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Growing Cocoa in Semi-Arid Climate – a Scalable Use Case for Digital Agriculture

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1 Abstract

Traditionally Cocoa is cultivated in agroforestry systems in the humid tropics. These offer high levels of biodiversity, but lead to minor crop yields of roughly 500 kilograms of dry beans per hectare. In order to improve productivity, Cocoa has recently also been cultivated as an unshaded monoculture. Further, there have been initial cultivation attempts in semi-arid regions. The successful cultivation in these regions would be beneficial with specific regard to reduced disease stress and would allow for an extension of the cultivation area. To better understand these systems, we carried out field trials on four unshaded Cocoa monoculture plantations. Two of these plantations were located in a semi-arid zone, while the other two plantations were located in a subtropical zone. The team studied the behaviour of the Cocoa plant in these regions and, based on the attained foundations, derived recommendations for an optimised cultivation and management.

The results demonstrate that the cultivation of Cocoa as a full sun monoculture in semi-arid regions is possible and enables high yields of up to 3000 kilograms of dry beans per hectare. These yields were achieved in plantations with 1200 trees per hectare. In comparison of the five varieties BN34, CCN51, Cepec 2002, PS1319 and Salobrinho 03, the vigorously growing Salobrinho 03 and CCN51 achieved the highest yields. The dry climate prevented the proliferation of most fungus diseases. We only discovered the fungi pathogens *Lasiodiplodia theobromae* and *Ceratocystis Fimbriata.*

The Cocoa plant has specific physiological characteristics. The plant opens its stomata's at sunrise and closes them at sunset. The plant can hardly regulate evaporation during the day. Consequently, sufficient water supply is essential. The plants growth stagnates during the development of new shoots and leaves (flush), because during this phase assimilates are required for the development of young leaves. In the meantime, the plants transpiration increases and may lead to water stress. The insufficiently developed wax layer (cuticle) and stomata cause this increased evaporation. The stem only starts developing after the young leaves have developed from an assimilate sink to an assimilate source. Due to the fruits growing on the stem, we conclude that the supply of the fruits is reduced during the development of young leaves, and that this lack in assimilates presents an important cause of fruit loss, which plays a vital role in yield productivity. It is therefore significant to provide a sufficient nutrient supply during the initial phase of fruit building, but not to encourage the development of new leaves by high nitrogen input.

Fully developed leaves already reach their maximal photosynthesis potential at solar radiations of 400 µmol $m^{-2}s^{-1}$, therefore, the light shading of Cocoa plants does not decrease the photosynthesis rate. Shading Cocoa plants with nets (30 % light absorption) does however reduce the water consumption by about 30 %, whilst yields increase by 20 %.

Furthermore, we found that Cocoa roots adapted well to drip irrigation and to shallow soils by developing shallow rooting systems (up to 25 cm depth) without building a taproot.

Dendrometers, which record the daily swelling, and shrinkage, as well as the growth of the stem diameter, reliably display the appearance of new flushes and water stress (strong shrinkage of the stem diameter). Dendrometry is well suited to record growth cycles and refine water management of Cocoa plants.

The newly developed plant model «CocoaFlo» allows the modelling of plant behaviour. This, as an example, enables displaying that plant densities of 2000 trees per hectare are ideal with the currently available rootstocks and varieties. CocoaFlo therefore offers the option to facilitate the further development of Cocoa plantation systems.

The potential for further improvement of plantation systems remains high. Better rootstocks for the production of homogenous plant material as well as standardized architectures present the most important levers for increasing yields, by improving plant protection and reducing the workload during pruning and harvest.

Zusammenfassung

Traditionell wird Kakao in den feuchten Tropen in Agroforstsystemen angebaut. Diese bieten eine hohe Biodiversität, führen jedoch zu geringen Erträgen von zirka 500 Kilogramm trockener Bohnen pro Hektare. Um die Produktivität zu optimieren, wird Kakao seit kurzem auch als unbeschattete Reinkultur angebaut. Weiter gibt es erste Anbauversuche in semiariden Gebieten. Gelingt der Anbau in diesen Regionen, hätte dies Vorteile im Hinblick auf einen reduzierten Krankheitsdruck und würde es ermöglichen, die Anbauflächen auszudehnen. Um diese Systeme besser zu verstehen, wurden im Rahmen des vorliegenden Projektes Feldversuche auf vier brasilianischen, unbeschatteten Kakaoplantagen in Reinkultur durchgeführt. Zwei der Plantagen befanden sich in einer semiariden Zone, während die anderen beiden Plantagen in einer subtropischen Zone lagen. Das Team untersuchte das Verhalten der Kakaopflanze in diesen Regionen und leitete anhand der gewonnen Grundlagen Empfehlungen zur Optimierung des Anbaus und Managements ab.

Die Ergebnisse zeigen, dass der Anbau von Kakao als Reinkultur in semiariden Gebieten möglich ist und hohe Erträge von bis zu 3000 Kilogramm trockener Bohnen pro Hektare ermöglicht. Diese Erträge wurden in Anlagen mit 1200 Bäumen pro Hektare erzielt. Im Vergleich der fünf Sorten BN34, CCN51, Cepec 2002, PS1319 und Salobrinho 03 erzielten die starkwüchsigen Typen Salobrinho 03 und CCN51 die höchsten Erträge. Das trockene Klima verhinderte die Ausbreitung der meisten Pilzerkrankungen. Einzig das Auftreten der Pilzerreger *Lasiodiplodia theobromae* und *Ceratocystis fimbriata* konnte beobachtet werden.

Physiologisch gesehen weist die Kakaopflanze einige Besonderheiten auf. Die Pflanze öffnet die Stomata bei Sonnenaufgang und schliesst sie bei Sonnenuntergang. Tagsüber kann die Pflanze die Verdunstung daher nur geringfügig regulieren. Deshalb ist eine gute Wasserversorgung essentiell. Während des Neuaustriebs junger Triebe und Blätter (Flush) stagniert das Wachstum der Pflanze, da die Assimilate in dieser Phase in die Entwicklung junger Blätter fliessen. Währenddessen erhöht sich die Transpiration der Pflanze und kann zu einem erhöhten Wasserstress führen. Die verstärkte Verdunstung wird auf die unvollständig ausgebildete Wachsschicht und Spaltöffnungen zurückgeführt. Erst nachdem sich die jungen Blätter von einer Assimilatsenke zu einer Assimilatquelle weiterentwickeln, wächst der Stamm wieder weiter. Da die Früchte am Stamm wachsen, wird davon ausgegangen, dass während des Austriebes junger Blätter, auch die Versorgung der Früchte reduziert ist und eine wichtige Ursache des Fruchtfalls darstellt. Dies spielt für die Ertragsbildung eine zentrale Rolle. Während der Anfangsphase der Fruchtbildung ist es von Bedeutung die Pflanzen gut zu versorgen, aber die Bildung neuer Blätter nicht durch hohe Stickstoffdüngung anzuregen. Da ausgewachsene Blätter schon bei einer Sonnenstrahlung von etwa 400 µmol $m^{-2}s^{-1}$ ihr maximales Photosynthese Potential ausschöpfen, reduziert eine leichte Beschattung die Photosyntheserate nicht. Eine Beschattung mit Netzen (30 % Lichtabsorption) reduziert jedoch den Wasserverbrauch um rund 30 % bei Mehrerträgen von über 20 %. Darüber hinaus konnten wir aufzeigen, dass sich die Kakaopflanze gut an Tröpfenbewässerung und flachgründige Böden anpassen kann. Sie bildet dann ein flaches Wurzelsystem (maximal 25 cm Tiefe) ohne Pfahlwurzel aus.

Dendrometer, die das tägliche Quellen-Schrumpfen sowie das Wachstum des Stammdurchmessers erfassen, zeigten die Erscheinung von Neuaustrieben oder Wasserstress (starke Schrumpfung des Stammdurchmessers) zuverlässig an. Dendrometrie eignet sich bei Kakaobäumen also gut, um die Wachstumszyklen zu erfassen oder das Bewässerungsmanagement zu verfeinern.

Das neu erstellte Pflanzenmodell «CocoaFlo» ermöglicht die Modellierung des Pflanzenverhaltens. Damit lässt sich beispielsweise aufzeigen, dass mit den aktuell vorhandenen Unterlagen und Sorten maximale Pflanzdichten von 2000 Bäumen pro Hektare optimal sind. CocoaFlo bietet somit die Möglichkeit, die weitere Entwicklung der Kakaoanbausysteme effizient zu unterstützen.

Das Potential für weitere Verbesserungen der Anbausysteme wird als hoch eingeschätzt. Verbesserte Unterlagen zur Erzielung von homogenem Pflanzmaterial sowie einheitliche Architekturen sind die wichtigsten Hebel um die Erträge zu steigern, den Pflanzenschutz zu verbessern und den grossen Arbeitsaufwand für Schnitt und Ernte zu vermindern.

Résumé

Le Cacao est traditionnellement cultivé dans des systèmes agroforestiers de la zone tropicale humide. Ils offrent une haute biodiversité mais produisent de faibles rendements, d'environ 500 kg de fèves sèches par hectare. Pour améliorer la productivité, le cacao est plus récemment planté dans des vergers de plein soleil. Des essais ont ensuite été réalisés en zone semi-aride. Si l'implantation dans de telles régions est couronnée de succès, le cacao pourrait profiter d'une pression plus basse des maladies fongiques et on pourrait assister à un accroissement des surfaces cultivées. Pour mieux comprendre ces systèmes, quatre essais en plein champs ont été établis dans le cadre du projet présenté au Brésil avec des vergers sans ombrage. Deux exploitations se situaient en zone semi-aride et deux en zone subtropicale humide. Le groupe de projet a étudié le comportement du cacaoyer dans ces régions. Sur la base des résultats, des recommandations pour optimiser les techniques culturales ont été émises.

Les résultats démontrent que l'implantation du cacao comme culture unique est possible dans des régions semi-arides et que des rendements de près de 3000 kilos par hectare peuvent être atteints. Ces rendements ont étés obtenus dans des vergers d'une densité de 1200 arbres par hectare. Les deux types vigoureux Salobrinho 03 et CCN51 ont livré les meilleurs rendements dans la comparaison des cinq cultivars BN34, CCN51, Cepec2002, PS1319 et Salobrinho03. Le climat sec a empêché le développement d'une majorité de maladies fongiques. Seuls *Lasiodiplodia theobromae* et *Ceratocystis Fimbriata* ont été observés dans les cultures.

Physiologiquement le cacaoyer possède quelques particularités. La plante ouvre ses stomates à l'aube et les ferme au coucher du soleil. Durant le jour, la plante ne peut régler sa transpiration que marginalement. Pour cela un bon approvisionnement en eau est essentiel. Durant l'apparition de nouvelles pousses végétatives (flush) l'accroissement des plantes stagne, car durant cette phase les assimilats sont utilisés pour le développement des jeunes feuilles, ce qui augmente la transpiration de la plante et peut causer un stress hydrique. Le développement incomplet de la cuticule et des stomates en sont la cause. Le tronc ne reprend sa croissance qu'après que les feuilles qui se sont développées à partir d'un puits d'assimilats deviennent source d'assimilats. Etant donné que les fruits poussent sur le tronc, on suppose que durant l'émergence de jeunes feuilles, l'approvisionnements des fruits est également réduit ce qui est à l'origine d'une importante chute de fruits. Ce phénomène a une forte incidence sur la formation du rendement. Durant la phase initiale de croissance des jeunes fruits, un bon approvisionnement de la plante est important, en évitant toutefois de trop favoriser la formation de nouvelles feuilles avec une fumure azotée élevée.

Un léger ombrage n'a pas affecté la photosynthèse, car les feuilles adultes atteignent un maximum à environ 400 µmol $m^{-2}s^{-1}$. Un ombrage par des filets (30 % d'absorption de lumière) a réduit la consommation d'eau d'environ de 30 % et augmenté les rendements d'environ 20 %.

De plus, nous avons pu observer la bonne adaptation du cacaoyer à l'irrigation au goutte-à-goutte et à des sols superficiels grâce à sa capacité à développer un système racinaire traçant (au maximum 25 cm) en l'absence de racine pivotante.

L'utilisation de dendromètres qui mesurent la dilatation et la contraction journalière des troncs a permis de signaler avec précision l'apparition des flushes et des stress hydriques (contraction des troncs). La dendrométrie permet donc d'enregistrer les cycles de croissance et de gérer l'irrigation du cacao de façon précise.

Le modèle "CocoaFlo" nouvellement créé permet de modéliser le comportement des plantes. Ainsi il a été démontré par exemple qu'avec les variétés et clones actuellement disponibles, des densités de plantation de 2'000 arbres/ha représentent un optimum. Cet outil a le potentiel pour soutenir efficacement le développement futur des systèmes de culture du cacao.

Le potentiel d'amélioration des systèmes culturaux du cacao peut donc être considéré comme élevé. Des porte-greffe sélectionnés pour obtenir du matériel végétal plus homogène ainsi que des modes de conduite favorisant l'uniformité des vergers sont les leviers les plus importants pour augmenter les rendements, pour améliorer la protection des plantes et réduire le volume de travail élevé pour la taille et la récolte.

2 Preface

By coincidence, in 2013, Hans Jöhr (Corporate Head of Agriculture, Nestlé) met with Bernard Lehmann (Director of the Federal Office of Agriculture) and Paul Steffen (Head of Corporate Research and Head of Institute for Sustainability Sciences, Agroscope) in the context of an international meeting in the Ivory Coast. They discussed how desperate the situation for Cocoa farms was, and during a spontaneously organised field visit, it appeared obvious to them, that the highly sophisticated Swiss orchard system (Niederstamm) could be utilized as a model for Cocoa. In parallel, Nestlé and Syngenta had cooperated in several projects to improve Cocoa cropping systems. To really make a change, Nestlé decided to learn more about the biology and agronomic traits of Cocoa. When learning about the advanced and solid EnvEve technology, and in discussion with Innosuisse, Hans Jöhr felt it was time to start thinking "out of the box" for this completely "forgotten" crop and start to leverage the Swiss knowhow for farms and farmers abroad. He felt that when working with the traditional experts, he was likely to get "more of the same", and not identify new, science-based ideas and concepts. By inviting CSEM to the consortium, the decision was taken to indeed follow an "interdisciplinary green-field approach" to the following core question: "Can we ensure sustainable supply of Cocoa cropping systems by building on the Agroscope fruit orchard (Niederstamm) expertise and other new innovative technologies?" During this process, which started in October 2013, the consortium's agronomy and technology experts met regularly and gradually became a true team, challenging each other and coming forward with new ideas. This project is the result of many months of intensive collaboration and all partners made significant upfront investments to complete this project.

The project **Sustainable Intensification of Agricultural Cropping Systems Supported by Smart Swiss ICT-AGRI Solutions** was carried out in partnership between private companies, Farms, the Federal Office for Agriculture and co-financed by the Swiss Innovation Agency.

3 Introduction

This project was set up as a Public-Private Partnership R&D Programme, co-funded by Innosuisse, the Swiss Innovation Agency because one of Switzerland's most regarded products "Swiss Chocolate" strongly depends on the provision of one main ingredient: Cocoa. Switzerland is one of the most important Cocoa trading countries. It is estimated that the Cocoa sector generates a tax income of over 100 Mio CHF each year. Switzerland produces about 180'000'000 kg of chocolate, 60 % is exported, 24 % to Germany (Anonym 2014). Further, the Swiss chocolate industry provides employment for about 4500 people.

Good chocolate starts with good raw materials. These raw materials are usually in high demand and availability varies strongly. Ageing Cocoa plantations and poor cropping practices result in low yields and a low overall productivity. Current farming practices might be well suitable for extensive production systems but may no longer respond to the new economic context. A direct relationship with farmers increases trust and improves loyalty. Furthermore, working together with Cocoa farmers provides insight into their agricultural production system and offers opportunities to provide advice on cropping and post-harvest practices to enhance productivity and reduce post-harvest losses. Therefore, great efforts are needed to render Cocoa farming economically viable. Currently, the productivity of Cocoa production systems with 350 to 550 kg/ha remains low, although theoretically yields of 3000 kg/ha or higher could be achieved.

Given the high dependency of a reliable and sustainable supply of quality Cocoa for the Swiss chocolate industry, the current project aimed to (i) explore new geographical regions for Cocoa production, (ii) develop new Cocoa production systems, and (iii) support transformation of traditional Cocoa production into advanced, economically viable production systems. Instead of producing Cocoa in humid tropics, growing Cocoa in semi-arid areas may open new opportunities for producers in countries such as Brazil. On the one hand growing Cocoa in semi-arid areas, could decrease the risk of Cocoa diseases, such as the fungus *Crinipellis perniciosa (*"Witch's Broom"), on the other hand, the dry climate demands a well-adapted management. However, the productivity and labour efficiency of Cocoa management offers a wide range of improvement potential. Compared to apple production systems, which have strongly evolved during the last decades, Cocoa is still grown as this was the case over 50 years ago.

In order to achieve an efficient production in semi-arid regions, it is essential to better understand the plants physiology. Within the presented handbook we aim to provide basic knowledge to help improve Cocoa production systems. Further, this handbook may offer additional insights to producers in humid regions, as it contains several ideas and propositions on the improvement of Cocoa growing systems in terms of yield, labour efficiency, plant protection and irrigation strategies.

4 Study description

The project was developed in collaboration with four farms in Brazil, two located in the semi-arid region, in which the main experiments were carried out. Hereby, we aimed to verify the development of Cocoa cultivation in an area too dry for traditional plantation practices. A second site in the tropical region, traditionally used for Cocoa plantations, served as reference (Figure 1). The Ibacem farm in Juazeiro (Bahia), was chosen as the main site for the experiments, due to their existing Cocoa plantations and their favoured water supply (Rio São Francisco). The Farms in Limoeiro do Norte (Ceará) and in Ilhéus (Bahia) were used to collect climatic data and later on for a density trial.

