, shrubs and trees, whereas grasses are only one of the five groups. As seen in figure 6 the apparent negative trend in these groups corresponds to the increase of lianas in the composition.

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4. Discussion

Our results show that rainfall has the strongest impact on species richness, the wetter regions being the most species rich. In addition, species richness was reduced with increasing number of weeding events and peaked at intermediate shade levels (40-80% of shade). Species composition differed among regions, with more distinct communities in the transition zone compared to the drier and more humid zones. Life forms of species (grasses, herbs, shrubs, trees and lianas) did not differ in sensitivity to environmental factors, but they did vary with vegetation structure. Liana abundance increased with shade cover, while grasses and herb abundance was reduced when litter layers were thicker and more weeding was applied.

Regional differences in species richness

The majority of the farms included in this study were located in the centre south and south western part of the country. The farms in this region had the highest species richness (Shannon). Several factors can potentially help explain this. It is a region with relatively humid conditions (rain >1800mm/y), the region has been converted into productive land only during the last phase of cocoa expansion (1980s) affecting thickness litter layer (Van Vliet & Giller, 2017) and presence of forest understory species in soil seed bank (N'Zi et al., 2022; Vroh et al., 2019), (mineral) soil conditions in this region are favourable to diverse vegetation (CNRA, 2021; Tondoh et al., 2015), the traditional agricultural practice of the population is similar within the production zone (Boko et al., 2020; Cissé et al., 2016; Dramane et al., 2023; Koulibaly, 2019; Kouman et al., 2022; N'Zi et al., 2022; Tondoh et al., 2015). (N'Zi, 2022; Cissé, 2016, Boko, 2020; Kouassi, 2023; Koulibaly, 2019).

Impact of climate on chorology of understory vegetation

An important explanation for the increase in the higher species richness in the more humid regions is related to the presence of species from both the semi-tropical and more temperate climate zone within the ground understory vegetation (Esquivel et al., 2023; Willig et al., 2003). The higher water availability is favourable to forest species that cannot survive in systems with a stronger seasonality in rainfall pattern and overall annual variability in rainfall. It is in line with the Latitudinal Diversity Gradient that is found from the equator towards the higher latitudes (e.g. Massante, 2019). Looking at the chorology of these the percentage proportion of the group of tropical species (GC) is higher in the humid zones than in, compared to the driest zones (55% of all individuals in the Humid-Wet region vs 38% in the driest region). This group also increases numerically in terms of species relatively to the temperate group (GC-SZ). There is a clear difference in species composition between the pluviometric regions. The Sörensen statistic shows differences in composition between the driest and most humid zone (the driest zone scores 0.59 vs the humid zone 0.71). A high Sörensen score indicates what percentage of species in area A are also found in region B. We found 83 species in the driest zone, compared to 152 in the humid-wet zone.

This is in line with the findings of Kpangui et al (2018) who looked at the transition zone and in the findings of Kouassi (2023) who looked at similar regions as we did (Kouassi et al., 2023; Kpangui et al., 2018). Jagoret et al also looked into the transitional zone in Cameroon where also a remarkable change in composition is found. Interestingly the expansion of cocoa into the drier regions affects the species richness positively (Jagoret et al., 2018). It might be that this is due to the more buffering effect against droughts that occurs.

Another factor that has impact on species composition is the time since conversion from forest to plantation. The South-Western region is one of the more recently converted regions. Unfortunately however this is also the most humid zone, so there could be a mixed effect here and more study should be carried out on this specific effect. Zooming in on species composition and percentage of specific groups, these differences using the classification of Tondoh (2016) we find 16.6% forest species in the two driest zones and on average 25% in the two most humid zones.

Impact of shade and light availability to understory vegetation

All farms in this study were selected in the traditional production regions of Côte d'Ivoire and had low density of associated shade trees within the plots. Therefore, in some fields the shade of the canopy of the cocoa trees themselves was the only shade available to understory vegetation. On average the plots in the higher shade classes also have a higher density of cocoa (1214 trees/ha), whereas the lowest only has 960 trees on average. Associated trees in the lowest shade class (40-60%) only account for 38 trees/ha versus an average of 145/ha in the fifth class (140-160%). This is still low compared to the densities of associated trees in cocoa agroforests in for example Cameroon (180/ha, Jagoret, 2014). The sixth class has a lower density of shade trees compared to the 5th, but still has a denser shade level as cocoa density is higher. Building on the work of Dramane we see that there is an optimum for productivity and also in terms of species richness with more heterogeneous conditions(Dramane et al., 2021). It seems the most dense class therefore is more homogeneous favouring only a specific group of species, being to dark for light loving species. Deheuvels et al (2012) also found that in more dense stands there is less herbs.(Deheuvels et al., 2012)

Studies focused on the impact of agroforestry practices on biodiversity in cocoa plantations have found a positive impact of diverse overstory. In the driest zone the majority (63%) of trees present had been planted, whereas in the Humid-Wet zone the distribution was more equal between remnant, spontaneous and planted (36%, 42%, 21 % respectively). In the intermediate transition zone and the humid zone the percentage of remnant trees was much higher than in the other zones, and as high as the planted fraction (38%).The fact that there is a larger part of planted trees in the drier zones makes that these trees are most likely trees that are only of a more restricted group and not forest species (Koulibaly, 2019; Smith Dumont et al., 2014). It makes the understory less likely to be diverse, then when there would be a mix with remnant and spontaneously grown trees (Boko et al., 2020). It remains to be seen whether this could be improved when more assisted regeneration would be applied. Kouman has shown that the potential is still there, and also Koulibaly (2019) states that after 20 years more forest species can regrow. (Konan et al., 2011; Kouman et al., 2022)

The identity of planted tree species may also influence the understory vegetation. For instance, one of the species with a known dense canopy is the Mango tree (*Mangifera indica*) that is planted frequently as an associated tree because of its valuable fruits and known shade input. It was one of the most frequent in our plots (36). Dramane et al (2023) studied different shade levels in cocoa plantations and the impact of shade on optimal productivity. One of his results was a table with established shade impact factors of tree species that were used frequently in plantations. One of the key characteristics that determines this factor is Leaf Area Index (LAI), which differs for many trees. Various models have studied the impact of LAI on shade below these shade trees also in cocoa plantations (Tosto et al., 2022; Zuidema et al., 2005).

In the study by Dramane (2021) trees with a high positive factor have a higher impact on shade level below their canopy than trees with a low factor (Dramane et al., 2021). He tried to differentiate between tree species that are used in farms in the country, to account for their impact. In his selection he focused mostly on the trees that were planted in plantations. As shown in figure 4 before, also in the visited plantations for this thesis the majority of associated trees was planted, which makes his findings in many of our plantations relevant. In those regions where planted trees were important in the total amount of trees, the impact of some of these 'Dramane'-factors was more substantial , in some farms changing the expected shade with more than 14%. Four popular species that accounted for 22% of all associated trees in this study have a high positive shade impact factor (*P. americana, M. indica* and *R. heudelotii, E. angolense*), which can have important implications for suggested management when shade levels should be stimulated.