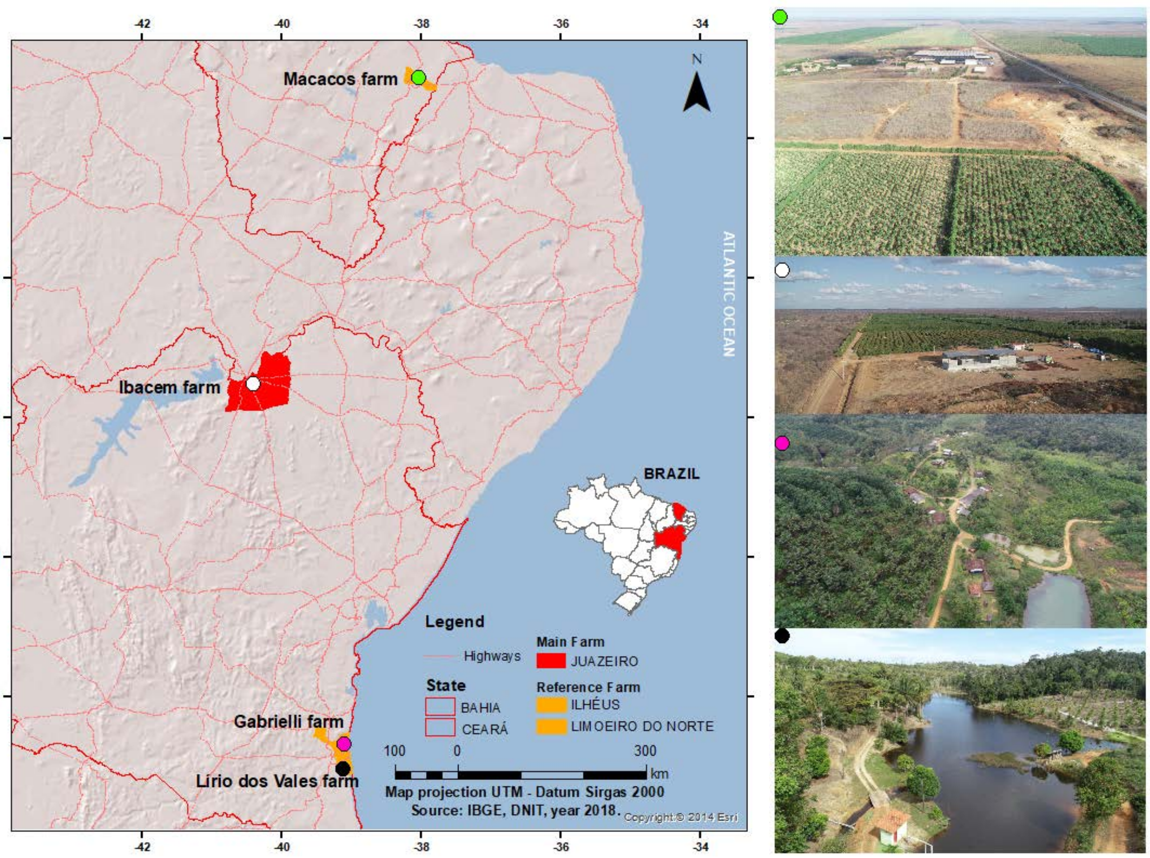

Figure 1: Location of the farms in Brazil. The location of each farm is indicated by coloured points on the map (left) corresponding to the coloured points on the pictures (right).

The field trials took place from 2016-2018 and the following parameters have been investigated in the main trial in Juazeiro:

Clones: Five different Cocoa cultivars (BN34, CCN51, Cepec 2002, PS1319 and Salobrinho 03) were compared with respect to:

- measurement of the leaf area
- number of pods per tree
- trunk diameter
- flowering and leaf flushes
- dry bean yield

Microclimate: Two blocks of the clone CCN51 were covered with shading nets (absorbing 30 % of the radiation) and protected by windbreaks to measure the influence of sun and wind.

Irrigation: Three plots with the clones CCN51, BN34, PS1319 were equipped with a semi-automated irrigation system. It allowed the management of irrigation by means of soil moisture sensors and automated valves. The idea of this experiment was to quantify the necessary amount of irrigated water.
Stress trial: To test the sensitivity of Cocoa trees to water stress, plots were isolated and the behaviour of the stem diameter was evaluated in relation to the amount of water applied. The trunk diameter and the observations of the physiological aspects of plants allowed for a quantification of stress levels.
Plant density: At the end of the project a density trial was installed on three farms (Juazeiro, Ilhéus and Limoerio do Norte). The plants were produced in the nursery of one farm and distributed to the others. The goal was to increase the productivity per area. The standard plant density lies at around 1200 trees/ha. As tree architecture is heterogeneous in the current plantations, we expected that a regular architecture will allow densities of over 2000 trees/ha. This experiment is still in progress.

The data obtained in the field trials was used to expand current knowledge on plant physiology and behaviour with specific regard to regional climatic differences.

5 Cropping systems of Cocoa

In contrast to other fruit growing systems cocoa is still grown in the same way as many decades ago. One goal of this project was to investigate the actual cocoa cropping systems and to point out possible improvements.

5.1 Actual status of Cocoa growing in humid areas

At present, Cocoa is usually planted with a tree density of about 500-1000 trees/ha. The low planting density, leads to the development of large trees creating plantations which are difficult to manage and associated with high labour input and a long establishing phase, characterised by small yields. Fruit tree plantations often use higher planting densities and smaller trees with homogeneous architectures. Adapting these systems offers the potential to improve the efficiency of Cocoa plantations.

5.1.1 Training systems

The most recent full sun orchards are generally based on the same model with an average tree density of 1200 trees/ha and a 4-5 open-shaped primary structure branches, such as described in chapter 7. Future developments could be explored following the experience of high density apple cropping systems with tree densities ranging from 2000-3000 trees/ha. These are generally based on a single stem tree shape. However, due to the relatively high vigour of Cocoa rootstocks and the requirement to maintain a high number of fruit bearing primary branches/ha without exceeding a planting density that would automatically affect the control over the plants vigour, two-stems trees could present an interesting option (see chapter 7.3).

5.1.2 Heterogeneity of orchards

If management, environmental factors and genotypes are not professionally monitored, orchards can become very heterogeneous, which is reflected in poor yield/ha. Examples of heterogeneous orchards are presented and explained in Figure 2.

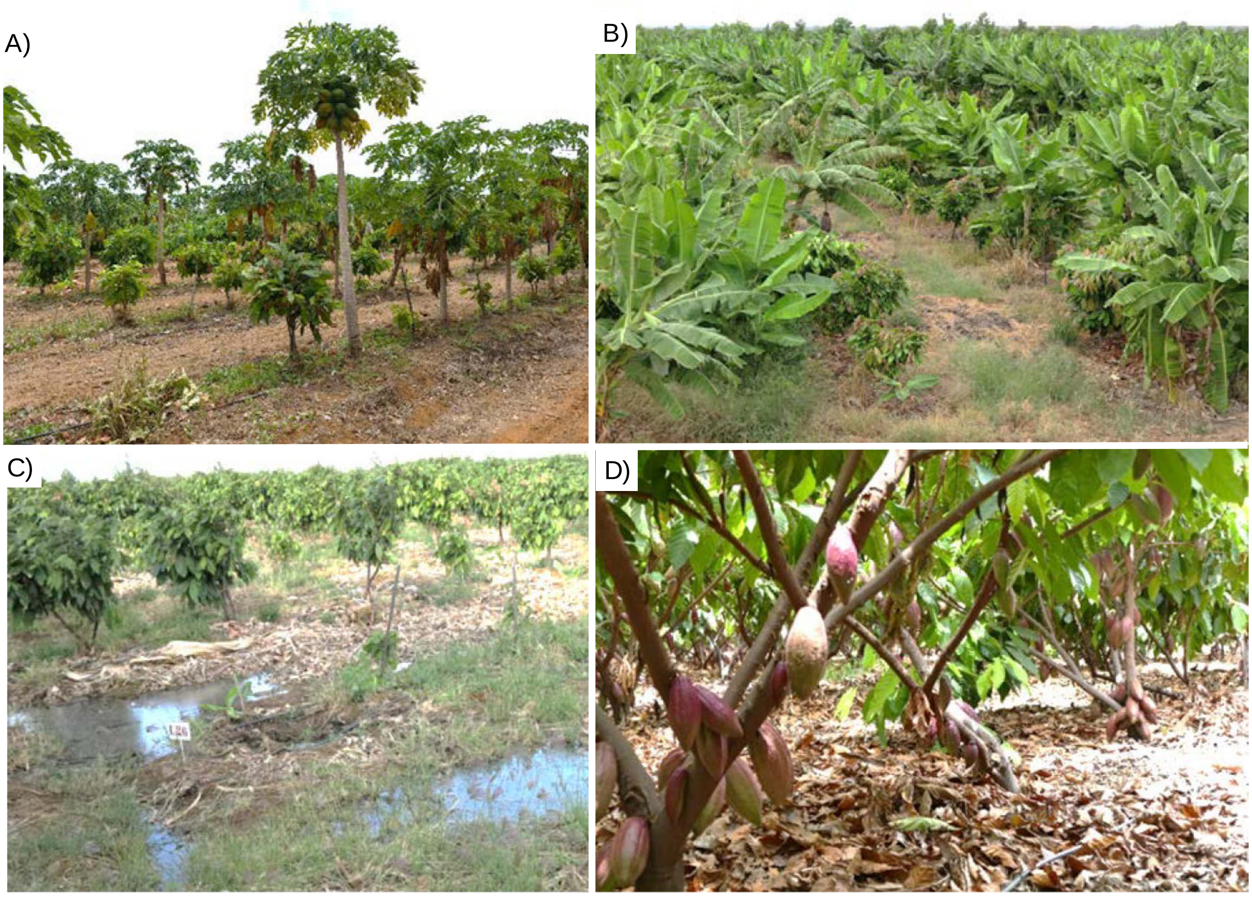

Figure 2: Lack of homogeneity within the Cocoa orchards depend on crop management, environmental factors (light, microclimate) and genotypes. The pictures show:

A) Lack of plantation care as well as insufficient shading which is crucial during the first 2 years of the establishment phase of the orchard.

B) Competition for nutrients, water and light by banana plants that are used for shading affect the crops homogeneity, in particular when the banana density is not under control or when the banana plants are maintained beyond a reasonable period.

C) In semi-arid conditions, irrigation is crucial. Consequently, over-irrigation is frequent which causes ponding water, especially on compacted soils where irrigation should be accurately managed.

D) Inadequate formation pruning leads to the development of asymmetrical and unbalanced tree crowns. The tree in the foreground shows good vigour and relatively well-balanced structure while its 2 neighbours on the right tend to crumble following the absence of primary structures on one side.

5.2 Full sun plantations and biodiversity in humid areas

The so-called full sun areas, which are monocultures without shading trees, are becoming increasingly common in the humid areas. The goal of suppressing shading trees is to simplify and improve the production system, and to increase yields. These systems are already well implemented in practice. Compared to 500 kg of dry beans per hectare and year in shaded systems, unshaded ones reach average yields up to 3000 kg. Etienne and Lecoeur (2019) reported yields up to 6000 kg/ha (Figure 3). Ahenkorah *et al.* (1987) demonstrated that yields increase as soon as shading trees are removed, taking into account the proper management of inputs. The investigation of yields in different countries reveals that low yields are currently being harvested in nearly all countries. To maintain a high yield level, Alvim (1977) further advise to adapt fertilization, irrigation and pest treatment to the higher production intensity.

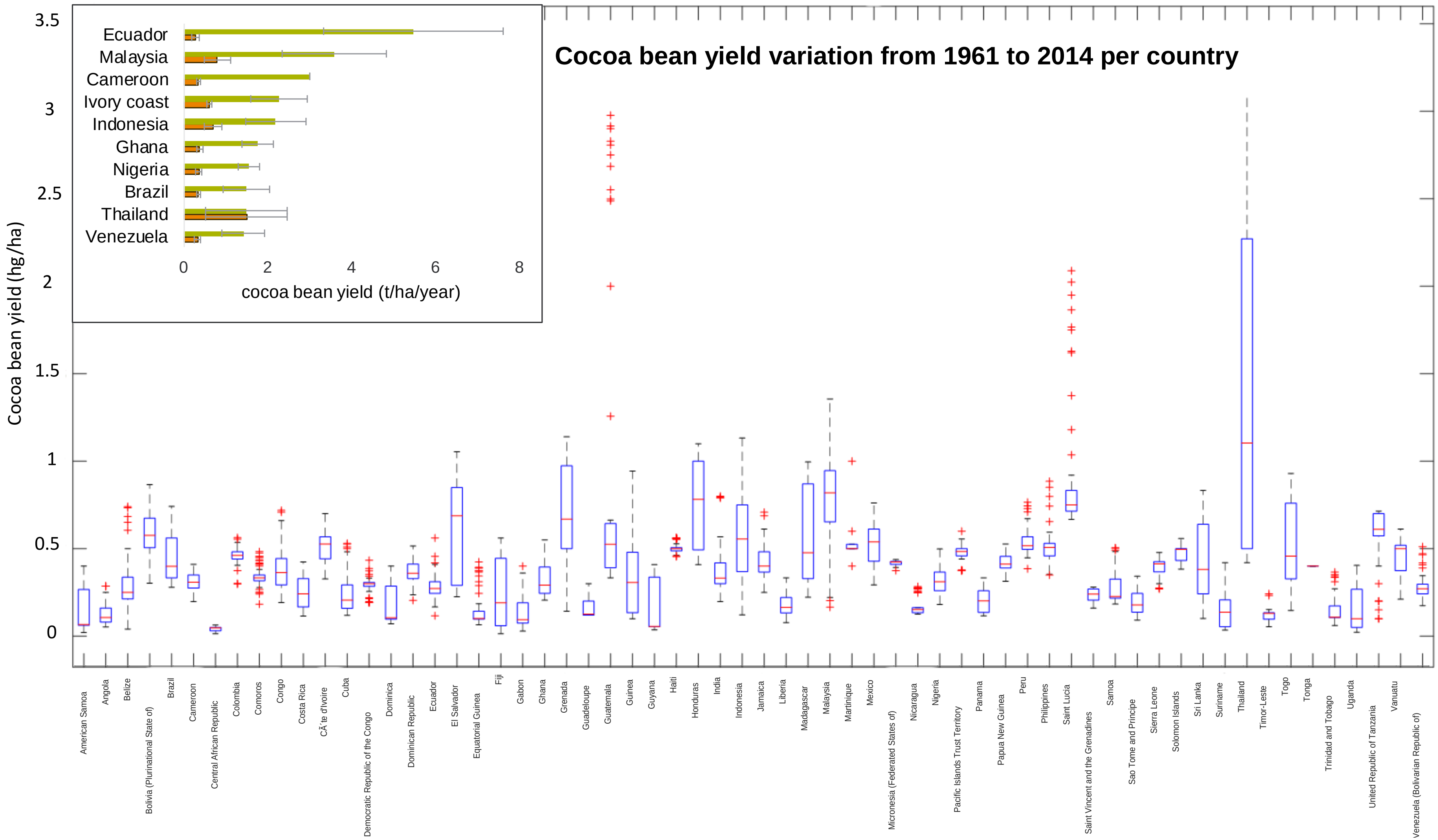

Figure 3: A): Mean ± SD of Cocoa dry bean yield between 1961 and 2014 (orange bar) and mean ± SD of observed technical potential yield (green bar) for 10 countries used for model validation. B): Location and yield variability from 1961 to 2014 for the 1200 data points collected from the literature (Etienne and Lecoeur 2019).

It is evident, that shaded areas with low tree densities, represent extensive cropping systems, with higher levels of biodiversity (Figure 4 and Figure 5). However, as non-native trees are sometimes used for shading, extensive Cocoa cropping systems may also alter existing ecosystems significantly. From our point of view, maintaining a high biodiversity does not exclude intensive cropping systems, but these need to be well planned and embedded into the environment. Future production systems may separate the production of Cocoa and the maintenance of biodiversity, as this is the case for other production systems such as meadows or apples.

Compared to Cocoa, which is commonly grown, as this was the case over 50 years ago, apple-growing systems have been strongly developed during the last decades. Extensive production systems marked by large trees were converted to very intensive ones, allowing a much better profitability (Hakim *et al*. 2014). These apple cultivation systems served as a showcase for the intensification of the Cocoa production system in semi-arid regions.

Figure 4: Cocoa plantation in full sun in southern Bahia.

Figure 5: Traditional Cocoa plantation system (Cabruca) with shading trees in southern Bahia.

5.3 Windbreaks

Cocoa needs to be protected from wind as its leaves are very sensitive and have a high evaporation rate (see 6.7.1). Silva Neto *et al.* (2001) reveals that wind speeds above 2.5 m/s have negative effects on Cocoa trees such as: increasing evapotranspiration, burnt leaves, and in some cases, leading to leaf falls, particularly the younger ones which are very thin. When exposed to strong winds the shape and development of the trees is compromised. Appropriate wind-breaking designs that protect Cocoa are therefore essential for successful production and have recently been described by Owen-Turner (2006). Table 1 shows the wind speed reduction at various windward distances, which must be adapted to each plantation. In Brazil Eucalyptus trees are often used to establish windbreaks. Although, they grow well, it takes more than 2 years of growth to provide adequate protection for Cocoa (6 meter). Further, these trees need to be well irrigated and fertilized to establish the windbreak quickly (Figure 6). To overcome this time, banana can be implemented as a temporary protection.

Table 1: Wind speed reduction in shelter at various distances windward and leeward of shelterbelts with different optical densities in Midwestern United States. Reductions are expressed as percent of open wind speed where open wind is assumed to be less than 10 meters per second and distance from the windbreak is expressed in terms of a multiple of the windbreak height (H) (Brandle *et al*. 2014).

Type of Windbreak	Optical density [%]	Percent of open wind speed at various distances								
		Windward			Leeward					
		-25H	-3H	-1H	5H	10H	15H	20H	25H	30H
Single row deciduous	25-30	100	97	85	50	65	80	85	95	100
Single row conifer	40-60	100	96	84	30	50	75	75	85	95
Multi-row conifer	60-80	100	91	75	25	35	85	85	90	95
Solid wall	100	100	95	70	25	70	95	95	100	100

Figure 6: Windbreaks established with Eucalyptus trees.

Effect of wind on the canopies

To assess the impact of wind on the leaf area in a plot of the variety CEPEC 2002, one out of ten leaves were collected in the field trial in Juazeiro. The removal of leaves was carried out at different heights and orientations of the tree crowns in order to obtain a representative sample of 75 leaves from 10 trees per treatment in

i. a wind-protected area (< 25 m away from windbreak) and
ii. an exposed area

From each sample, we measured the leaf area from high resolution images by means of the photo editing software (GIMP v2.8).

An average of 72.3 and 102.1 cm^2/leaf respectively was measured for damaged (Figure 7) and protected (Figure 8) leaves, representing a loss of 29 % for trees in the non-protected area.

Figure 7: Leaves damaged by the wind in a non-protected area (left).The foliage is practically intact in an area protected by a high Eucalyptus windbreak (right).

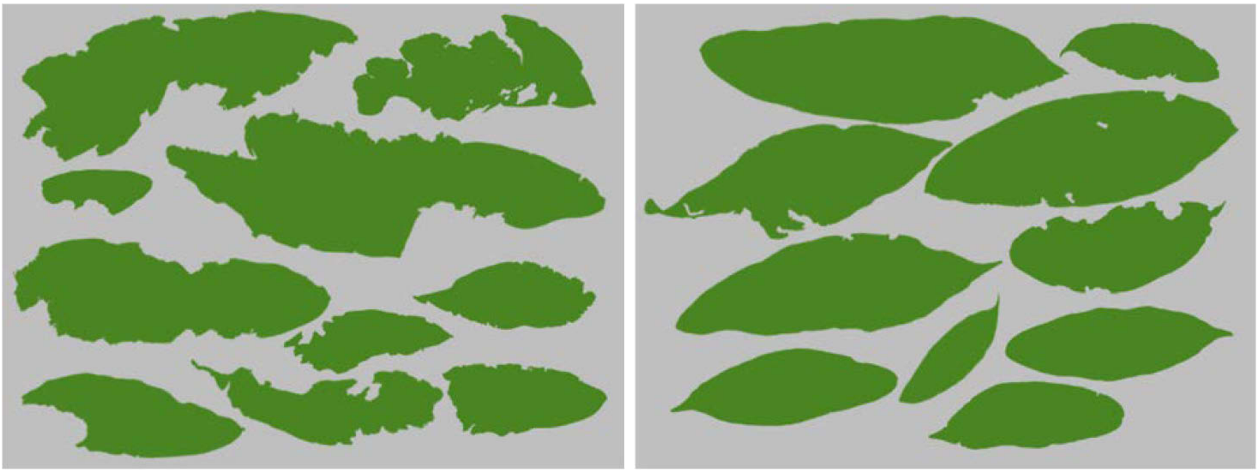

Figure 8: Sample of leaves damaged by the wind in the non-protected area (left). The foliage is almost intact in the protected area (right).

5.4 Climatic conditions

Traditionally Cocoa is grown as a sub-forest tree in humid tropical areas. These areas are characterized by moderate temperatures above 21 °C, air humidity around 70 % and precipitation between 1200 and 3000 mm/year (Götz *et al.* 2016). However, even in these conditions, climate change causes longer drought periods, which lead some farmers to install irrigation systems in case of critical periods. In semi-arid regions, irrigation (usually drip systems) is mandatory and used during at least 8-9 months. Figure 9 demonstrates the monthly rainfall in the semi-arid region of Petrolina and the humid region of Ilhéus. At Juazeiro farm (60 km from Petrolina) the level of precipitation was low, particularly with regard to the limited precipitation during the rainy period (- 40 %).

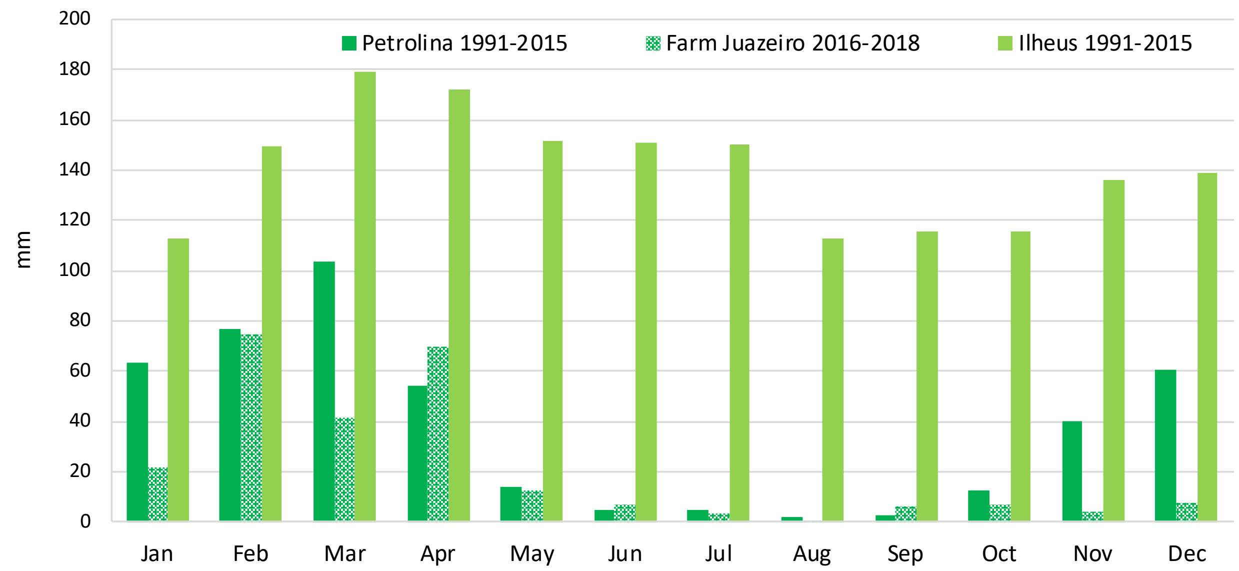

Figure 9: Monthly rainfall in the semi-arid region of Petrolina, the farm in Juazeiro (own measurements) and the humid region of Ilhéus (Anonym 2019).

Our trials in the semi-arid region aimed to understand how Cocoa plants behave in this very dissimilar climate, which is marked by minor levels of precipitation, low air humidity and high temperatures. It is well known that the physiological processes of Cocoa are inhibited by low temperatures, but when it comes to high temperatures a positive influence on the growth of the trunk and fruit, especially during the hottest seasons has been reported (Hardy 1960).

To compare semi-arid and humid climates, the evapotranspiration average (ET0) is a useful reference parameter (Pereira *et al.* 2006, Allen *et al.* 1998). The ET0 expresses the amount of water in millimeters evaporated per day (equal to liters per square meter and day). The parameters taken into account include air temperature, radiation, air humidity, and wind speed, which have been measured by weather stations. With a mean ET0 of about 4.5 mm/day in Ibacem – Juazeiro BA plants are exposed to much higher climatic stresses all year round, compared to the conditions in Ilhéus (traditional Cocoa area) with a mean ET0 of 2.6 mm/day in 2017 (Figure 10).

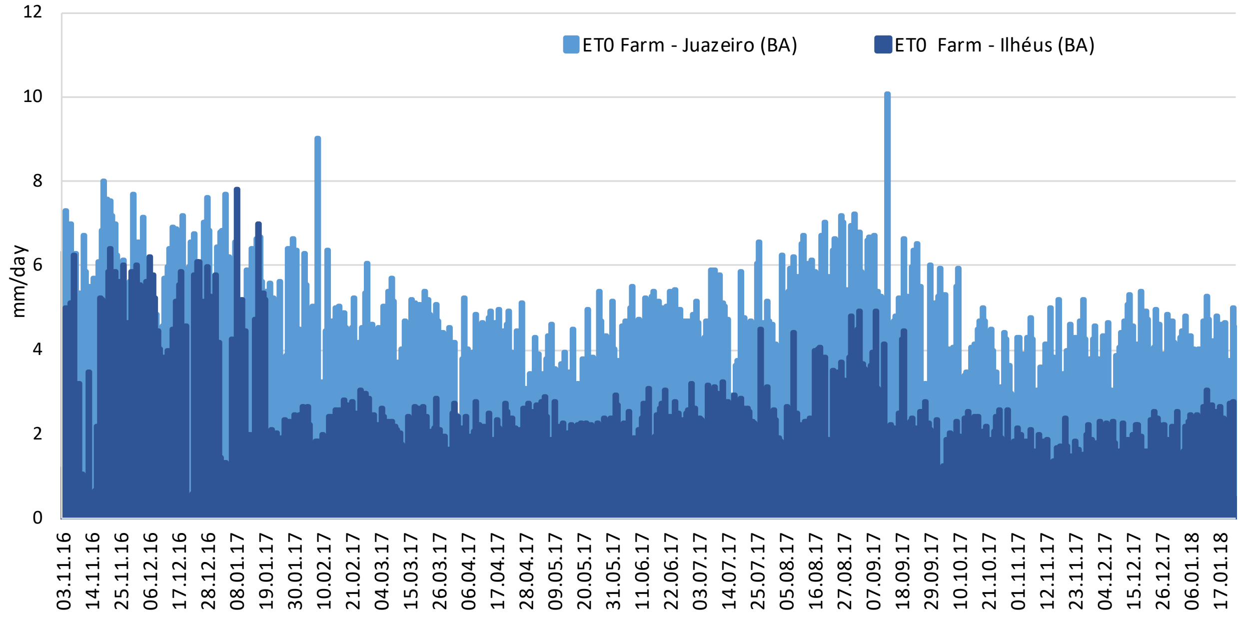

Figure 10: ET0 of the semi-arid location in Juazeiro and the humid region of Ilhéus from 2016 to 2018.

The dry climate combined with high temperatures of the semi-arid region presented in Ibacem hinders the proliferation of diseases caused by fungi, being one of the great advantages found in semi-arid climate. Compared to the traditional regions of Cocoa plantations, the semi-arid climate is marked by high temperatures and low air humidity, which results in higher reference evapotranspiration rates (Figure 11).

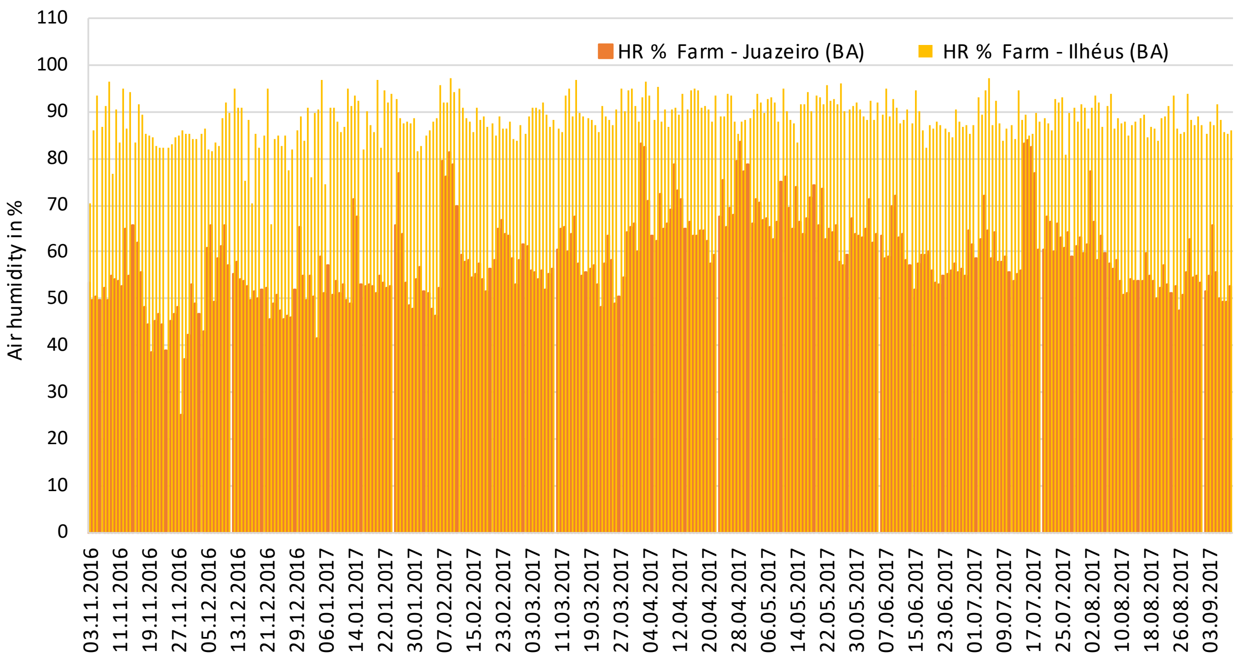

Figure 11: *Mean daily air humidity of the farm in Juazeiro and the farm in Ilhéus between November 2016 and October 2017.*

6 Plant management

Cocoa's particular characteristics, such as high sensitivity to light and low water regulation ability, make it essential to understand the management of this plant.

6.1 Sensitivity of Cocoa to solar radiation

Cocoa leaves exposed to direct sunlight may be burned by the sun and therefore decrease their photosynthesis (Figure 12). In unshaded systems, these leaves serve for the self-shading of trees and help protect subjacent leaves and pods from being burnt by the sun.

Figure 12: First layer leaves are quickly burnt by the sun. Fruits are also very sensitive to direct solar radiation which can heavily damage fruits and serve mainly for the self-shading of trees.

The sensitivity of Cocoa plants to direct sunlight has been investigated in a field trial in Juazeiro where unshaded plots have been compared to plots protected by a shading net absorbing 30 % of radiation (Figure 13). Trees were equipped with dendrometers to measure continuous variations of their stem diameter (see 6.7.4). Stem radius variations can be separated into growth-induced irreversible stem expansion and tree water deficit-induced reversible stem shrinkage (Zweifel *et al.* 2016). A main driver of tree water deficit is the evaporative demand (Figure 14A) and B)). We found that unshaded trees suffered from higher water deficits than shaded ones. This is due to the ET0 being about 30 % lower under shade, resulting in less evapotranspiration of the leaves. This difference between shaded and full sun trees might explain the enhanced vegetative growth and fruit setting (Figure 15) as well as the better yield observed in the shaded/windbreak trees (Figure 16). Shaded plants showed a better development, lower water requirements and higher yields. If we assume a Cocoa yield of 3000 kg/ha and a price of 1,2 USD/kg then an annual yield increase of 20 % would result in an additional income of 720 USD/year. However, this additional income does not cover the price for shading nets.

Figure 13: Cocoa trees protected by a shading net absorbing 30 % of sunlight.

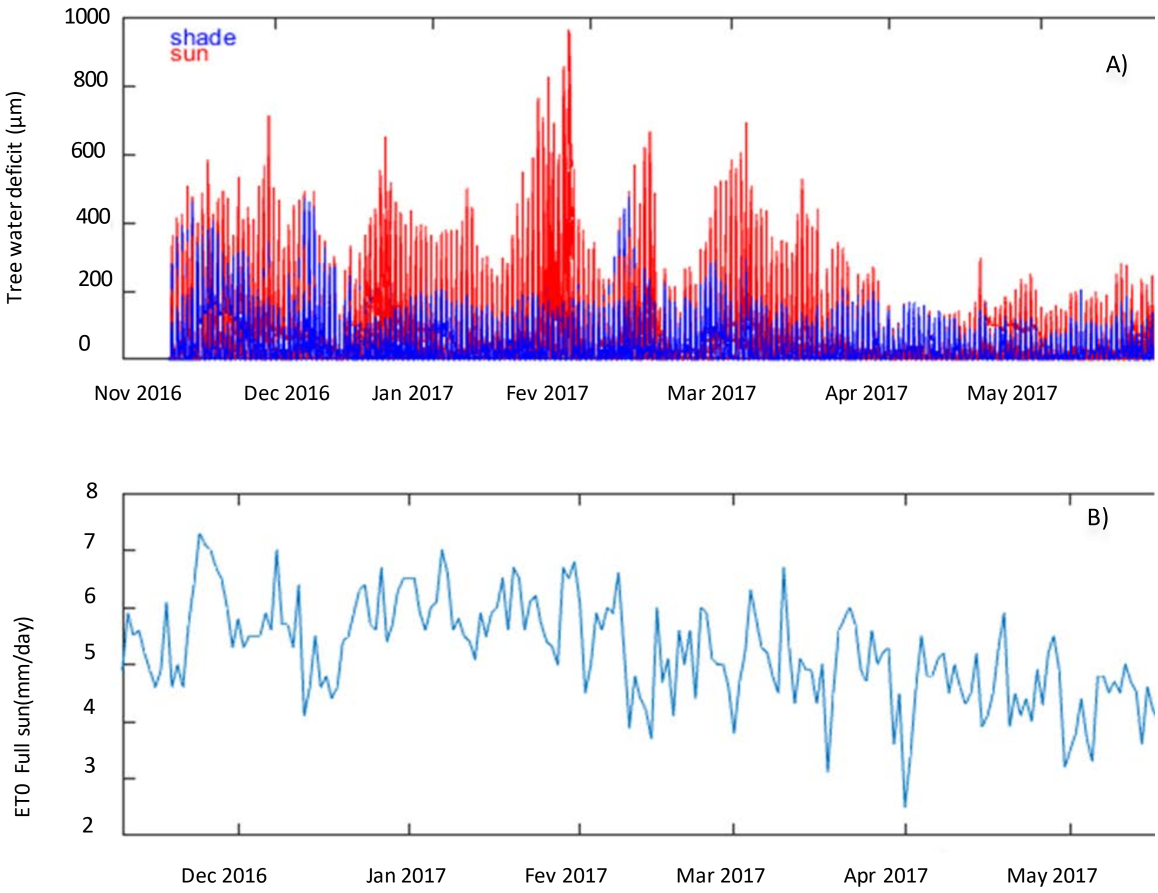

Figure 14: A) Tree water deficit (µm) of shaded and unshaded (sun) trees, calculated from dendrometer data according to Zweifel et al. 2016. B) ET0 measured in full sun plots (mm/day) in Juazeiro, Bahia, BR.

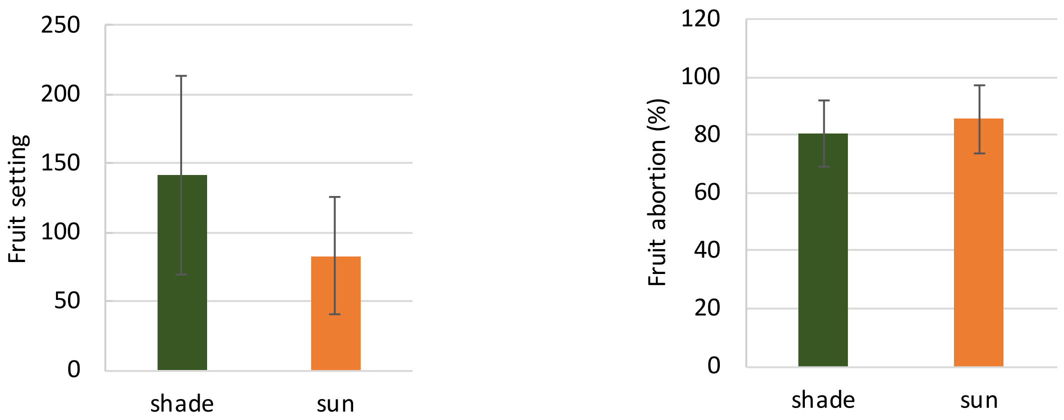

Figure 15: Shaded trees showed higher fruit setting rates than full sun trees.