There are some clear shifts in species composition from low to high shade. The intermediate shade levels have the highest species richness (III and IV; 171 and 158 respectively). The most important trend in terms of number of species per group is a visible decrease in both the relative abundance of shrub and grass species and an increase in the shade loving species groups trees and lianas. This can be explained by the specific light requirements by these groups and their reproductive strategy, for instance lianas can grow well in dark conditions (Esquivel et al., 2023; Hawthorne & Jongkind, 2006; Toledo-Aceves & Swaine, 2008). Similarly, the classification by Tondoh (2015) shows a high number of pioneer species in the light rich conditions and more forest and shade loving species in the highest classes. The responses in terms of composition seem to follow the trends in number of species; however there are some exceptions that show the complexity.

The relative number of herb species specifically shows a strong reduction going from lighter to intermediate levels; but then shows a renewed upward trend towards the highest shade levels. It would be a relevant further research to see whether there are more forest species in the darker areas as was found by Steffan-Dewenter et al(2007) (Steffan-Dewenter et al., 2007). This seems to be related to the group of shade loving forest herb species that benefit from the protection against direct sunlight. Marconi (2022) also writes about the dependence of some species on these shade levels(Marconi et al., 2022). There is thus an increase in herb species, but the species composition is very much different from the full sun vegetation. Their abundance however in the understory does follow the trend of pioneer species such as the grasses. So overall we can say that the light loving species benefit proportionally much more from high light levels, which was also found in the research of Cicuzza et al. 2011 (Cicuzza, Clough, et al., 2011). The number of shrub species found in the intermediate zone is relatively higher than in both the extremes on the spectrum. This might be while shrub species benefit from their ability to grow in more abundance of light and grow sub optimally in understory conditions, unfortunately there are not many specific papers on shrubs in cocoa understory, but it seems to be backed by Li et al (2012) that focuses on the impact of changes in conditions for shrubs (Li et al., 2012) and Ramadanil (2008) that looks at the dynamics in understory between the different strata(Ramadhanil et al., 2008).

The importance of structural heterogeneity

Building on the observation that the more species rich plantations had a higher shade level than the monocultures there is an incentive for further research to derive more characteristics of these plantations. Subdividing the vegetation in height classes also could provide information on stratification, such as applied in Boko (2018) and Dramane (2023). The shade optimum for the highest biodiversity found in our study results lays below that found by Steffan Dewenter and Bisseleua (2009), and that of Koulibaly (2019) and Dramane (associated tree canopy cover between 20-40%). This could be while the first two focus on the AFS context, whereas the Ivorian papers are focused more on the drier central production regions and not on the core region of the visited areas.

Other factors that affect diversity

One of the complementary relations that was shown of importance to the development of herbs was that of the thickness of the litter layer. Unfortunately not much research has been done on litter and understory vegetation in plantations, but it could be a relevant line of enquiry when farmers look to diversification. A thicker layer had a negative impact on species richness for the groups herbs, grasses and shrubs. Following research of van Vliet (2017) and Wartenberg (2020) (Van Vliet & Giller, 2017; Wartenberg et al., 2020) the thickness and composition of the litter layer is determined by the canopy cover, age of the plantation, climatic conditions and soil conditions. Depending on composition of litter different functional groups will be able to establish themselves.

Soil as a factor

At the initiation of the CocoaSoils project in all countries specific core trials were established, to capture the diversity in the ecological zones in the country related to differences in soil. In Côte d'Ivoire three distinct zones were identified with each one core trial site. All three sites are managed by another partner of the program: the site in Divo is managed by the CNRA, the site in Tiassalé by SACO/Barry Callebaut, and the site in Aboisso by Nestlé (see figures 9 A B and C).
These sites were thoroughly inventoried by the CNRA and soil samples were taken as well as a complete removal of tree cover.

One of the first assessments in 2018 after removal of tree cover was to see whether specific herb species would be found on specific soil zones. This proved to be the case (CNRA, 2021). Their findings seem to suggest that despite similar starting shade conditions, vegetation in the more humid zone with a more clay rich substrate (5% more clay on average) showed more diversity in ground covering species, whereas the more sand-rich and dryer region did show more uniform vegetation, which still shows in 2023. This variation shows that the factor of soil composition plays an important role in the dynamics for pioneer species and likely later succession. Simplifying the explanation of variation in species to only shade or rainfall would therefore not be satisfactory.

In general reduced permeability of soil strata (due to clay content) also contributes to higher soil acidity and accumulation of organic material (Osman & Osman, 2013). This however also could lead to a reduced species richness as more specialized species benefit (Ma, 2005).

A

B

C

Figure 9 A: Core site near Divo, CNRA research facility, central south western region. In initiation phase bananas used as shade cover
B Core site near Tiassalé, central part of the country, site managed by SACO. On picture right a pit dug for a soil sample. Every typical zone has its own pit.
C Core trial at Aboisso, region in the eastern part of the country. Site with much grass and fairly exposed. No plaquette, but with bar codes like in the other trials on each tree.

Management as a factor

In the study sites, management in three of the four treatments was prescribed and uniformly applied. Aside from the use of mineral fertilizer aimed at maintaining productivity and stability, removal of spontaneous vegetation is an integral part of management in most plots. The fertilizer treatments did not have a significant impact on species richness in general, but the weeding events did affect herbs and liana richness negatively. We found that 55% (27) of farmers removed understory 3 times per year. Farmers rarely would keep specific plants, as for them regeneration during the rainy season would always continue, and their removal of understory plants would not have a negative effect on the system. On the contrary, to some of them a less diverse understory is considered positive for productivity. Many considered a plantation that would regenerate few herbs under its canopy as ideal growing conditions.

Conversely, in the interviews farmers showed to be conscious about specific tree species they liked to implement in their fields and others that they would not want because of their soil impact. Smith Dumont (2014) and Boko (2020) have tried to document the perceived values of the species most frequently tolerated or implemented in plantations. The demand driven approach to preserving and implementing these specific species shows however some weaknesses. When only seedlings would be used that are provided by the cooperatives the risk some of the seedlings are a weaker exists (Kouassi 2023), as it was found that a large percentage does not survive transplanting. On top of this some of the spontaneous species will provide in more diversity in-field as naturally regenerated seedlings are more often forest species (Kouakou, 2019). The most frequently found tree species in the surveys were in majority the same tree species that were valued for their fruit and stable growth characteristics.

Research recommendations

The unpublished report by CNRA (dr. Kotaix Alain and Kouakou Stanislas) provides in a relevant basis of further possible research into the dynamics within ground vegetation in different soil types. In the scope of the initial research already key species were identified by ecologists involved for each zone. Knowledge on these zones could explain some of the diversity found. I would recommend new students or research being caried out on the same areas and zones 5 years later, and to see if clear zonation is still in place, and if so what would be indicators pointing in that direction. Having good indicators could provide in an insight into the dynamics elsewhere in the Ivorian context.

A second recommendation would be to try and establish means to use LAI of all species as a secondary tool to assess possible shade impact. A height factor might help too in establishing overall plot impact of specific shade trees.

Use the research done on specific farmer preferences in relation to tree species in their field to establish what species would both suit uses and biodiversity for vegetation and soil biota.

Conclusion

We have seen that species richness in cocoa plantations is affected greatly by both rainfall and shade cover. This strong relation makes that the effect of climate change on the production sector in the country is reasonably large, especially in those regions that are on the transition zone. Shade cover is considered an important tool to protect plantations against these changes. However planting only desired species from nurseries has less success than natural regeneration. As shown in our data in all regions spontaneous and useful species are found. It would be interesting to see if farmer managed natural regeneration could also be an option in plantations. There is however an optimal shade cover, both for production and biodiversity. I would recommend farmers to only apply weeding twice a year, as it impacts the water retention in the system, protects against the sun and has shown a significant effect on species richness when farmers don't weed too much. Fertilizer use in plantations only seem to favour a specific group of weeds that is less diverse. These however are random effects that would need more study.