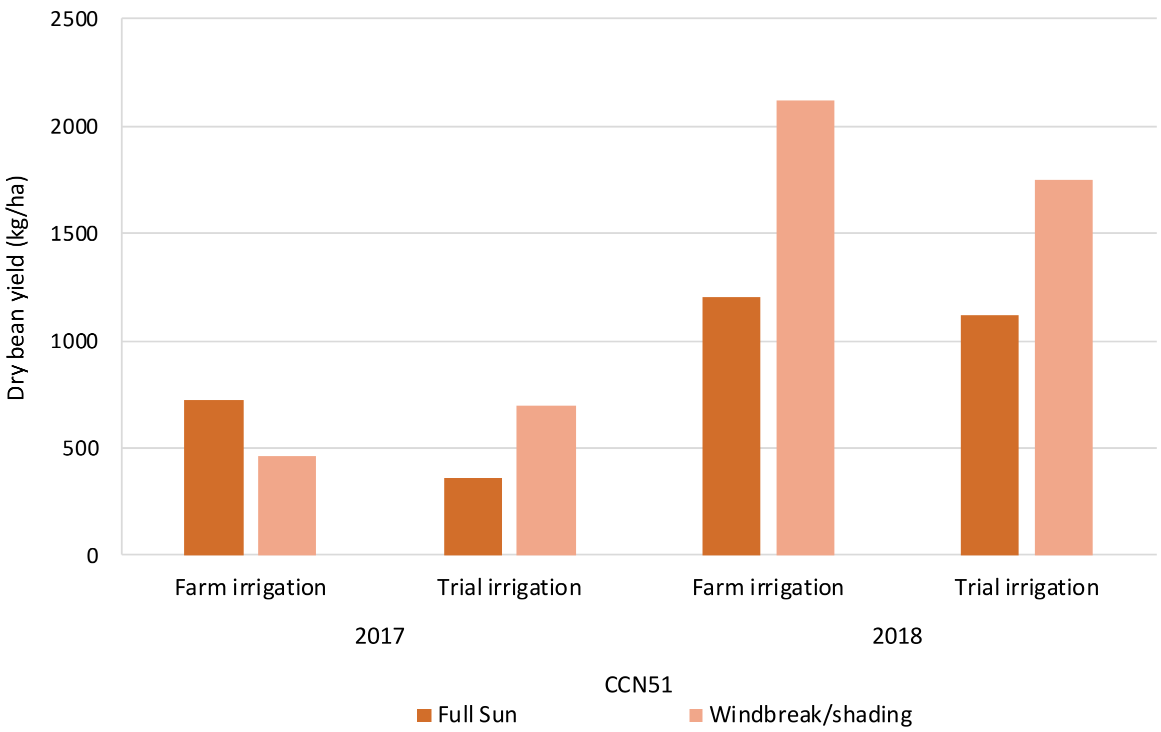

Figure 16: Dry bean yield (kg/ha) of unshaded trees (Full Sun) versus shaded and wind protected trees (Windbreak/shading) in Juazeiro for the main harvests in 2017 and 2018.

6.2 Light absorption of Cocoa leaves and yield response to shading

Photosynthesis light response curves were measured on leaves of four ages from freshly flushed to fully developed Figure 17. Measurements were performed on two years old Cocoa cultivar CCN51 trees grown in a greenhouse with a Licor LI-6400 gas analyser.

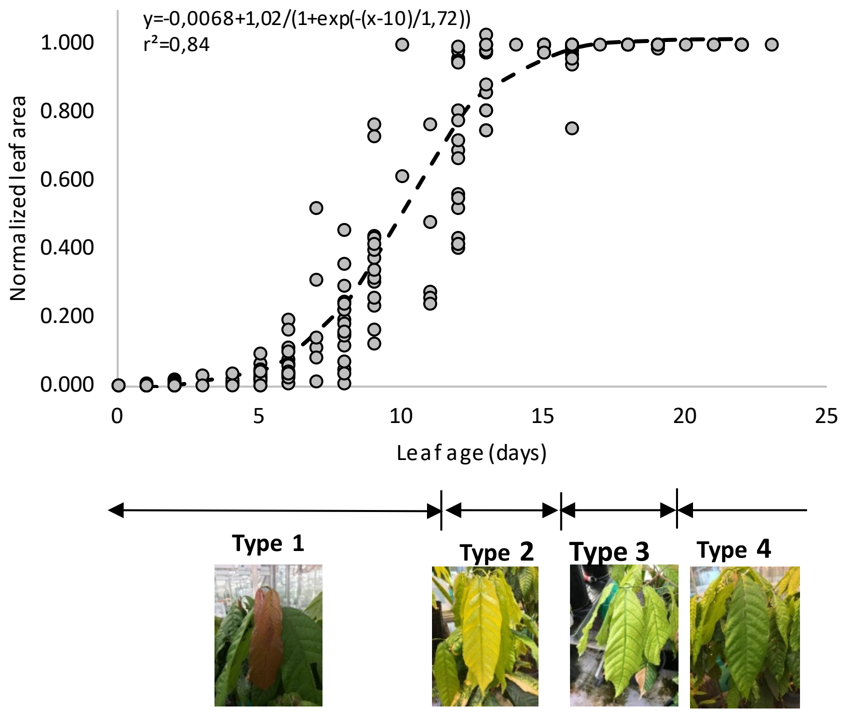

Figure 17: Leaf area development of Cocoa leaves from freshly flushed to fully developed leaves. According to their development stage, leaves can be ranked into 4 different types.

Young leaves of type 1 and 2 (Figure 17) are not able to perform photosynthesis and have a negative net photosynthesis due to carbon consumption for respiration (sink), while fully expanded leaves of type 3 and 4 have a positive carbon balance (source) (Figure 18). These results show that Cocoa leaves shift from carbon sink to source around 15 days after emergence. Adult leaves reach their maximum photosynthesis rate at approximately 400 µmol/m²/s (Figure 18), whereas other plants, such as apples, reach their maximum photosynthesis rate at around 600 µmol/m²/s (Campbell *et al.* 1992).

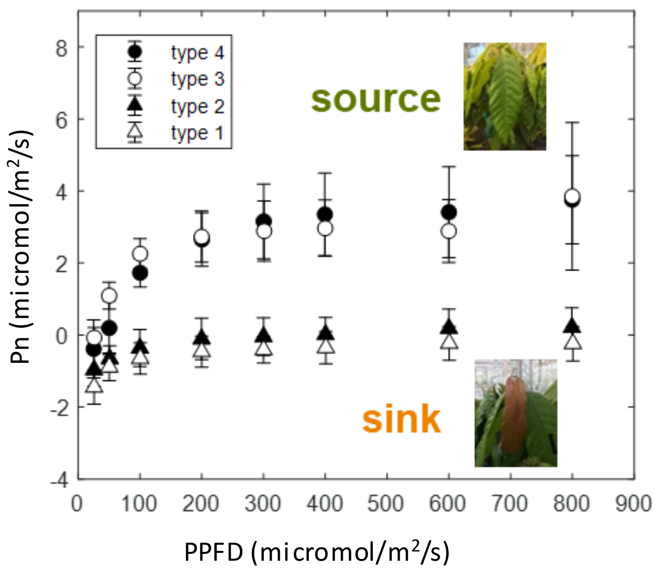

Figure 18: Photosynthesis light response curve of four different types of leaves of Cocoa plants grown in a greenhouse. Type 1 = freshly flushed – type 4 = fully developed (see Figure17).

These results demonstrate that shading does not decrease Cocoa's photosynthesis potential. A moderate shading of about 20 % allows for maximal production (Figure 19) at reduced water requirement, due to lower water deficit within the tree (Figure 14).

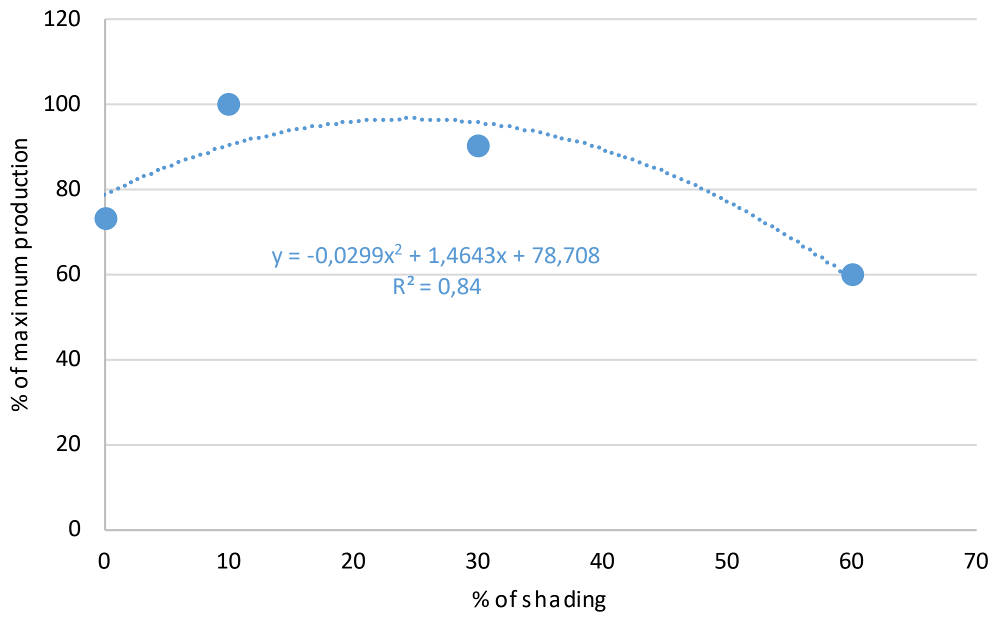

Figure 19: Predicted effect of the level of shading on the Cocoa orchard production (Model calculation with the crop model "Cocoa Flo", E. Audrey, Syngenta).

6.3 Soil and root system

In the main field trial in Juazeiro the soil was medium sandy with about 15 % clay, 15 % of silt, 70 % of sand and 1.5 % organic matter. Due to a strong clay lixiviation from the surface to the layer below 30 cm depth the soil was very compact and showed an extremely low permeability in this layer (Figure 20). Field observations showed that ponding water remained on this layer without infiltrating the subsoil for days. Nevertheless, Cocoa plants are capable of dealing with such difficult conditions.
Cocoa performed well under drip irrigation on shallow soils without building a taproot, showing the high flexibility of the plants rooting system (Figure 20 and Figure 21). The soil profiles in the experimental areas in Juazeiro showed, that due to the very compact subsoil, nearly all roots were concentrated in the first 25 cm. This rooting system is marked by a drip irrigation system with two dripper lines per tree row. All fine roots were concentrated below the dripper lines. This goes in line with Alvim (1977), who reported that "*80 % of the absorbing roots of Cocoa are usually found in the top 20 cm of soil*". Therefore, when planning irrigation, the soil water content of the first 20 cm is essential.

Figure 20: Soil profile in Juazeiro. Root growth is concentrated in the first 20 cm. Hardly any roots can be found below 30 cm.

Figure 21: *Drip irrigation determines the formation of fine roots, which can only be found under the dripper lines. The formation of a taproot is inhibited by the compact subsoil.*

6.4 Vegetative growth of Cocoa

The observations of leaf flushing on fifty four trees in Juazeiro were collected by visual estimation. These trees of the cultivar CCN51 were equipped with dendrometer sensors (Figure 22) which measured the variation and growth of the stem diameter.

The dendrometers are useful for fine monitoring of plant growth. Thanks to their high sensitivity, they can be used for analysing the successive dilatation and constriction phases during a 24 hour cycle. They have a resolution of some micrometers (µm) while changes at daily scale are around 100-200 µm (even up to 500 µm).

Figure 22: Dendrometer measuring the variation of stem diameter of a main tree branch.

Figure 23 shows a typical curve from dendrometer over a 4-day period with alternating phases of constriction from early morning to late afternoon and dilatation from late afternoon to the next morning. The daily constriction (DS) reflects the stress intensity, while the evening and night phase respectively characterize the recovery (the balance between water uptake and transpiration being generally negative during the day) and the daily net growth (DG, biomass increase).

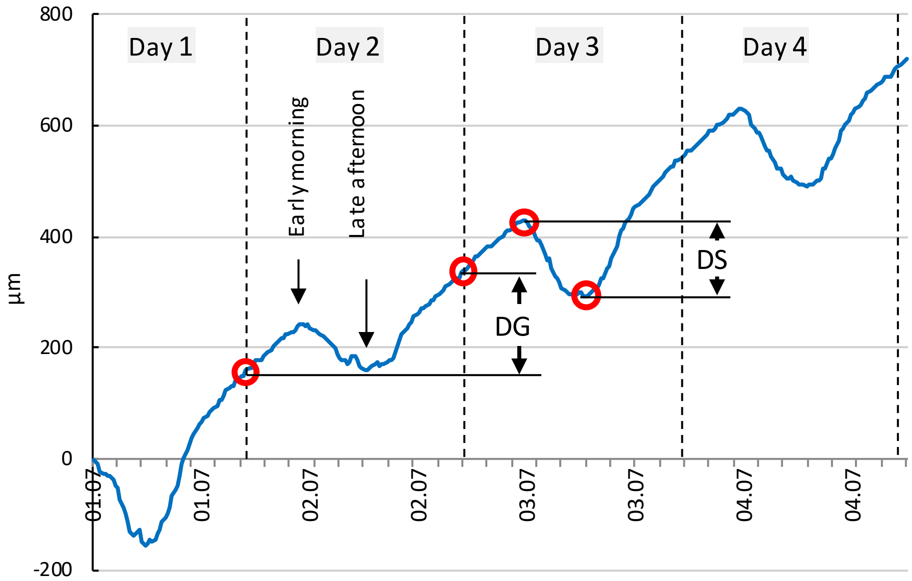

Figure 23: Different indexes can be used to represent the growth and the water stress, such as the Daily Growth (DG = max value Day+1 – max value day) or Daily Shrinkage (DS = max value AM – min value PM).

A typical rhythmic growth of the Cocoa shoots is illustrated in Figure 24. Unlike growth patterns observed in most temperate species, the elongation phase of shoots and the flushing of new leaves reveals as a stagnation phase of stem growth. This stagnation phase, lasting about 15 days, is followed by a stem growth phase lasting about 1 month, as highlighted in Figure 25. In the average of 23 trees a flushing intensity of over 50 % provoked a significant decrease of stem growth (Figure 26).

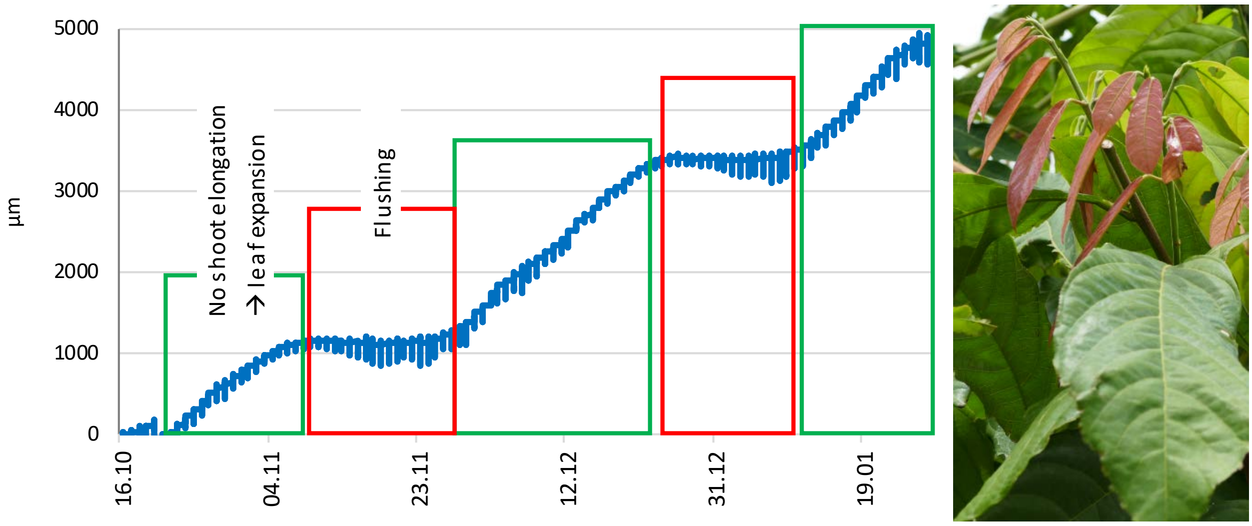

Figure 24: Growth monitoring during a 15-week period showing alternate phases of leaf expansion (areas surrounded by green line) and flushing phases (red line). Picture on the right illustrates the size difference between young leaves (red colour) and fully developed leaves, which may partially explain the very rapid biomass increase reflected by the curve during the leaf expansion phase.

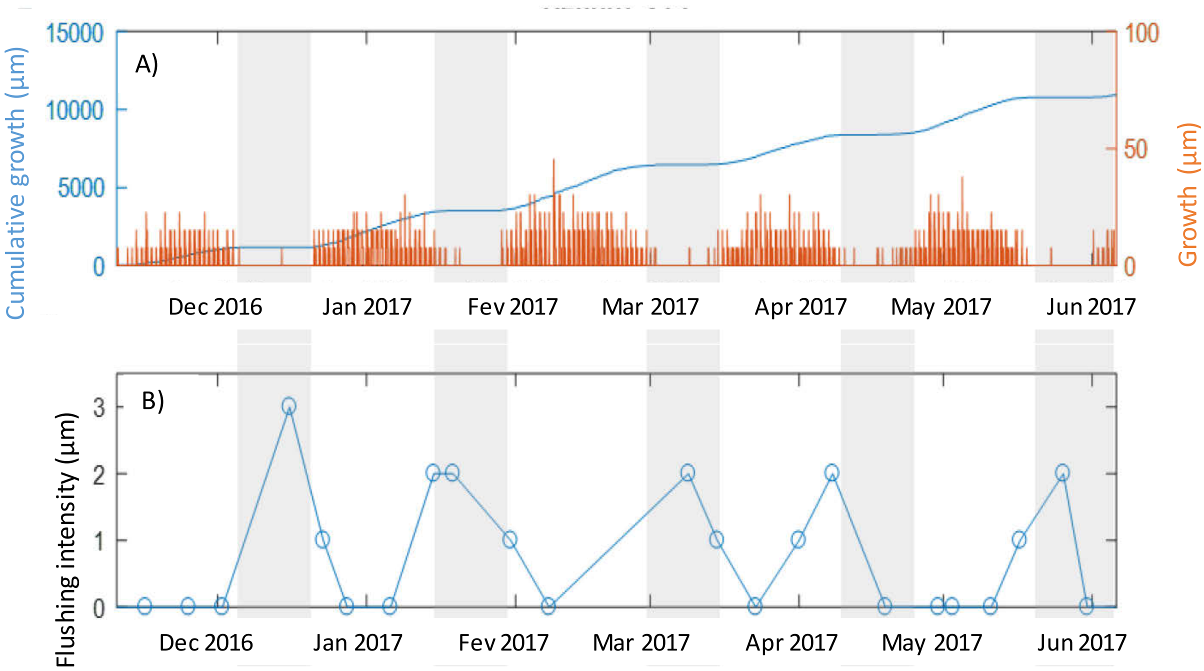

Figure 25: A) Growth-induced irreversible stem radius expansion (orange line) and cumulative stem radius growth (blue line) shown for one tree. B) Scouted flushing intensity (0 = no flushing – 3 = full flushing). Grey zones show stagnation of stem growth (23 trees).

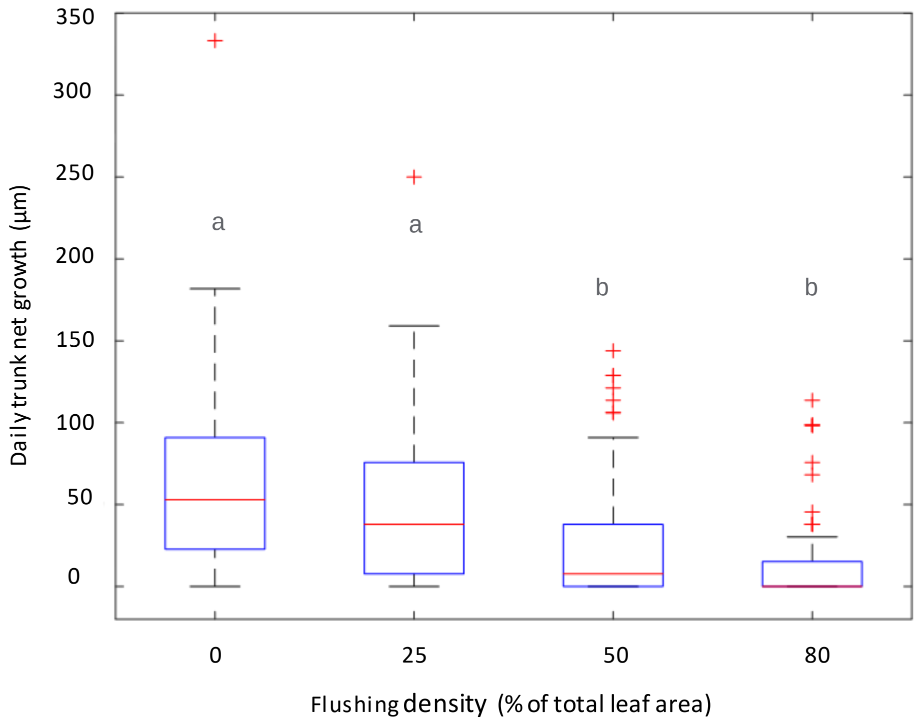

Figure 26: Daily net growth of stem (micrometer) for the different classes of flushing density (expressed in % of total leaf area). Letters compare differences between flushing densities (p<0.05, n = 23 trees).

As the evaluation of flushing intensity was performed every 15 days, the direct comparison of flushing and stem growth can only be carried out with a limited resolution. However, as presented in Figure 17, newly flushed leaves initially absorb assimilates and are sinks before they become sources after 15 days. These results support the hypothesis, that fresh leaves are priority sinks for carbon and have a higher priority than stem growth. Once the new leaves are fully developed, stem growth initiates again. Since the fruits are attached to the stem, we assumed that leaves have higher priority for the attribution of assimilates than fruits. Carr and Lockwood (2011) report that initially approximately 10 leaves begin to flush, then around 40 days later a second flush occurs and so on. This is in line with our observations. Between the reference evapotranspiration (ET0) and the flushing activity (Figure 27) only a very loose correlation could be found.

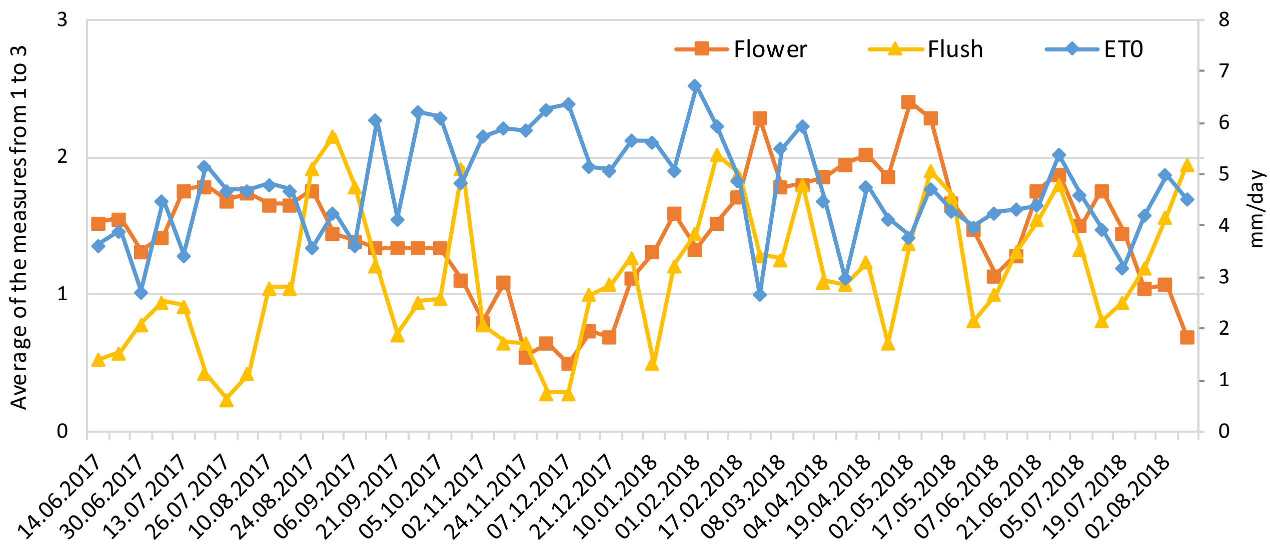

Figure 27: Leave flushing and flowering intensity (visual estimation 1 = low – 3 = high) and reference evapotranspiration (ET0) of 54 trees of the variety CCN51 during 2017-2018.

The maximum of evapotranspiration in Nov/Dec corresponds to the minimum flushing activity. As this is the period of maximal fruit growth, it is probable that fruit growth has further suppressed the flushing activity. It is not yet possible to quantify the influence of these two parameters, but we assume fruit growing to be more influential than climatic conditions.

6.5 Flowering, fruit setting and fruit abortion

Cocoa trees flower almost all year round. In accordance to flushing, flowering intensity was minimal during Nov/Dec 2017 (Figure 28). As described above, this is probably driven by fruit growth and may be due to low air humidity. Alvim (1977) reported that the common plant behaviour, of fruit growth inhibiting flowering and flushing activity, also takes place in Cocoa. In the current study, we focused on flowering intensity between shaded and full sun trees and found no difference.

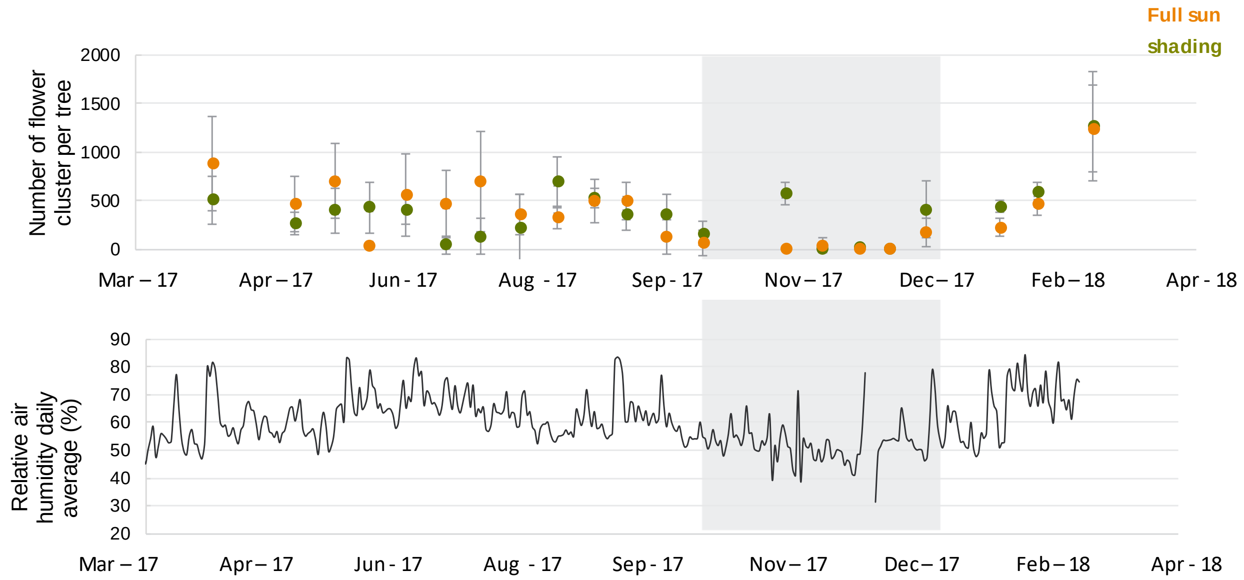

Figure 28: Flowering pattern over the growing season for shaded and full sun trees of cultivar CCN51. Relative air humidity (daily average in %) measured at full sun plots.

Unfortunately, fruit abortion can be very high and seems to be the main yield limiting factor. In the semi-arid climate trees showed two main fruit setting periods in Mar/Apr and in Aug/Sep. However, during Aug/Sep 2017 and Nov 2017 many fruits have been lost (Figure 29). Known by the name of cherelle wilt, fruit abortion is a physiological process involving competition mainly for carbohydrates.

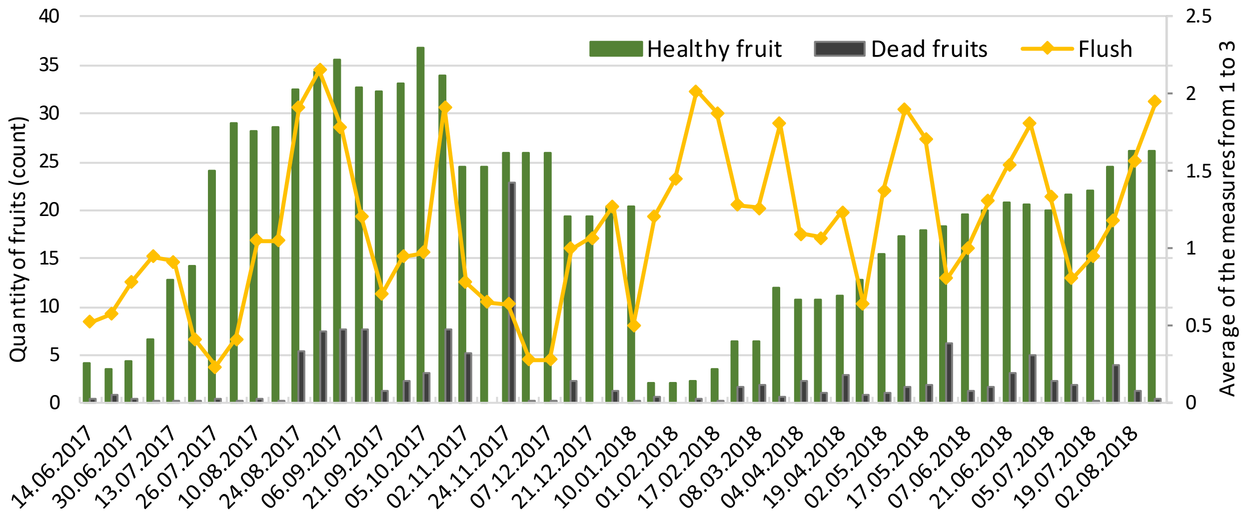

Figure 29: Visual estimation of number of healthy and aborted fruits/tree (n = 54 trees) of CCN51 in relation to flushing during 2017-2018.

Fruit abortion occurs only until the fruits reach a length of about 15 cm (Figure 30 A)). This confirms findings by Carr and Lockwood (2011), which mentioned that small pods are more prone to wilt than bigger ones. The fruits reach their final size after about 1500 growing degree days (Figure 30 B)). In the semi-arid climate of Juazeiro this was the case after about 3 months. The growing degree days were calculated according to the following formula:

Growing degree days (GDD) = $\max\left(\frac{Tmax+Tmin}{2} - 10°, 0\right)$.

Fruit abortion can be seen as a competition between the vegetative and generative growth of the plants. NAIR (2010) reported the highest quantities of the so-called cherelle wilt during and after leaf flushes. This behaviour is partially reflected by the field data (Figure 29). High flushing activities in Sep/Oct were correlated with fruit abortion. This underlines the hypothesis, that newly flushed leaves are primary sinks for carbon and compete with fruit growth. The large amount of fruits lost in Nov can be explained by excess water in the soil.

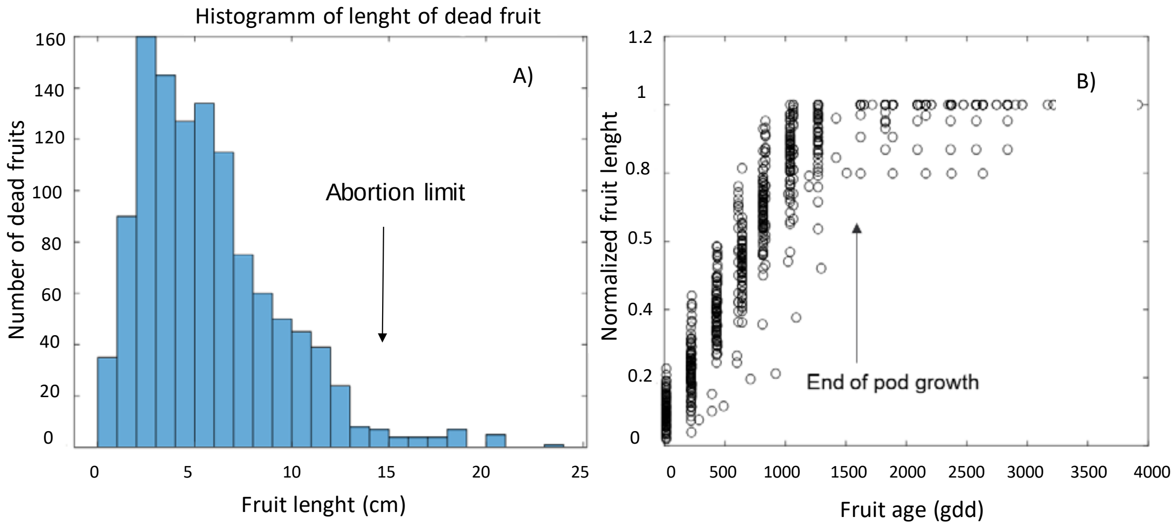

Figure 30: A) Length of aborted fruits showing the final stage of fruit abortion around 15 cm. B) Normalized fruit length in function of fruit age expressed in growing degree days. These data were collected on cultivar CCN51.

In order to obtain a high fruit setting, Sodré *et al.* (2017) encourage to maintain water storage above 60 % when flowering is more intense. This level of water storage must be sustained for seven weeks after the fruit emerges. Many field observations have shown, that small, well pollinated fruits are aborted by the trees and thus pollination doesn't seem to influence this process (Figure 31). The continuous building of new fruits is responsible for the numerous scattered, little harvests over the year (see 6.10).

Figure 31: Small aborted fruits were all well pollinated.

6.6 Balancing vegetative and generative growth

Sufficient numbers of flowers and young fruits are produced in the semi-arid climate, but fruit abortion is limiting the yield. Leaf flushes are priority sinks and can therefore impair fruit growth. In consequence, fruit abortion occurs favourably during and after flushing periods. The trials in Juazeiro showed that Cocoa trees show a strong vegetative development, which can reach Leaf Area Indices (LAI) up to 6. These high values were not correlated to higher yields, so even very vigorous trees can abort high amounts of fruits, resulting in suboptimal yields. Therefore, in order to decrease the number of aborted fruits, methods to reduce the vegetative growth after fruit setting have to be established.

6.6.1 Water and nitrogen

As nitrogen and water are the main drivers for vegetative growth, it needs to be questioned how this growth can be reduced during the fruit setting period. A study on young plants grown in containers revealed that out of nitrogen quantities ranging from 0 to 480 g/plant, no significant increase in vegetative developments above 120 g/plant (corresponding to 150 kg nitrogen /ha at 1250 trees/ha) was obtained (Ribeiro *et al.* 2008).
These experiments with differentiated applications of nitrogen and water levels confirm that it requires strong trees to achieve high yields. However, so far no study has presented a nitrogen response curve for dry bean yield and/or vegetative plant growth. It is well known from other fruit trees, that vegetative and generative growth need to be well balanced and that high amounts of nitrogen favour mainly vegetative growth. Figure 32 shows a high rate of cherelle wilt on CP49 in semi-arid farm Ibacem. There is no evidence that this damage rate could be attributed to inadequate nutrition, but this hypothesis is formulated by some researchers.

Figure 32: A very high rate of cherelle wilt on CP49 in the semi-arid farm Ibacem.

6.7 Water requirement and irrigation

Due to limited precipitation in semi-arid climates, efficient irrigation management presents one of the largest challenges in Cocoa production. Understanding the particular physiology of Cocoa allows developing optimized irrigation practice.

6.7.1 Water stress sensitivity

Stomata are tiny openings in the tissue of plant leaves (Figure 33). They allow for gas exchange and regulate transpiration of plants. Stomata are able to open more or less according to weather constraint (temperature, air humidity, wind) to maintain the highest photosynthesis rate. However, under certain conditions, they tend to close in order to reduce excessive water loss. The critical thresholds that affect the stomatal function, particularly water stress, differs among species. Cocoa is considered very sensitive, although differences among genotypes have been evidenced by some authors (Alban *et al.* 2016). The stomatal reactivity is particularly low on young leaves, which explains stress symptoms during flushing cycles.

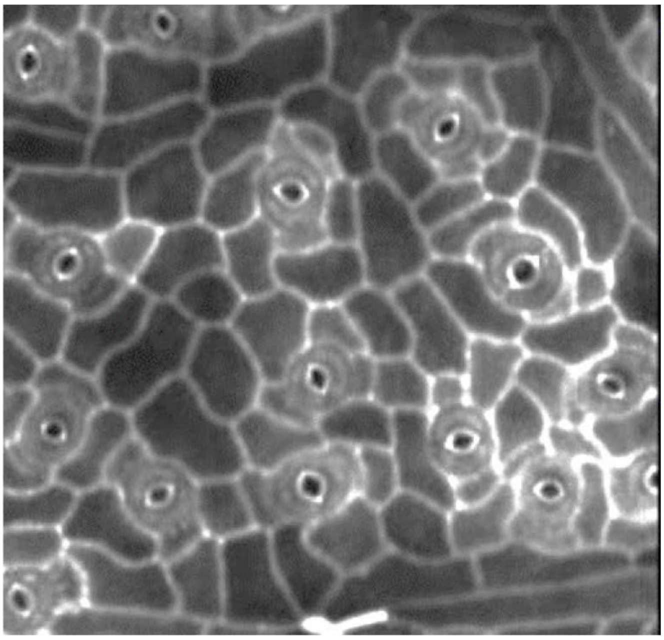

Figure 33: Mature leaves of Cocoa showing the particularly high density of stomata mentioned by many authors.