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Annexe 1 – Figures Methods

In each treatment a rope was used to mark the centre of the plot and was placed perpendicular to the side

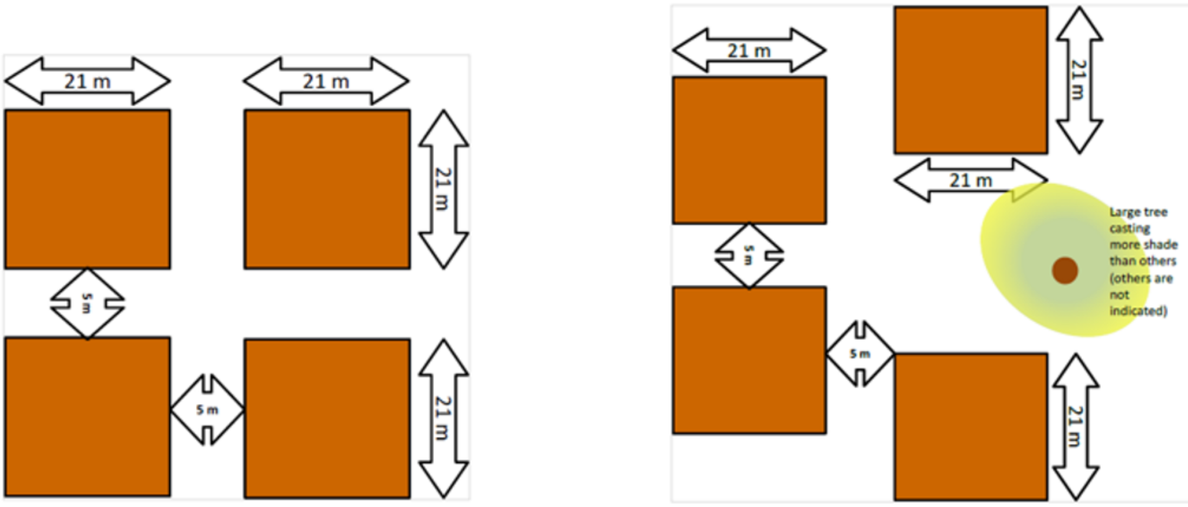


Figure 10: In the selection phase of the cocoasoils farms all treatments would ideally be located 5 meters from each other, to have more uniform conditions. In a situation with a large tree present that would cause a difference in conditions, the plots are selected on a distance from this tree to maintain uniformity.

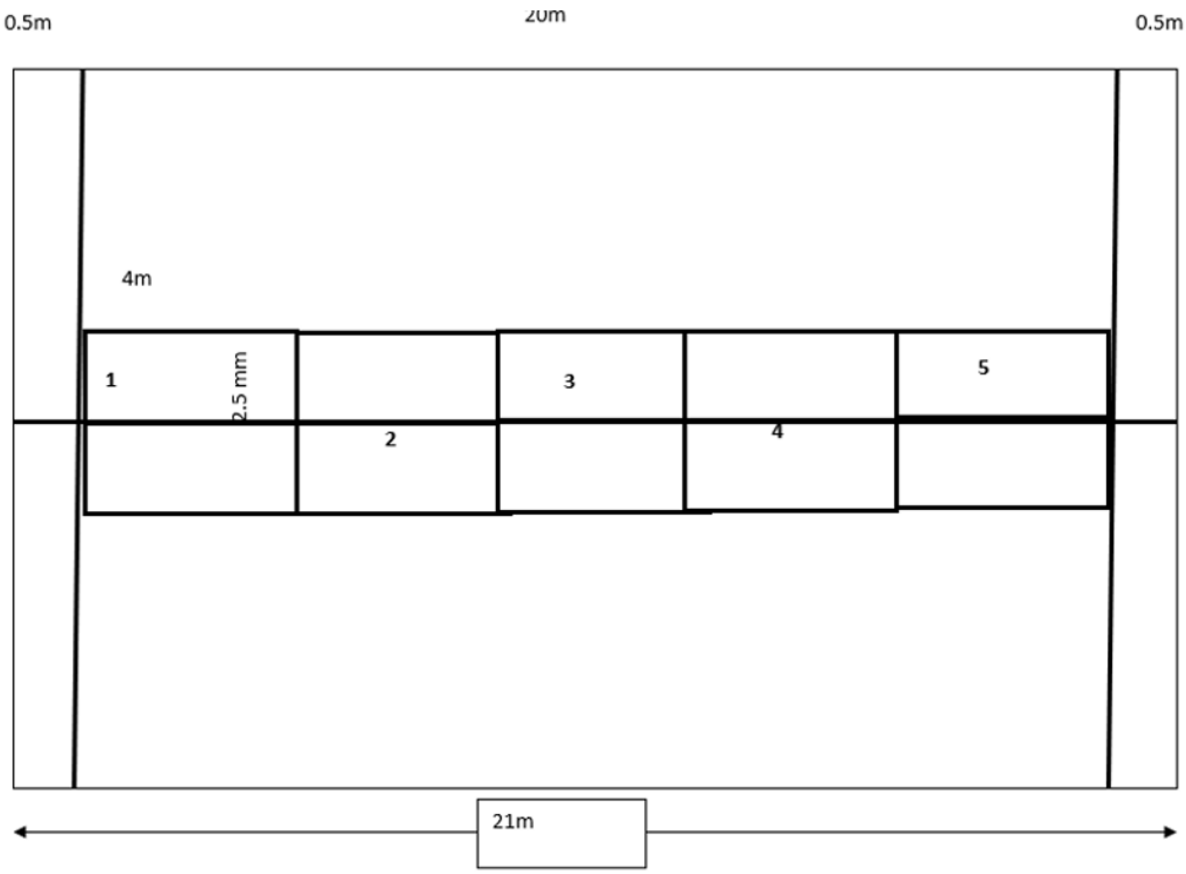


Figure 11: Transect for vegetation survey. Five quadrants of five by four meters were identified, 2.5 m on each side of the central line. Numbers of species and individuals were identified.

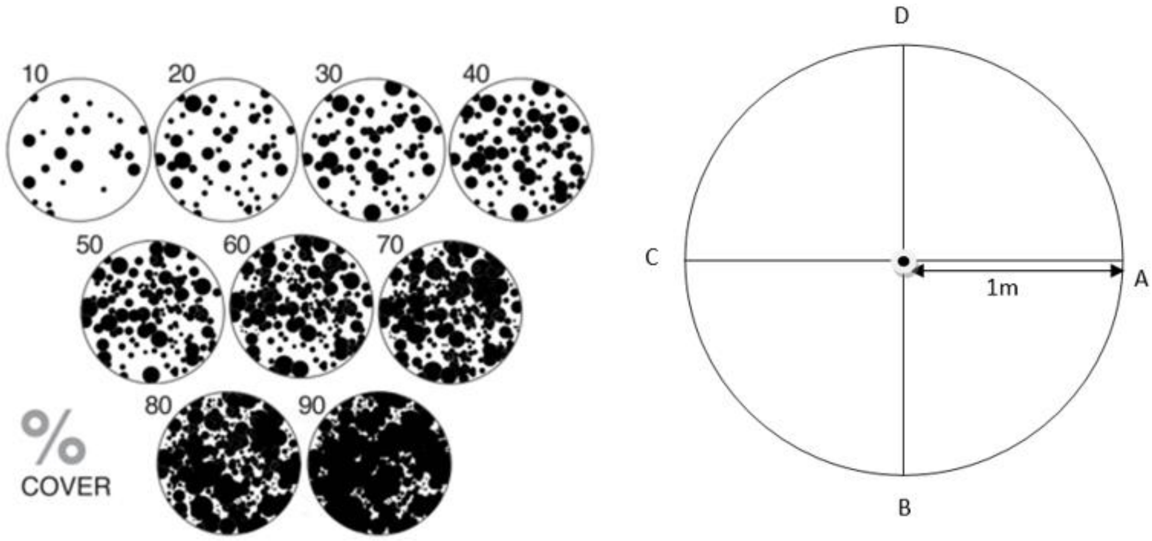


Figure 12 : Assessment scale of ground cover percentage. Building on the amount of soil and litter particles cover percentage can be scored. In 11B schematic overview of the standard grid used for a registered point. At each of the five positions near the corners of the treatment plots a marker stick was placed in the middle, and using a 1m ruler a circle with a 1 m radius was created onto the litter. A measure stick was then used to measure depth at point A-D and the litter composition was assessed using a questionnaire (conform protocol) For this thesis only litter depth was used.

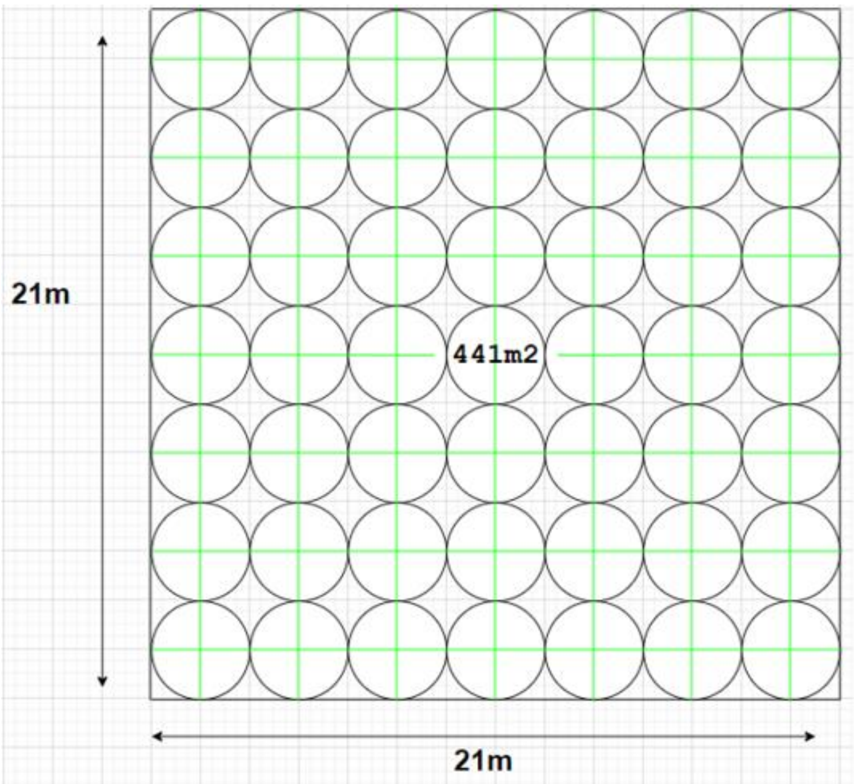


Figure 13: Schematic overview of a field with 49 trees in standard grid. In reality distribution would not be as perfect and densities would change. The sum of all shade surfaces per cocoa tree canopy would be 346.4m^2 The shade area per cocoa tree is simplified to be as large as its canopy area. In reality this will vary and tree canopies often are irregular in shape.

Annexe 2 – Interview questions and protocols

Interview questions farmer interview

The specific questions that were asked and that I used for this thesis were:

- When did you establish the farm?
- How often do you apply weeding in the plantation and in what months?
- Have you planted/kept trees elsewhere on your own land?
- If so, what species, why and where (e.g. in cocoa or other plantations, as woodlots, near the house etc)?

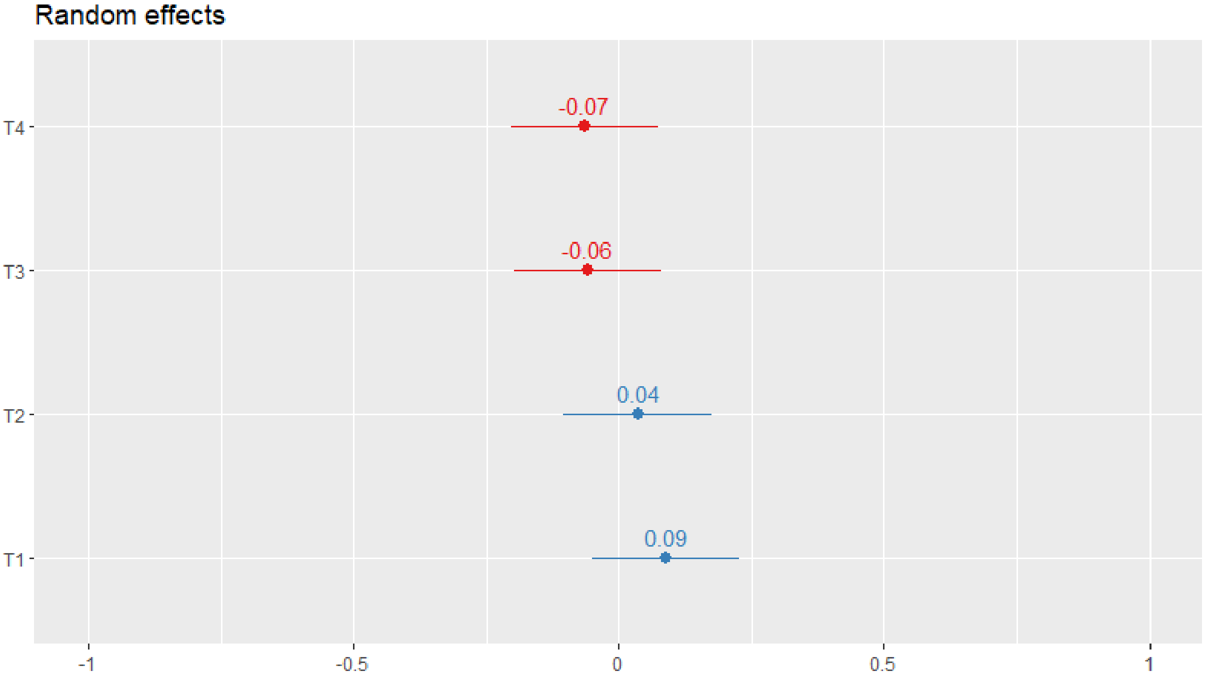
Annexe 3 – Summary selection Linear Models with highest AIC