We observed that Cocoa leaves (CCN51) have about 900 stomata/mm^2, which is about 10 x more than corn (Liu *et al.* 2015). According to Hardy (1960) the stomatal density is higher in full sun areas, because the epidermal cells are smaller than in shaded areas, which has been confirmed by Daymond *et al.* (2009), who counted 788 to 1081 stomata/mm^2 according to light exposure. Almeida and Valle (2007) reported that ineffectiveness of stomatal closure to water loss is probably due to a high cuticular transpiration. This relation has not been observed in the trials in the semi-arid region. The very distinct start and stop of shrinkage at sunrise and sunset shows, that stomatal opening and closure is highly determined by the sunlight.

The water potential (ψ) measured with the Schollander bomb (or pressure bomb) is often used as reference for plant stress. It is currently used in research for measuring the water status of plants in function of water availability in the soil and transpiration rate due to climatic constraints. For water management, ψ_{noon} (water potential measured at noon), which reflects the water status of the entire plant, would be the most accurate and useful indicator for water stress. In semi-arid conditions, it is used on different perennial crops (wine and fruits) to regulate deficit irrigation. This requires threshold values indicating a stress level that induces acceptable incidence on the crop productivity and yield quality. Observing four different genotypes for drought tolerance, De Almeida (2016) reported values of - 0.65 MPa for well-watered plants and values ranging between - 1.08 and - 2.08 MPa for plants which received deficit irrigation. No references were found regarding water potential measurements applied to irrigation management.

6.7.2 Water requirements according to climate

Evapotranspiration is a common indicator to express the level of climatic constraint induced by weather parameters (air temperature, solar radiation, air humidity, wind speed). For agronomical application, other parameters that play a minor role can be ignored. However, for adequate irrigation management, the characteristics of the cropping systems must be taken into consideration. The leaf area index (LAI = leaf area of the crop/m^2 of soil) is the most useful parameter to reflect the relative evaporative leaf area of an orchard. There is a specific fraction of the ET_0 (Crop Coefficient = K_c) that reflects the needs of the most common cultivated species. For fast growing species such as maize, K_c is given for different development stages. For most perennials and particularly Cocoa, the FAO (Food and Agriculture Organization of the United Nations) gives a single information irrespective to canopy development which is between 1.0 and 1.05 (Allen *et al.* 1998). However, we can assume that this value can be applied for adult trees in cropping systems with LAI ≥ 3.0.

For an applied procedure of irrigation management, Pereira *et al*. (2006) suggests to use a value derived from FAO grass reference evapotranspiration (= 2.88) for the water use per unit leaf area of the irrigated trees.

To calculate the daily water needs according to the crop LAI, the generally accepted coefficient would be 1/2.88 = 0.347 from which we can obtain a simplified value of K_c = 0.347 * LAI. Therefore, the complete equation for daily calculation of irrigation can be obtained as following:

mm irrigation/day = ET_0 * 0.347 * LAI

ET_{LA} is the evapotranspiration per unit leaf area grows linearly up to LAI between 3 and 4, which can be considered representative for adult orchards. In our experiments, we used a specific device (Licor LAI 2200, Lincoln, Nebraska USA) for direct measurements and in very vigorous plots, we obtained maximal values of 6.0. These high values have been confirmed by manual measurements of six single trees of the variety CCN51. However, many experiments realized with perennials show that the K_c does not significantly increase above a LAI level of 3.5.

6.7.3 Soil humidity measurements as a tool for irrigation management

Irrigation can efficiently be managed by using soil humidity sensors. Different types of sensors can be used to this end. Tensiometers or Watermarks® proved to be suitable for the drip irrigation management, as their affordable price allows to install a measurement set up based on some replications. Figure 34 shows correct positioning of the sensors in relation to the position of the drippers. Most of the time, we used 3 replications per soil layer, which results in a total of 6 sensors per measurement station.

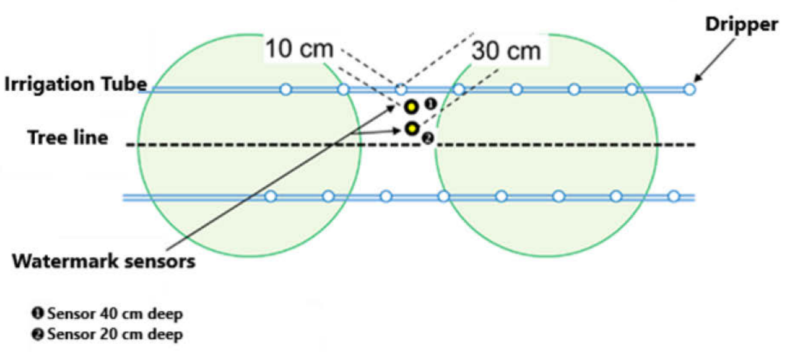

Figure 34: Installation of soil moisture sensors in the soil to control the irrigation. For one plot 3 sensors in 20 cm and 3 sensors in 40 cm have to be installed to get a good picture of the irrigation quantity.

The sensors must be placed at the correct depth in order to reflect the water distribution in the wet bulb. Correct positioning can be determined according to the texture of the different horizons. In very old soils where clay lixiviation formed a compact and impermeable layer, the maximal potential root depth showed to be around 40 cm (Figure 35).

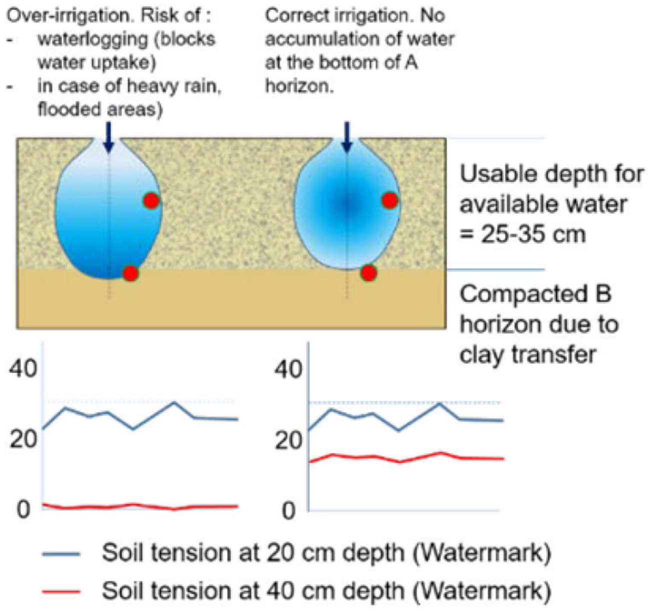

Figure 35: Schematic sectional view of the water distribution produced by a single dripper. On the left, the typical image of over-irrigation leading to water accumulation on the bottom of the upper layer. Consequently, the curve of the 40 cm sensors constantly reports soil saturation (0 KPa). On the right, the curves reflect a correct situation without waterlogging danger.

The optimal irrigation is obtained by adjusting the daily water quantities in such a way that soil humidity remains constant at both soil depths, avoiding waterlogging such as explained in Figure 35.
Thresholds between - 30 KPa to - 60 KPa and - 20 KPa to - 40 KPa respectively for soil and sub-soil are generally used as threshold values. Figure 36 shows that the daily irrigation was insufficient during the first week. From Jan. 5th, the first rain after a long dry period helped stabilize the curves, although the lower soil layer (40 cm) could have been a little more humid (especially compared to the upper one), the values are not too far from optimal. However, watering twice per day efficiently avoided waterlogging which was not easy most of the time. The daily irrigation was 1.6 mm (ranging from 1.5 to 2.3) and the average ET_0 was 5.1 mm. Rainfall contributed to the water inputs with 30 %. Therefore, the optimal retroactively calculated Kc coefficient is K = (irrigation + rain) / ET_0.

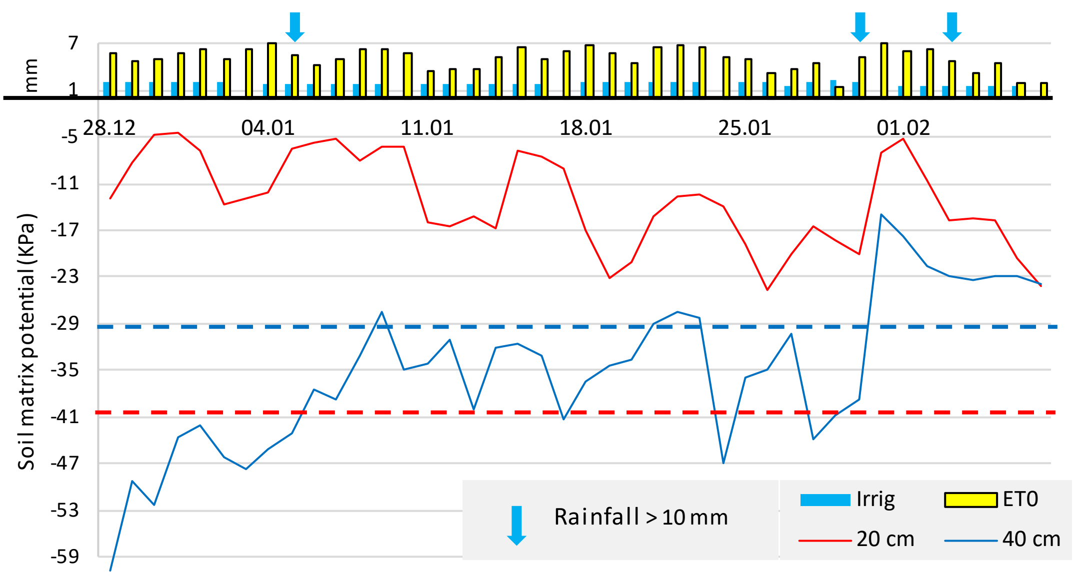

Figure 36: Example of a 6 week irrigation period applied to a Cocoa orchard at Juazeiro farm conducted according to soil humidity. To keep the soil humidity within an acceptable range, the programmer's setup was adapted every week.

In case of low water capacity of the root profile illustrated in Figure 36, the best solution is to split the irrigation in 2-3 so-called “pulses” per day. This helps minimize the water stress during hot days and contributes to avoid water logging, with water accumulation above compacted layers. Unfortunately, due to technical and labour management limitations (time window limited to a relative short period of the day, complexity of the water distribution network, irrigation sectors which brings together plots with different water needs, manual command of valves etc.), differentiated irrigation is not possible in any context.

6.7.4 Plant indicators as a tool for irrigation management

Irrigation management with plant indicators by the Schollander bomb method is shortly discussed in section 6.7.1. Dendrometers that provide continuous measurement of stem growth, present another solution (see 6.4). Dendrometer measurements showed that stem shrinkage started at sunrise and stopped at sunset. By comparing daily shrinkage (DS), described in section 6.4, with the stem growth (Figure 37) shows a trend to higher stress during the stagnation phase of stem growth. This stress increase is probably due to new flushes resulting from the missing of stomatal control of young leaves. In addition, the red circle shows an extreme stress caused by a possible lack of irrigation.The relationship between climatic constraint and tree water deficit (as an index corresponding to DS) signals that dendrometer measurements can be used as good stress indicators to drive the irrigation of Cocoa.

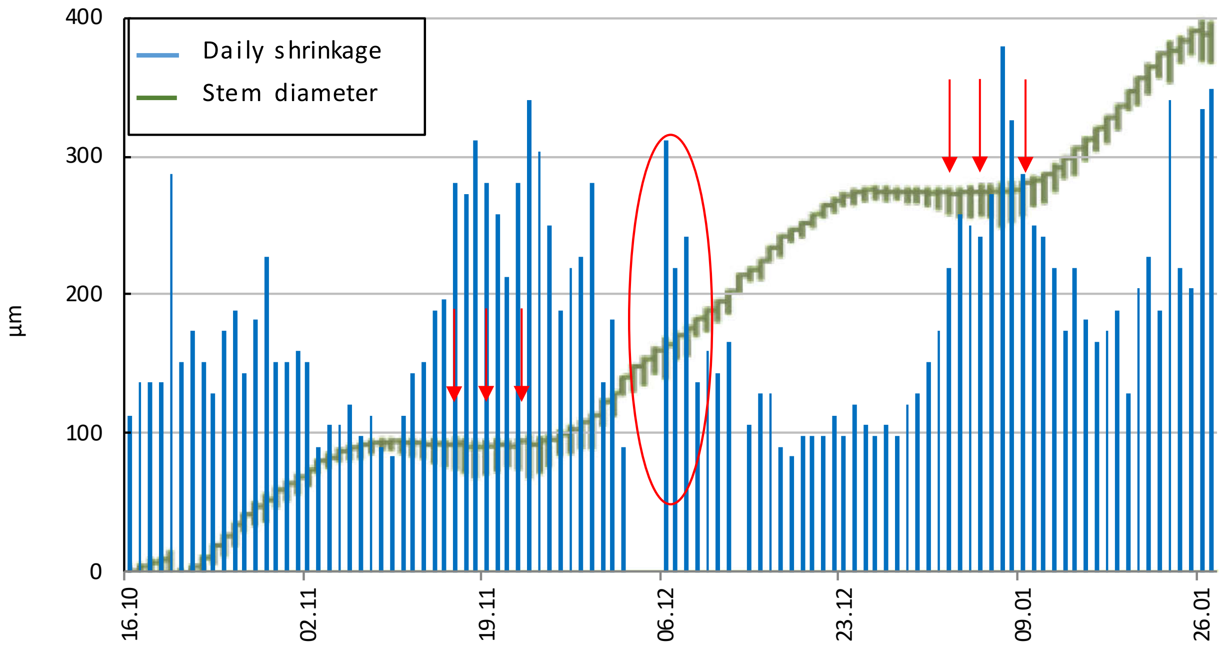

Figure 37: Daily shrinkage (DS) extracted from the dendrometers curve (blue) and the stem diameter (green). Red arrows indicate a correlation of stagnation in stem growth with a constant increase of the daily shrinkage and the red circle indicates a possible water deficit.

Figure 38A) confirms the higher sensitivity of the trees to hydric stress during the flushing periods, which goes hand in hand with the lack of stomatal control of part of the canopy. In contrast, Figure 38B) shows that Cocoa is more tolerant during the leaf expansion phase.

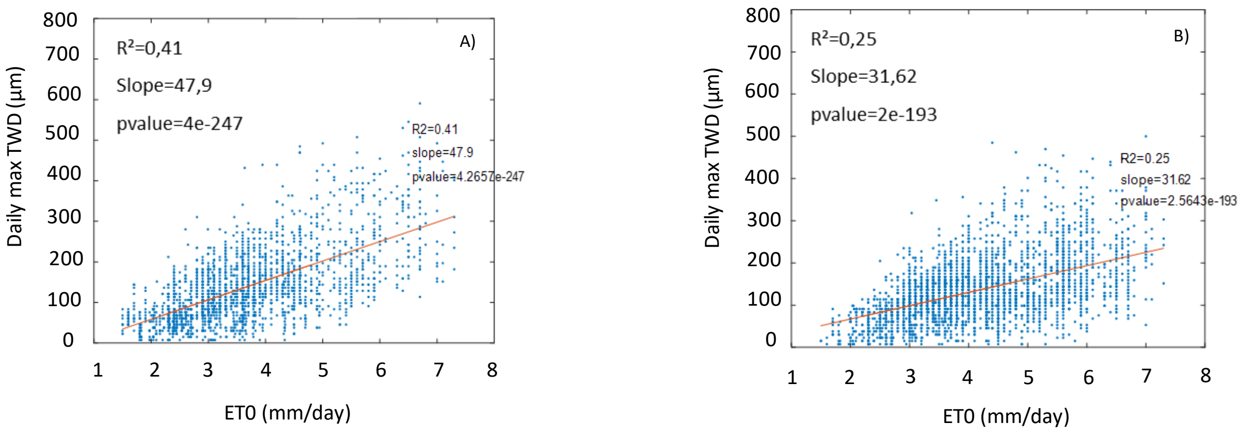

Figure 38: Relation of daily maximum tree water deficit and daily ET0 A) during period of flushing and B) during period of trunk growth for cultivar CCN51.

6.7.5 Tree reaction to water stress

To test the sensitivity of trees of the variety CCN51 to water stress, a three-week experiment has been established where irrigation was reduced in intermediate periods by 100 %, 50 % and 0 %. After about three weeks of limited irrigation the soil moisture content measured by soil water probes Watermark (Irrometer, Riverside CA, USA) reached a level of 180 cbar in 20 cm and more than 160 cbar in 40 cm depth. During this period, ET0 showed average values of 4.4 mm. This induced a strong stress in the trees. The leaves wilted intensely, showed a brighter coloration and started to fall (Figure 39).

Figure 39: Same tree without water stress (left) and with water stress at 180 cbar soil moisture (right).

In addition, it has been observed that new flushed leaves have fallen earlier than older ones and the flush was stopped. During such a stress period, the dendrometers indicated a strong shrinkage of the stem diameter of about 1000-1300 µm (Figure 40).

Three days after the restart of the irrigation with 2.5 mm/day the leaves recovered and the stem reached the original diameter again. This shows that a water stress of about 180 cbar soil moisture content seems to apply a strong stress to the trees. The cambial activity was not completely blocked since the shrinkage was mainly caused by dehydration of the bark (Alvim and Alvim 1980). According to our observations no wilted leaves appeared above a soil moisture content of 100 cbar. It has to be kept in mind, that the soil of the trial was very shallow and had a rooting depth of only 30 cm. Below that depth the soil was impermeable for roots and water. This means that soil water storage capacity is very limited. So in another type of soil the duration until an extreme stress will be different.