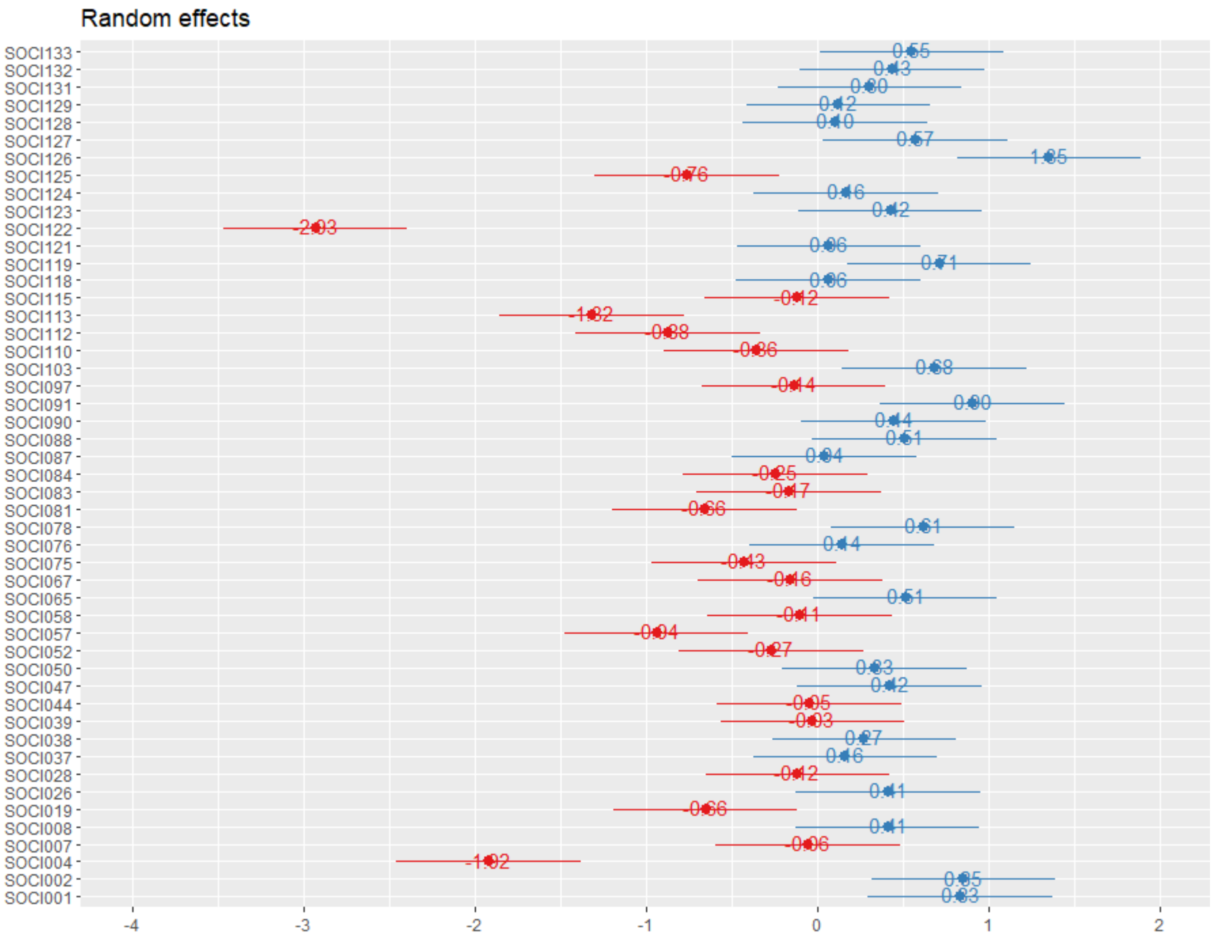
Table 9: Linear models ordered based on lowest AIC and fit

N Species						
Predictor	**Df**	**Sum of sq**	**RSS**	**AIC**	**F value**	**Pr (>F)**
Rainfall	1	5.9548	89.618	-149.38	12.89	0.0004184
Rainfall + Shade level (perc c	1	1.3429	87.853	-149.28	2.9348	0.0883
Rainfall + Litter	1	0.094908	89.421	-145.81	0.2038	0.6522
Rainfall + Treatment	3	1.0696	87.365	-142.37	0.7672	0.5137
Litter	1	0.39954	95.174	-137.59	0.8144	0.3679
Rainfall + Litter + Treatment + Shade level (perc covered)	3	3.2102	72.067	-132.1	2.4352	0.0667

Annexe 4 – Random effects

Figure 13a and 13b: visualization of random effects; expected vs real. In 4a the impact of region is visible, with much lower richness than expected. In figure b we can see the two treatments with fertilizer application are impacted differently than those without





Annexe 5 – Species richness and Abundance per region

Regions

Table 10: Summary statistics on farm level per region. 3 regions only have one farm and therefore no summary statistic.

N spec	Mean	SD	SE	Min	Max	Count
Abengourou	29.66667	19.65536	11.34803	7	42	3
Bouaflé	25.5	3.535534	2.5	23	28	2
Diékolilié (L)	26.33333	10.21437	5.897269	19	38	3
Divo	38.75	7.719024	3.859512	28	46	4
Fresco	47	8	4.618802	39	55	3
Gbélié (L)	48.33333	15.63117	9.024658	34	65	3
Gragba Dagolilié (L)	45.6	21.5244	9.626006	22	75	5
Gragbalilié (L)	28.33333	20.20726	11.66667	5	40	3
Grogouya (L)	42.25	4.716991	2.358495	39	49	4
Guitry	34.83333	3.371449	1.376388	32	40	6
Hère Mankono Diès	42	14.14214	10	32	52	2
Hère Mankono Garo	27					1
Méagui	27					1
Oumé	38.66667	7.966597	3.25235	29	52	6
Soubré	23.5	10.6066	7.5	16	31	2
Vavoua	23					1

N Ind	Mean	SD	SE	Min	Max	Count
Abengourou	571.6667	609.0824	351.6539	13	1221	3
Bouaflé	100.5	45.96194	32.5	68	133	2
Diékolilié (L)	117	56.66569	32.71595	66	178	3
Divo	566.75	431.4521	215.7261	191	1187	4
Fresco	784.6667	259.0836	149.582	489	972	3
Gbélié (L)	275.3333	203.8562	117.6964	142	510	3
Gragba Dagolilié (L)	525.8	366.5729	163.9364	50	1076	5
Gragbalilié (L)	283.6667	237.0239	136.8458	14	459	3
Grogouya (L)	445.75	191.7366	95.86829	241	668	4
Guitry	403.6667	319.4925	130.4323	142	1014	6
Hère Mankono Diès	840.5	12.02082	8.5	832	849	2
Hère Mankono Garo	245					1
Méagui	136					1
Oumé	559.6667	345.2568	140.9505	79	971	6
Soubré	220	124.4508	88	132	308	2
Vavoua	108					1

Shade

Table 11: Summary statistics on shade classes; shade class is calculated on treatment plot level; therefore aggregation levels are different from Rain and Region, leading to lower averages.

N Spec	Mean	SD	SE	Min	Max	Count
Class I (40-60%)	18.25	4.112988	2.056494	13	22	4
Class II (60-80%)	19.35	8.761609	1.959155	2	34	20
Class III (80-100%)	23.74359	9.882781	1.582512	1	42	39
Class IV (100-120%)	25.30769	13.69604	2.686015	6	66	26
Class V (120-140%)	24.83333	10.25126	2.416244	7	52	18
Class VI (140-200%)	14.85714	7.010197	2.649605	6	25	7

N Ind	Mean	SD	SE	Min	Max	Count
Class I (40-60%)	156.25	157.7052	78.85258	35	388	4
Class II (60-80%)	126.8	135.4344	30.28406	2	626	20
Class III (80-100%)	211.4872	220.6404	35.33075	1	1221	39
Class IV (100-120%)	219.9615	180.2186	35.34378	6	585	26
Class V (120-140%)	201.5556	190.4488	44.8892	13	849	18
Class VI (140-200%)	87.28571	59.76263	22.58815	12	181	7

Rain

N Spec	Mean	SD	SE	Min	Max	Count
Very Dry	27.16667	12.8595	5.249868	7	42	6
Dry	39	7.509993	3.065942	31	52	6
Dry-Humid	24	7	4.041452	16	29	3
Humid	38.34783	14.87099	3.100815	5	75	23
Humid-Wet	40	9.560335	2.882549	27	55	11

N Ind	Mean	SD	SE	Min	Max	Count
Very Dry	337.3333	463.3757	189.1723	13	1221	6
Dry	597.8333	289.678	118.2606	247	971	6
Dry-Humid	152	84.78797	48.95236	79	245	3
Humid	412.6522	322.9179	67.33303	14	1187	23
Humid-Wet	528.0909	316.6476	95.47284	136	972	11

Annexe 6- Trees per hectare and trees per plot for the regions and shade levels

Trees/ha	Mean	SD	SE	Min	Max	Count
Abengourou	107.7097506	49.420623	28.53301	73.696145	164.399093	3
Bouaflé	22.67573696	8.0170837	5.66893424	17.006803	28.3446712	2
Diékolilié (L)	49.13076342	22.910725	13.2275132	28.344671	73.69614512	3
Divo	89.28571429	18.730374	9.36518689	62.358277	102.0408163	4
Fresco	236.2055933	82.99392	47.9165621	147.39229	311.7913832	3
Gbélié (L)	71.80650038	47.203311	27.2528441	34.013605	124.7165533	3
Gragba Dagolilié (L)	56.6893424	46.918779	20.982716	17.006803	136.0544218	5
Gragbalilié (L)	39.68253968	19.637764	11.3378685	28.344671	62.35827664	3
Grogouya (L)	49.6031746	21.894615	10.9473075	28.344671	79.36507937	4
Guitry	52.91005291	17.806831	7.26960849	34.013605	73.69614512	6
Hère Mankono Diès	113.3786848	72.153753	51.0204082	62.358277	164.399093	2
Hère Mankono Garo	107.7097506					
Méagui	39.68253968					
Oumé	84.08919123	23.624338	9.64459573	45.351474	113.3786848	6
Soubré	104.8752834	68.145211	48.185941	56.689342	153.0612245	2
Vavoua	28.3446712					

Trees/field	Mean	SD	SE	Min	Max	Count
Abengourou	4.75	2.1794495	1.25830574	3.25	7.25	3
Bouaflé	1	0.3535534	0.25	0.75	1.25	2
Diékolilié (L)	2.166666667	1.010363	0.58333333	1.25	3.25	3
Divo	3.9375	0.8260095	0.41300474	2.75	4.5	4
Fresco	10.41666667	3.6600319	2.11312039	6.5	13.75	3
Gbélié (L)	3.166666667	2.081666	1.20185043	1.5	5.5	3
Gragba Dagolilié (L)	2.5	2.0691182	0.92533778	0.75	6	5
Gragbalilié (L)	1.75	0.8660254	0.5	1.25	2.75	3
Grogouya (L)	2.1875	0.9655525	0.48277626	1.25	3.5	4
Guitry	2.333333333	0.7852813	0.32058973	1.5	3.25	6
Hère Mankono Diès	5	3.1819805	2.25	2.75	7.25	2
Hère Mankono Garo	4.75					
Méagui	1.75					
Oumé	3.708333333	1.0418333	0.42532667	2	5	6
Soubré	4.625	3.0052038	2.125	2.5	6.75	2
Vavoua	1.25					

For shade classes

Trees/ha	Mean	SD	SE	Min	Max	Count
Class I (40-60%)	37.79289494	47.203311	27.2528441	0	90.70294785	4
Class II (60-80%)	51.02040816	80.482008	18.463839	0	362.8117914	19
Class III (80-100%)	59.27517206	43.934273	7.12708018	0	192.7437642	38
Class IV (100-120%)	91.91232048	51.098733	10.2197467	22.675737	226.7573696	25
Class V (120-140%)	145.5026455	110.01806	26.6833	45.351474	498.8662132	17
Class VI (140-200%)	114.8331053	63.042944	23.8279932	68.027211	226.7573696	7

Trees/plot	Mean	SD	SE	Min	Max	Count
Class I (40-60%)	1.666666667	2.081666	1.20185043	0	4	4
Class II (60-80%)	2.25	3.5492566	0.8142553	0	16	19
Class III (80-100%)	2.614035088	1.9375014	0.31430424	0	8.5	38
Class IV (100-120%)	4.053333333	2.2534541	0.45069083	1	10	25
Class V (120-140%)	6.416666667	4.8517966	1.17673353	2	22	17
Class VI (140-200%)	5.064139942	2.7801938	1.0508145	3	10	7

Annexe 7 – List of tree species with their abundance, shade impact score, suitability rank and Boko group

Name species	**N observations**	**Shade impact (Dramane)**	**Suitability class (Smith)**
Acacia mangium	3		
Albizia adianthifolia (Schumach.) W.F. Wright	5	0.49	Less suitable
Albizia lebbeck (Linn.) Benth.	1	0.49	Less suitable
Albizia zygia (DC.) J.F. Macbr.	5	0.49	Less suitable
Alstonia boonei De Wild.	8	0.51	Highly appreciated
Amphimas pterocarpoides Harms	6		
Anacardium occidentalis Linn.	5		
Anonidium mannii	1		
Anthocleista djalonensis A. Chev.	3		
Anthocleista nobilis G. Don	1		
Antiaris toxicaria var. africana (Engl.) C.C. Berg	10	2.23	
Artocarpus altilis	2		Most appreciated
Artocarpus heterophyllus Lam.	1		
Baphia pubescens Hook.f.	2		
Blighia unijugata Baker	1		
Bombax buenopozense P. Beauv.	2	2.94	
Bridelia micrantha (Hochst.) Baill.	2		
Carapa procera DC. De Wilde	1		
Carica papaya var. papaya Linn.	15		
Cedrela odorata L.	10		
Ceiba pentandra (Linn.) Gaerth.	4	2.78	Appreciated
Celtis milbraedii Engl.	1		
Celtis zenkeri Engl.	1		
Chrysophyllum sp.	1		
Citrus grandis Osbeck	3	0.22	
Citrus limon Burn. f.	3	0.22	
Citrus reticulata Blanco	2	0.22	Highly appreciated
Citrus sinensis (L.) Osbeck	51	0.22	Appreciated
Cocos nucifera Linn.	2		Appreciated
Coffea arabica L.	37		
Cola gigantea A. Chev. var. glabrescens Brenan & Keay	1		
Cola nitida (Vent.) Schott & Endl.	28		Less suitable
Diospyros mespiliformis Hochst. ex A. DC.	2		
Elaeis guineensis Jacq.	53		Least suitable
Entandrophragma angolense (Welw.) C. DC.	10	2.04	
Erythrina senegalensis DC.	1		
Ficus exasperata Vahl	21	0.33	Appreciated
Ficus mucuso Welw. ex Ficalho	7		
Ficus sur Forsk.	14		