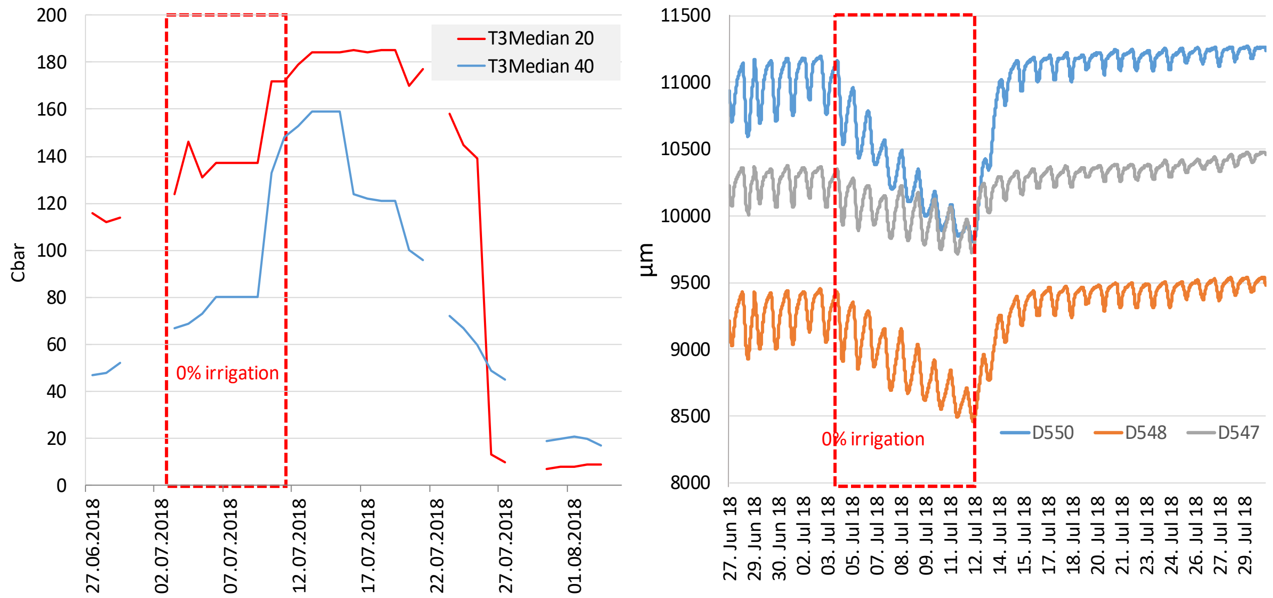

Figure 40: Soil moisture development in 20 and 40 cm soil depth (left hand side). Stem diameter of 3 trees: D550, D548, D547 (µm) during a period without irrigation from July 4 to July 12 2018.

According to Alvim (1977) the decrease of soil moisture resulted in stem shrinkage and chlorosis of the leaves, which was mainly the case for the older ones. Very few leaves dropped during wilting. However, as soon as soil moisture increased again, shedding of leaves occurred simultaneously to an abrupt increase of the stem swelling. He explained that "*the increase in leaf fall appeared to result from rupture at the abscission layers of the leaves following the rapid swelling of the shoot bark. Seven to eight days after rewatering, many terminal buds started swelling, initiating a new flushing cycle".*

6.7.6 Excess of water

Like for other plants, Cocoa reacts sensitively to excess of water (Figure 41). Such an overhydration causes anoxia in the root zone, which may lead to a reduced tree growth and to a complete loss of fruits. In addition, strong losses of nitrogen are enhanced by the denitrification. In any case a good control of soil moisture during rainy periods is important. Almeida and Valle (2007) reported that flooded soils can cause "*decreases of leaf area, stomatal conductance and photosynthetic rates in addition to inducing formation of lenticels and adventitious roots".* Whereas Gomes and Kozlowski (1986) described that waterlogging was followed by leaf epinasty, extensive decay of roots, and formation of hypertrophied lenticels and adventitious roots on submerged stems.

Figure 41: Waterlogging can create big damages from poor growth up to complete fruit loss.

6.8 Fertilization

Fertigation with drip irrigation is well suited to feed the Cocoa plants. During the experiment in the farms, fertilization was the responsibility of each farm and not part of the trial. A technical report with information about the amount, composition and fertilizer doses that should be applied in the plantation, from the nursery to its production is available (Chepote *et al.* 2013). The main advice given is that the fertilization must take the development of the plant into account and that the amount of fertilizer needed for the plant, must be proportional to its phenological stage.

Nitrogen is often regarded as the most important mineral nutrient, limiting crop production in many agricultural crops worldwide. However, many studies report that nitrogen supply rates are often much higher than the tree requires. On the one hand, the latter are often overestimated, especially in mature orchards. According to the Swiss guidelines for fruit growing fertilization, apple orchards producing 60'000 kg/ha of fruits require 80 kg/ha nitrogen to cover their needs. Some ponderation factors such as shoot vigour, yield of the previous year, blooming intensity, rootstock vigour, useful depth of soil and soil organic matter must also be considered for a good estimation.

In the guidelines published by Tagliavini *et al*. (2016) the optimal nitrogen fertilization can be based on the net removal of this element nitrogen (N) in g N/kg fresh fruit. The values differ considerably according to tree species (for example 0.9 for apple, 2.7 for peach, 10 for walnut and 22 for olive). In the case of an apple orchard producing 60'000 kg of fruit/ha, the optimal fertilization would be 60 * 0.9 = 54 kg N/ha.

Regarding Cocoa fertilization, Jiska *et al.* (2015) point out the numerous knowledge gaps that remain to be filled. In their review, the authors note that much of the primary research related to nutrition in Cocoa production was conducted over 40 years ago. Many results highlight the positive effect of fertilization according to orchard management (nitrogen fixation, organic matter) and crop system (density, shading) but there are still deficiencies regarding the uptake and use of the nutrients.

However, despite lacking information regarding the quantitative understanding of nutrient uptake and use, guidelines based on crop age (Table 2A) or on double the amounts of nutrients removed by the crop (Table 2B) are proposed to growers as guidelines.

Table 2: Nutrient guidelines. A) Brazil BA, based on tree density of 1300 trees/ha (Cabala Rosand *et al.* in De Geus, 1973) B) Based on twice the amount of nutrients removed by the crop (Von Uexküll and Cohen 1980).

A		B	
Year	kg N/ha	Targeted yield (dry beans(t)/ha)	kg N/ha
Planting	9-14	1	40
2	18-28	2	80
3	28-42	3	130
Adult	45-70	4	190

Figure 42 shows a high vigour of CCN51 trees (4th year after planting) under a shading net intercepting 30 % light. Compared to full sun trees, their vigour was 90 % higher. Both plots received the same fertilization, although it is generally considered that shaded trees have a lower nitrogen requirement. At this level of solar radiation reduction, light is not considered a limiting factor, thus it can be reasonably argued that the low productivity is due to competition between vegetative growth and fruit setting as a possible consequence of nitrogen over-fertilization (Zuidema 2005).

Figure 42: A very high vigour of CCN51 trees after 4 years planted.

6.9 Plant protection

As expected, after 4 years of plantation in the semi-arid climate of Juazeiro, so far only the fungus *Lasiodiplodia theobromae* (Figure 43) and *Ceratocystis Fimbriata* or *Ceratocystis Cocoafunesta* (Figure 44) have been found. According to Sodré (2017) this type of disease is quite common in dry climates with unshaded areas and less fertile soils. Oliveira and Luz (2005) showed a higher incidence and intensity in plants with low vegetative growth under stress in full sun areas and also due to the large number of insect attacks found. These fungi are described as secondary pathogens that normally require injury to enter the host.

Figure 43: Lasiodiplodia theobromae fungus in the pods (left). Characteristics and symptoms of descending death caused by the Lasiodiplodia (right).

Fungus *Lasiodiplodia theobromae* (Sodré 2017; Oliveira and Luz 2005)

Symptoms:

- Dark spots on the skin.
- Progressively cuts deeper into the wood.
- Hypertrophy of areas attacked in stems.

Recommendations:

- Elimination at 20 or 30 cm below the necrotic areas.
- Apply 5 % sodium hypochlorite and 5 % cuprous oxide solution.
- Spray affected and surrounding plants.
- Avoid mechanical damage (Pruning and Harvest).
- Spraying with insecticides or mixtures with fungicides.

Figure 44: Plants affected by the fungus of the wilt of Ceratocystis (evil of the machete) that occurs due to injuries caused in the plant by insects.

Ceratocystis Fimbriata or Ceratocystis Cocoafunesta (Sodré 2017; Oliveira and Luz 2005)
Symptoms:

- Wilt, yellowing and dry leaves, partially or generically.
- Necrotic lesions.
- Sometimes exudation of a dark liquid.

Recommendations:

- Burn diseased and dead plants.
- Avoid mechanical damage (Pruning and Harvest).
- Clean all working tools with 1: 6 sodium hypochlorite or formaldehyde.
- Management practices for area care.
- Apply 5 % sodium hypochlorite and 10 % cuprous oxide solution and carbendazim ($C_9H_9N_3O_2$) 1 %.
- Quarterly spray with 3 % cuprous oxide with Methamidophos 0.5 % (*APUD* Ram *et al.* 2004).

The treatments required for each type of disease and insect are described in Sodré (2017), Oliveira and Luz (2005). Quite a few types of insects have been found in the orchard of Juazeiro during these years facilitating the manifestation of fungi as mentioned above. The two most frequent were Cochineal (*Planococcus citri*) shown in Figure 45 and Cocoa thrips (*Thrypidae Selenothrips rubrocinctus*) in Figure 46.

Figure 45: Cochineal (Planococcus citri) living in mutualism with the ant "pixixica" Wasmannia auropunctata.

Cochineal (*Planococcus citri*) (Agrolink 2019; Sánchez 2011)
Symptoms:

- Suction of the sap.
- Reduces fruit quality by causing cracking and formation of liquid excrement macerations.
- Direct damage.

Recommendations:

- Perform spraying with soluble oils in the coolest hours of the day or mix with phosphorus insecticide. Suggestions for market oils: Argenfrut RV, Assist and Dytrol.

Figure 46: Symptoms caused by the insect THRYPIDAE Selenothrips rubrocinctus - Cocoa thrips. The attack of this insect is more intense with absence of shading, prolonged drought and the presence of leaves partially ripe.

***Thrypidae Selenothrips rubrocinctus* - Cocoa thrips** (Agrolink 2019; Menezes *et al*. 2005)
Symptoms:

- Inflorescences.
- Damages the fruits.
- Leaves: occurs mainly on the surface inferior near the central vein causing necrosis and later, falling.

Recommendations:

- Pluck and burn plants with symptoms of the disease.
- Spray with specific insecticides such as Actara 250 WG or Adage 350 FS.

Pest and disease management in semi-arid regions also requires a lot of effort. In fact, the dry climate and low humidity favour the plantations of Cocoa reducing the proliferation of diseases caused by fungi, mainly the *Crinipellis perniciosa (*"Witch's Broom") but other types of diseases can be found evidencing the importance of periodic control and management of the plantation.

6.10 Harvest and yield expectations

The harvested yields of dry beans in Juazeiro for the different varieties from October 2017 to September 2018 are presented in Figure 47. Salobrinho 03, CCN51 and CEPEC2002 showed the highest yields. However, the variation between the highest and lowest yields of the same treatments were very large. Whereas the best plots performed with more than 3000 kg/ha of dry beans, the poorest ones reached less than 1500 kg/ha (Figure 47).

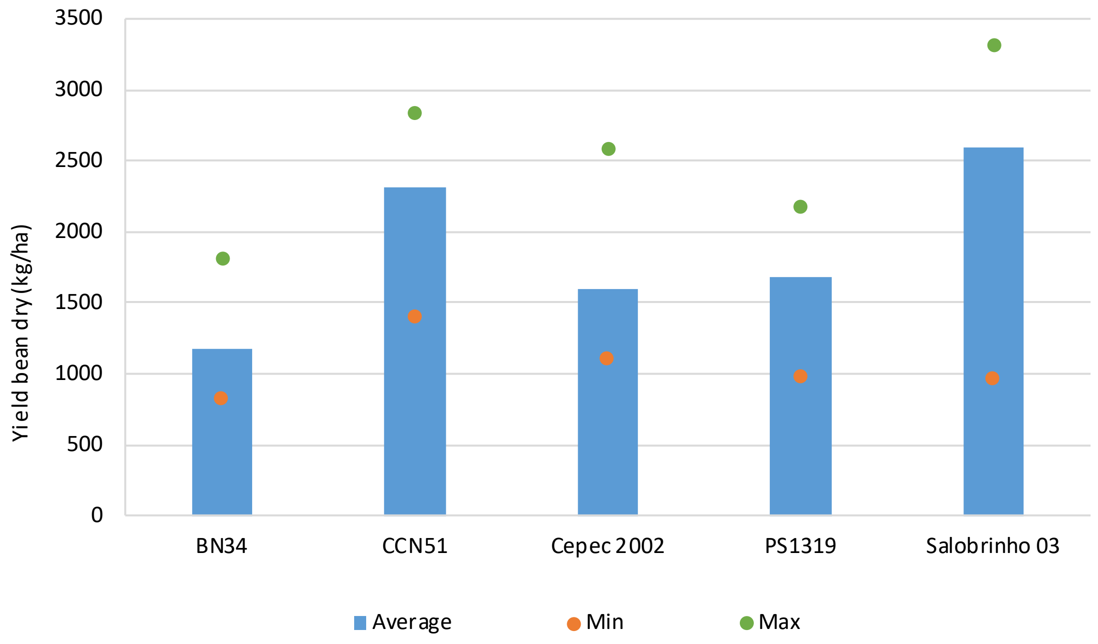

Figure 47: Dry bean yield (kg/ha) of 5 different varieties in Juazeiro from October 2017 to September 2018. (Average of 4 plots with 10 trees each).

Figure 48 shows all harvests over the years 2017 and 2018, with many little ones occurring during the year. The most important harvests took place in the month of Nov/Jan. This is in accordance to the known harvest periods in humid regions and goes in line with the ongoing flowering and fruit setting process of the plants (see 6.5). Performing so many small harvests is extremely labour intensive and therefore expensive. Solutions have to be found to better manage the trees and decrease the number of harvests, leading to more distinct periods of fruit setting and harvests. Knowing the right time to ripe the fruit is not as easy as it seems, each variety has specific characteristics that indicate the right time to harvest through their colour and sound indicated by knocking on the fruit.

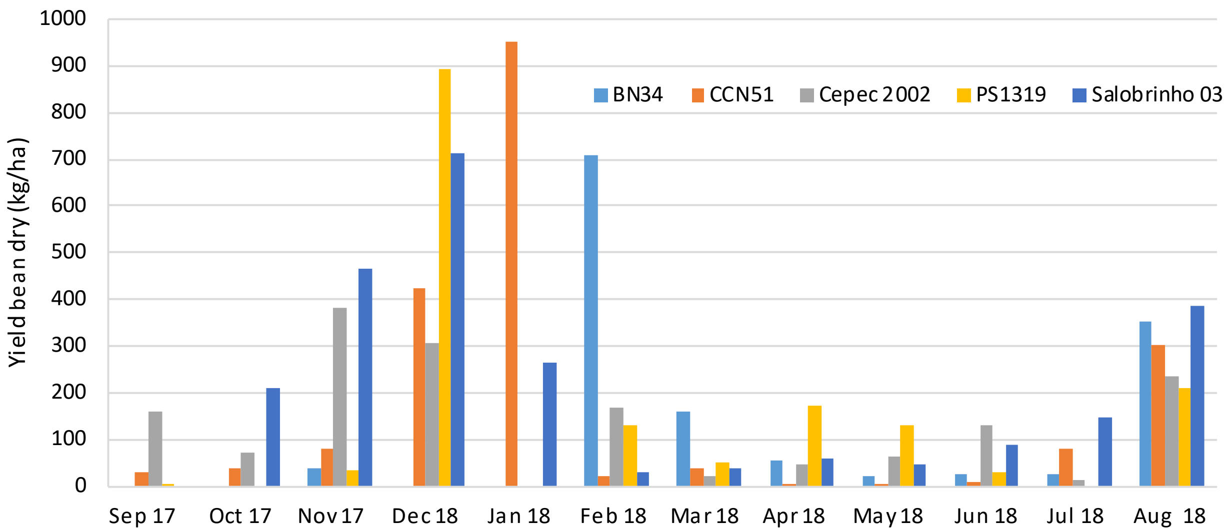

Figure 48: Single harvests and their yield (kg/ha) in Juazeiro in 2017 and 2018.

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7 Future cropping systems for Cocoa

The knowledge discussed in the previous chapters was obtained through field data, experience and literature review. This chapter will share the knowledge of our team. For apple plantations, several cultivation procedures have been developed and proven efficient. These procedures can be applied to Cocoa crops in order to improve the structure and management of the plantation. Some potential improvements include:

- Increasing planting densities to improve the efficiency of the production system.
- Smaller and standardized trees to facilitate the work of pruning and harvest.
- Reduced application of plant protection products by a better penetration of small trees compared to large ones.
- Decreasing the occurrence of fungal pests due to smaller plants drying quicker after rainfall than large ones.
- Usage of clones instead of seed plants: As juvenile plants are traditionally grafted on seedlings, the heterogeneity of the trees is high, hindering an efficient management of the plantations. So far, cloned and dwarfing rootstock, which result in more homogenous plants, have not been implemented in the production of Cocoa.

These aspects point out the great potential for improving Cocoa cropping technologies that could be exploited in the future.

7.1 Semi-intensive cropping systems

The density of semi-intensive cropping systems ranging between 1000 and 1300 trees/ha is based on a training method such as described in Figure 53. Their open shape offers several advantages:

- High light interception (Figure 53B)).
- Training and pruning being affected in such a manner that the crown heights remain under control (generally around 3.0 m).
- Rational use of a relative high vigour, the growth potential being distributed among several primary structures, also called scaffold branches.

However, this canopy configuration offers only limited opportunities for densification.

7.1.1 Training young trees

The length of the graft (blue circle in Figure 49A)) influences the number of new shoots. If 3 or 4 shoots of similar vigour develop regularly around the trunk, they will form the future primary structure. In Figure 49A), 6 buds produced 6 lateral shoots of unequal vigour, thus only 2 of them (4 and 5) can be used to form the basic structure of the tree. Shoot 6 develops almost vertically, which would boost its vigour and produce an unbalanced crown. In contrast, shoots 1-3 grow almost horizontally and thus would produce poor structures. Furthermore, due to the opposite phyllotaxy, all shoots develop in the same vertical plane (1, 3 and 5 on the right and 2, 4 and 6 on the left).

Figure 49B) demonstrates a relative uncommon case where at least 3 (maybe 4) well balanced and well oriented shoots can be used to form the primary structure as shown on Figure 49C). Contrarily, Figure 50A) illustrates a very common case with 2 buds (at the distal end of the graft) growing vigorously and thus themselves producing many strong laterals. Pruning as displayed in Figure 50A) allows forming a balanced base structure such as presented in Figure 50B). In Figure 51A), the graft (blue circle) produced only 1 vigorous vertical stem which developed 3 lateral shoots.

After pruning (Figure 51B/C)), 3 relatively well oriented shoots remain. The weakest, being in apical position has a good chance of catching up its delayed development.