Funtumia africana (Benth.) Stapf	2	0.41	
Gliricidia sepium (Jacq.)Walp.	11		
Harungana madagascariensis Lam. ex Poir.	8		
Heritiera densiflora Kosterm	3		
Hevea brasiliensis (Kunth) Müll.Arg	24		
Holarrhena floribunda (G. Don) Dur. & Schinz var. floribunda	5		Less suitable
Jatropha curcas Linn.	1		
Khaya anthotheca (Welw.) C. DC.	1		
Lannea welwitschii (Hiern) Engl.	2	0.49	
Macaritaria discopia	2		
Mallotus oppositifolius (Geisel.) Müll. Arg.	1		
Mangifera indica L.	36	1.48	Least suitable
Manihot esculenta Crantz	2		
Mareya micrantha (Benth.) Müll. Arg.	2		
Milicia excelsa (Welw.) Benth.	7		Highly appreciated
Milicia regia A. Chev.	1		
Millettia zechiana Harms	1		
Morinda lucida Benth.	14		
Moringa oleifera Lam	2		
Napoleonaea vogelii	1		
Nesogordonia papaverifera (A. Chev.) R. Capuron	1		
Newbouldia laevis (P. Beauv.) Seemann ex Bureau	27	0.29	
Persea americana Mill.	77	1.08	Highly appreciated
Piliostigma thonningii	1	1.46	
Piptadeniastrum africanum (Hook.f.) Brenan B	1		Less suitable
Psidium guajava Linn.	5		Most appreciated
Pterocarpus santalinoides L'Hérit. ex DC.	2		
Pterygota macrocarpa K. Schum.	1		Less suitable
Pycnanthus angolensis (Welw.) Warb	1		Appreciated
Rauvolfia vomitoria Afzel.	2		
Ricinodendron heudelotii (Baill.) Pierre ex Pax	16	3.25	Most appreciated
Solanum torvum Sw.	1		
Spathodea campanulata P. Beauv.	8		Most appreciated
Spondias mombin Linn.	11		Less suitable
Sterculia tragacantha Lindl.	3	0.9	Less suitable
Syzygium malaccense (L.) Merr. & L.M.Perry	6		
Tectona grandis Linn.f.	14		
Terminalia ivorensis A. Chev.	10	0.83	Most appreciated
Terminalia mentaly H. Perrier	1	0.83	
Terminalia superba Engl. & Diels	19	0.83	Most appreciated

Trichilia monadelpha (Thonn.) J.J. De Wilde	2		
Triplochiton scleroxylon K. Schum.	2		Appreciated
Vernonia amygdalina Delile	4	0.95	
Xylopia aethiopica (Dunal) A. Rich.	9		

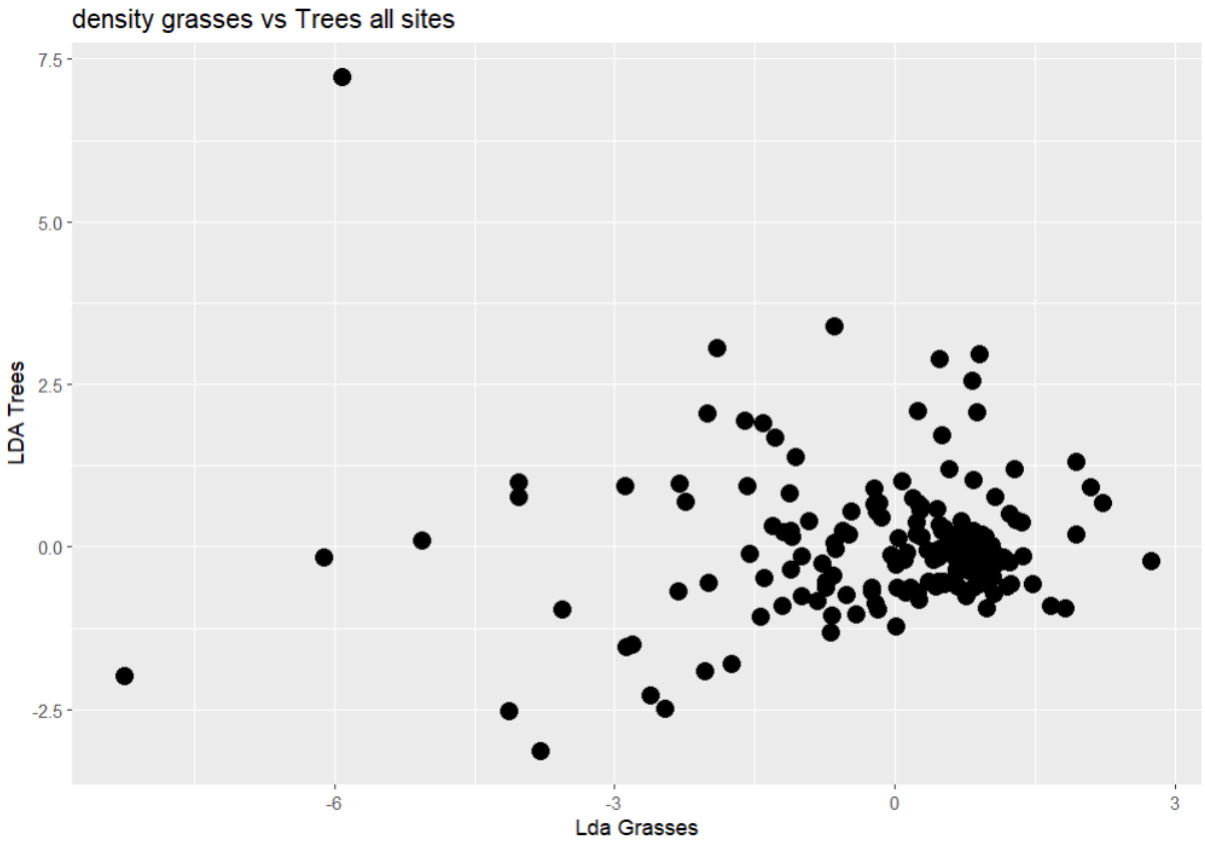
Annexe 8 – Soerensen index

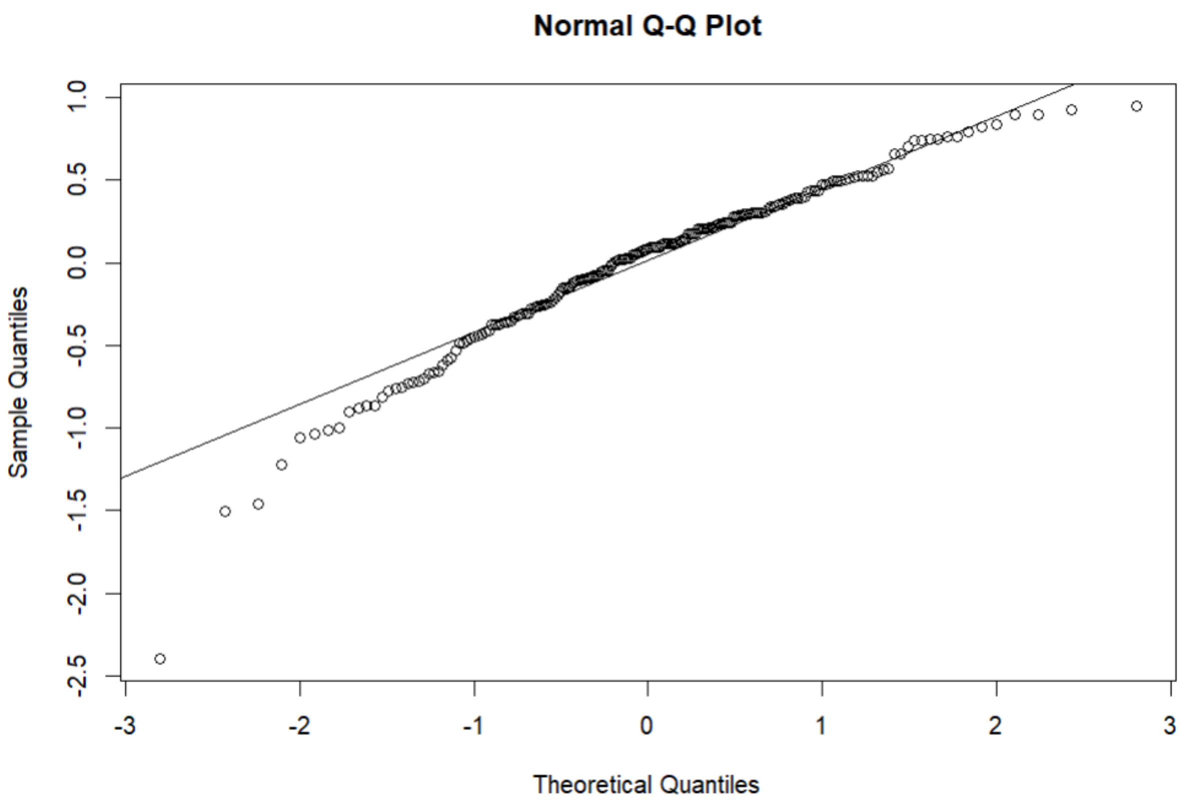
Region	N Spec	Mean	SD	SE	Abengour	Bouaflé	Diékolilié	Divo	Fresco	Gbélié (L)	Gragba Da	Gragbalili	Grogouya	Guitry	Hermankc	Hermankc	Méagui	Oumé	Soubré	Vavoua
Abengourou / Niablé	59	0.494977	0.079249	0.020462	x	19	29	39	37	30	45	28	32	44	41	20	21	47	21	15
Bouaflé	35	0.416135	0.048539	0.012533	0.404255	x	22	23	18	26	29	20	28	24	20	14	14	28	17	11
Diékolilié (L)	56	0.508859	0.075213	0.01942	0.504348	0.483516	x	38	31	40	50	35	42	37	31	17	18	37	27	15
Divo	82	0.530529	0.111613	0.028818	0.553191	0.393162	0.550725	x	48	47	67	36	50	59	46	21	23	57	25	19
Fresco	84	0.424577	0.108618	0.028045	0.517483	0.302521	0.442857	0.578313	x	36	49	29	33	54	36	16	16	48	18	17
Gbélié (L)	86	0.489877	0.131681	0.034	0.413793	0.429752	0.56338	0.559524	0.423529	x	68	48	56	46	38	16	22	51	25	16
Gragba Dagolilié (L)	107	0.526235	0.143524	0.037058	0.542169	0.408451	0.613497	0.708995	0.513089	0.704663	x	49	62	62	53	21	22	62	29	19
Gragbalilié (L)	58	0.480851	0.107678	0.027802	0.478632	0.430108	0.614035	0.514286	0.408451	0.666667	0.593939	x	41	34	32	13	20	38	20	12
Grogouya (L)	80	0.495556	0.125521	0.032409	0.460432	0.486957	0.617647	0.617284	0.402439	0.674699	0.663102	0.594203	x	47	36	16	20	49	22	16
Guitry	101	0.476035	0.12092	0.031222	0.55	0.352941	0.471338	0.644809	0.583784	0.491979	0.596154	0.427673	0.519337	x	50	24	19	59	22	20
Hermankono Diès (G)	67	0.48766	0.120092	0.031008	0.650794	0.392157	0.504065	0.61745	0.476821	0.496732	0.609195	0.512	0.489796	0.595238	x	16	21	49	18	11
Hermankono Garo	27	0.355593	0.059216	0.01529	0.465116	0.451613	0.409639	0.385321	0.288288	0.283186	0.313433	0.305882	0.299065	0.375	0.340426	x	10	24	10	9
Méagui	27	0.39338	0.069185	0.017864	0.488372	0.451613	0.433735	0.422018	0.288288	0.389381	0.328358	0.470588	0.373832	0.296875	0.446809	0.37037	x	24	16	7
Oumé	94	0.51773	0.096698	0.024967	0.614379	0.434109	0.493333	0.647727	0.539326	0.566667	0.616915	0.5	0.563218	0.605128	0.608696	0.396694	0.396694	x	30	20
Soubré	42	0.377019	0.088379	0.022819	0.415842	0.441558	0.55102	0.403226	0.285714	0.390625	0.389262	0.4	0.360656	0.307692	0.330275	0.289855	0.463768	0.441176	x	6
Vavoua	23	0.315397	0.053765	0.013882	0.365854	0.37931	0.379747	0.361905	0.317757	0.293578	0.292308	0.296296	0.31068	0.322581	0.244444	0.36	0.28	0.34188	0.184615	x

Rain levels	N spec	Mean	SD	SE	Very Dry	Dry	Dry-Humid	Humid	Humid-Wet
Very Dry	84	0.596274	0.028478	0.014239	x	58	40	73	70
Dry	98	0.602176	0.031158	0.015579	0.63736	x	43	79	77
Dry-Humid	54	0.523806	0.057454	0.028727	0.57971	0.5657895	x	52	50
Humid	170	0.585732	0.102322	0.051161	0.5748	0.5895522	0.4642857	x	115
Humid-Wet	152	0.602236	0.093929	0.046964	0.59322	0.616	0.4854369	0.71428571	x

Summary stats	Mean	SD	SE
Region	0.582045	0.071028	0.022461
Rain	0.613361	0.127909	0.033026
Shade	0.455651	0.116787	0.010661

Shade levels	N spec	Mean	SD	SE	Class I (40-60%)	Class II (60-80%)	Class III (80-100%)	Class IV (100-120%)	Class V (120-140%)	Class VI (140-200%)
Class I (40-60%)	51	0.480151	0.044543	0.01992	x	47	47	50	48	27
Class II (60-80%)	124	0.674163	0.098036	0.043843	0.53714	x	111	106	95	58
Class III (80-100%)	171	0.648613	0.164828	0.073713	0.42342	0.7525424	x	133	113	63
Class IV (100-120%)	158	0.671025	0.141147	0.063123	0.47847	0.751773	0.8085106	x	111	64
Class V (120-140%)	138	0.659409	0.107901	0.048255	0.50794	0.7251908	0.7313916	0.75	x	60
Class VI (140-200%)	68	0.546808	0.059133	0.026445	0.45378	0.6041667	0.5271967	0.56637168	0.58252427	x


density grasses vs Trees all sites
LDA Trees
Lda Grasses
7.5
5.0
2.5
0.0
-2.5
-6
-3
0
3


Normal Q-Q Plot
Sample Quantiles
Theoretical Quantiles
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3
-2
-1
0
1
2
3