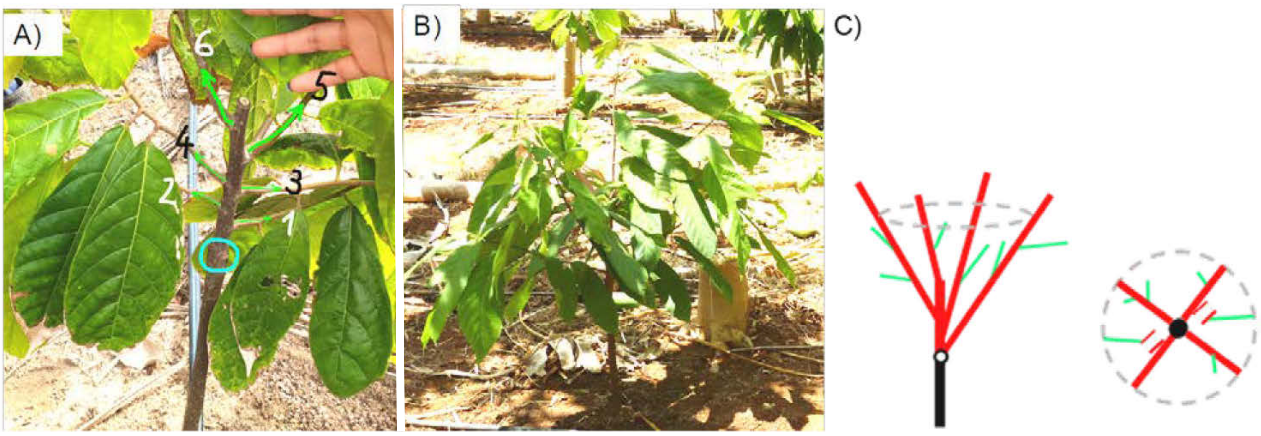

Figure 49: Training of young trees just after their initial growth in the orchard. To obtain a classical "vase shape" based on 3-4 main structures.

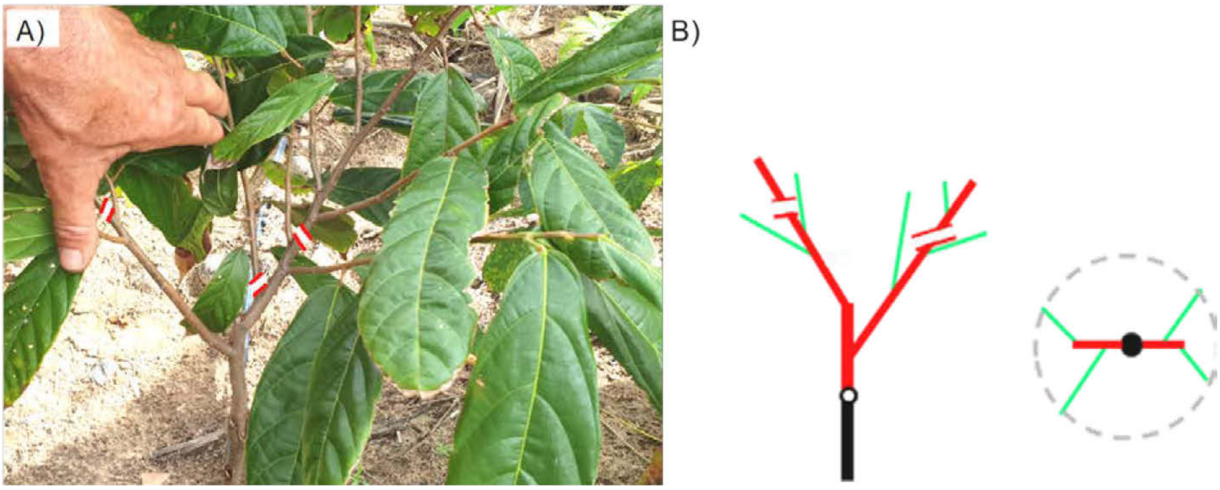

Figure 50: A very common case with 2 buds growing vigorously and thus themselves producing many strong laterals.

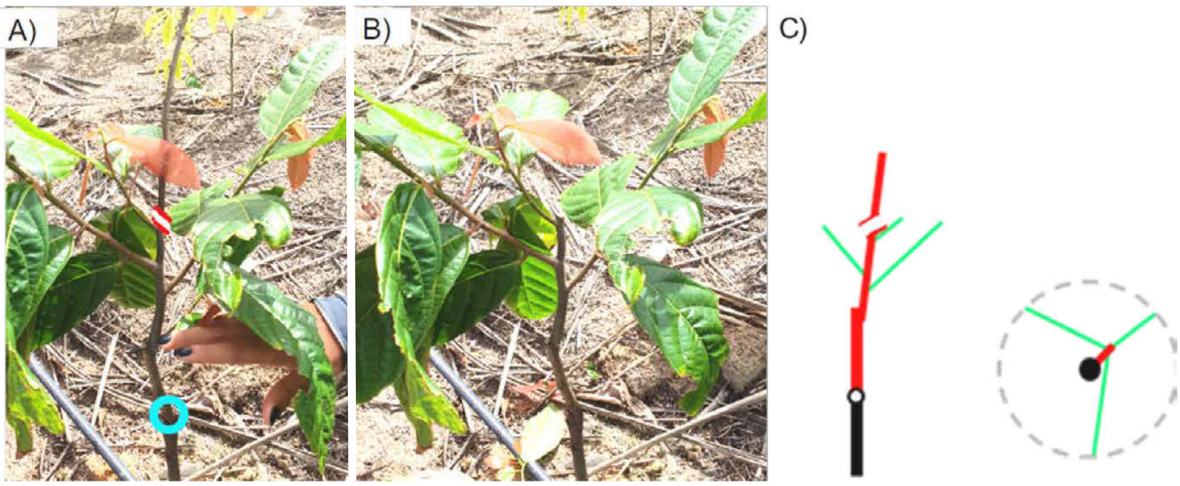

Figure 51: Only 1 vigorous vertical stem which developed 3 lateral shoots initial training must be adapted to the wide diversity of plantlet morphology due to non-standardized pre-shaping at the nursery.

7.1.2 Controlling adequate branching

The ability to induce sufficient branching in order to obtain a good primary structure depends on the variety. For instance, PS1319 and BN34 generally produce enough lateral shoots for the training of the tree, while CCN51 offers less possibility to build a balanced base structure. Pruning young shoots is an efficient way to induce lateral vegetative reaction in case of insufficient ramification. Figure 52A) shows the result following the pruning of the main shoot. Selecting the adequate lateral shoots according to their respective growth angle and vigour offers the possibility to form many branches (generally 2) from the primary shoot. It is even possible to achieve new vegetative reaction by shortening branches of a certain age Figure 52B).

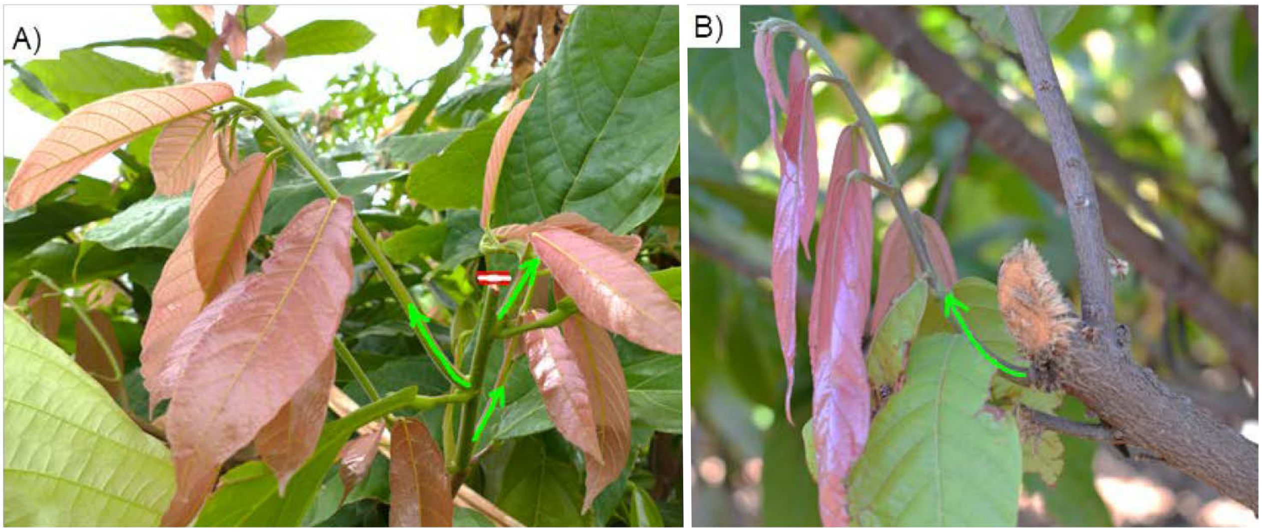

Figure 52: Shortening shoots (A) or branches (B) is often useful to obtain the adequate branching during the shaping phase of young trees.

7.1.3 Apple tree shape models

In apple cropping systems with same tree density and rootstock, tree shape strongly influences productivity (Henriot and Monney 2003). Vertical narrow trees (Figure 53A)) compared to V-shaped trees (Figure 53B)) intercepted less photosynthetically active radiation (respectively 32 and 48 %). Their leaf area index was also lower (- 44 %) which resulted in lower productivity (- 21 %) during the entire production period (7th to 11th planting year).

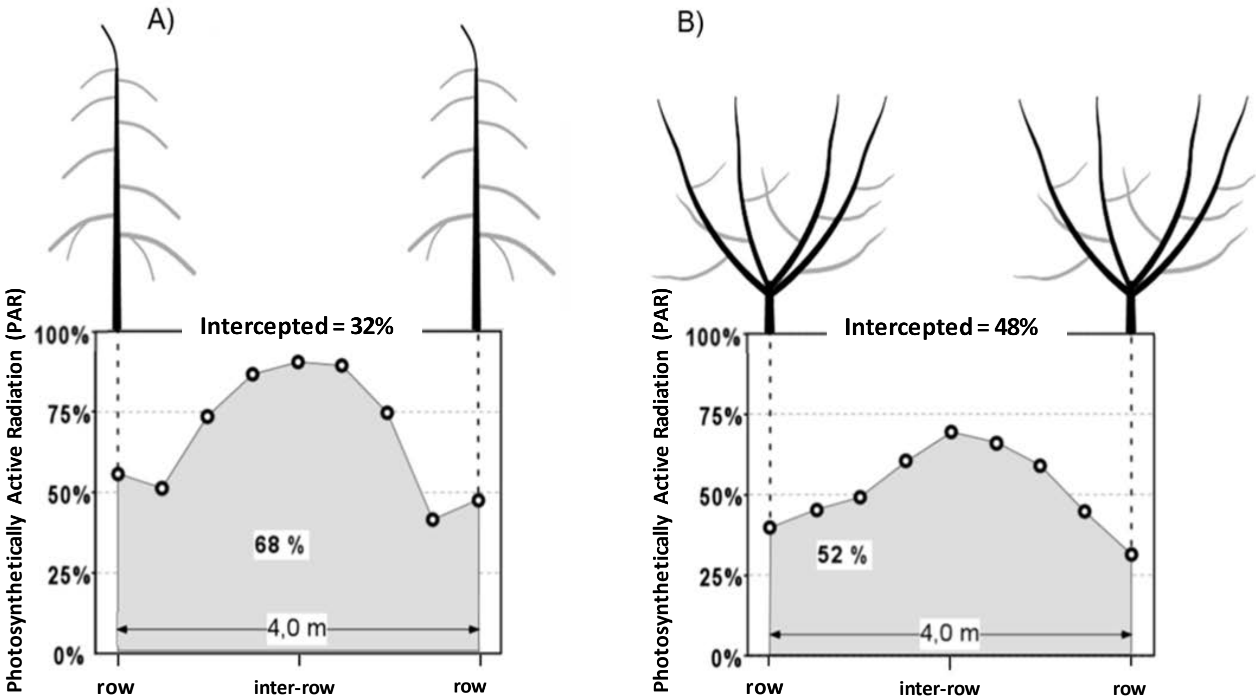

Figure 53: Photosynthetically Active Radiation (PAR) measured under the canopies of a single stem vertical shape A) and a V-shaped training system B). Intercepted PAR is the difference between available total (100 %) and average measured every 50 cm on a line perpendicular to the tree rows during a 24-hour period.

7.1.4 Application to Cocoa according to growth habit

In the experiments carried out on the farm in Juazeiro, the cropping system for all varieties was the same. It is based on the scheme as presented in Figure 53 with a tree density of 1250 trees/ha (interval of 4 m between rows and 2 m on the row). This shape is often called “vase”. The tree structure is based on primary branches (black lines) and secondary elements (grey lines), the formers being subordinated to the latter’s. In reality, some secondary structures are often trained as primary structures to compensate the insufficient branching of certain individuals. This is the case for the branches 3 and 4 in picture Figure 54A) which grew as laterals of the 2 main stems 1 and 2. Nevertheless, the tree shows quite a well-balanced structure with a high light interception rate. In contrast, the tree in Figure 54B) has a much lower ability to intercept light energy.
The variety BN34 displayed in Figure 54C) has a spreading growth, which tends to expose fruits to direct sunlight. The lack of vigour limits the emergence of shoots in the middle of the crown that would form a protective shield. PS1319 (Figure 54D)) shows a similar growth habit but its high vigour leads to the formation of a more compact canopy, which prevents the fruits from being damaged by direct sunlight. However, the spreading habit becomes an obstacle for mechanization and labour efficiency, especially fruit harvest.

In the Juazeiro farm, the lower area of the trees has remained congested by a too large number of small branches for a long time. Figure 54E) visualizes the result of manual pruning that allowed relieving the fruiting zones. The vegetation of the upper canopy areas is sufficiently dense to prevent sunburn of fruits. Mechanical pruning has recently been introduced. In a CP49 plot with open shaped vigorous trees, mechanical pruning has proved to be an efficient way to restore enough space for the free movement of mechanization and labour force (Figure 54F)). Manual pruning would have been more precise, but at a much higher labour cost.

Figure 54: Once the initial shaping is completed, adequate pruning is applied taking the phenotypic characteristics into account.

7.1.5 The challenge of the trees main structure

Poor branching is a common situation with some varieties, especially CCN51. It results in an insufficient number of primary structures (Figure 55A)) and thus, poor light interception, but also a lower production potential since fruit yields largely depend on the cumulated length per tree of strong branches that support the fruits. In contrast, the tree in Figure 55B) obviously presents a better bearing capacity. As a reaction to insufficient branching in the early development stage, many trees produce an excessive ramification in the upper part of the crown Figure 55C), which results in a non-optimal tree shape.
The variety PS1319 illustrates that the number of branches determine the potential yield of the tree as shown in Figure 55D). However, a lower number of branches Figure 55E) improves the manpower efficiency at harvest and pruning and reduces the risk of forming a humid microclimate in the middle of the tree which favours fruit diseases. Figure 55F/G) illustrate that excessive branching may result in poor shape (excessive layering and proliferation of branching in the upper layer respectively). This could be avoided through better attention in the early training stage (Figure 55F)) and pruning in the later phase (Figure 55C/G)).

Figure 55: To maintain or restore an adequate structure, congested areas of the crowns must be cleared by removing excess or improperly positioned branches.

7.2 The model of apple training

The performance of apple cropping systems has considerably increased over the past 50 years. This is due to the adoption of the central axis shape on M9 rootstock at tree densities of 2000 to 4000 trees/ha by most growers in Western Europe and the high quality of plant material provided by specialized nurseries (Figure 56 and Figure 57).

Figure 56: Apple trees during their first growing season. Lateral shoots that developed in the nursery are ready to bear fruits next year. Almost no pruning is needed after the 1st growing season as the final tree shape is already determined during the nursery training process. The yield in the 2nd year is generally between 5 and 8 kg/tree, which corresponds roughly to 15'000 kg/ha at a tree density of 2500 trees/ha.

Figure 57: Apple tree structure based on 2 main branches (left), thanks to V-shaped conception, the double stem was able to produce high quality and very high yields with 2000-2500 trees/ha (right).

Following the achievements within apple plantations, we aimed to implement the same basic idea within Cocoa plantations. Most young Cocoa trees develop their main structure from 2 initial shoots and due to lack of selection, lateral shoots that derive from the 2 main branches develop in free spaces, resulting in very heterogeneous tree crowns. The 2 main branches are equivalent in strength while the others show much heterogeneity.

7.3 Possible future plantation designs and tree architectures

The design of the orchards determines their productivity and efficiency in terms of yield, labour and plant protection. As growing Cocoa is very labour intensive, high attention has to be attributed to the choice of future orchard design.

The goals of new designs are:

- Good and regular exploitation of sunlight and self-protection of plants to an excessive exposure to sunlight and consequently leading to higher and more regular yields.
- Ease the work for pruning and harvest (good accessibility).
- Efficient application of plant protection products.

According to our experience, Cocoa trees usually formed two main stems by themselves, which could present a first approach for future tree architecture (Figure 58).

Design with 2 main branches **1 main branch**

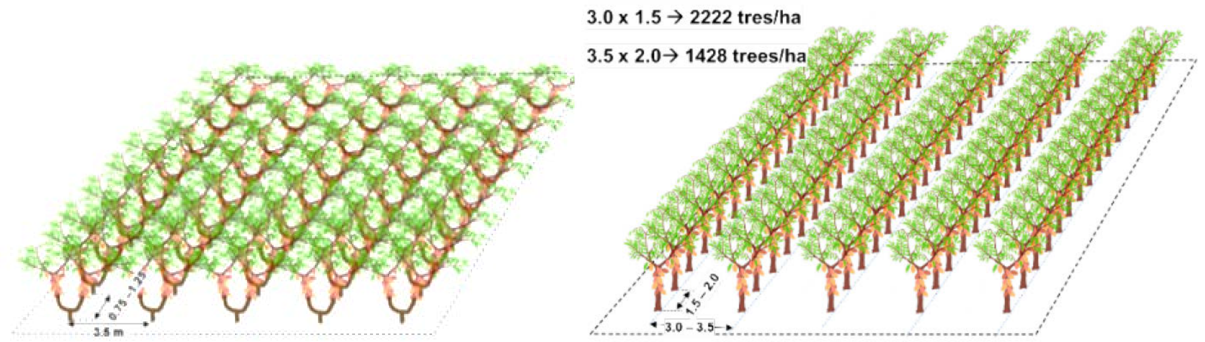

Figure 58: Design of Cocoa plantations built with trees with one or two main stems.

According to the experiences in Brazil ideal tree densities seem to be around 2000 trees/ha. So double stemmed trees could be planted at 3.5 m (distance between rows) x 1.5 m (distance in the row) which will result in 1904 trees/ha. These field observations are in agreement with the simulations made with Cocoa crop model “CocoaFlo” (Audrey E. and Lecoeur J. in prep.) (Figure 59).

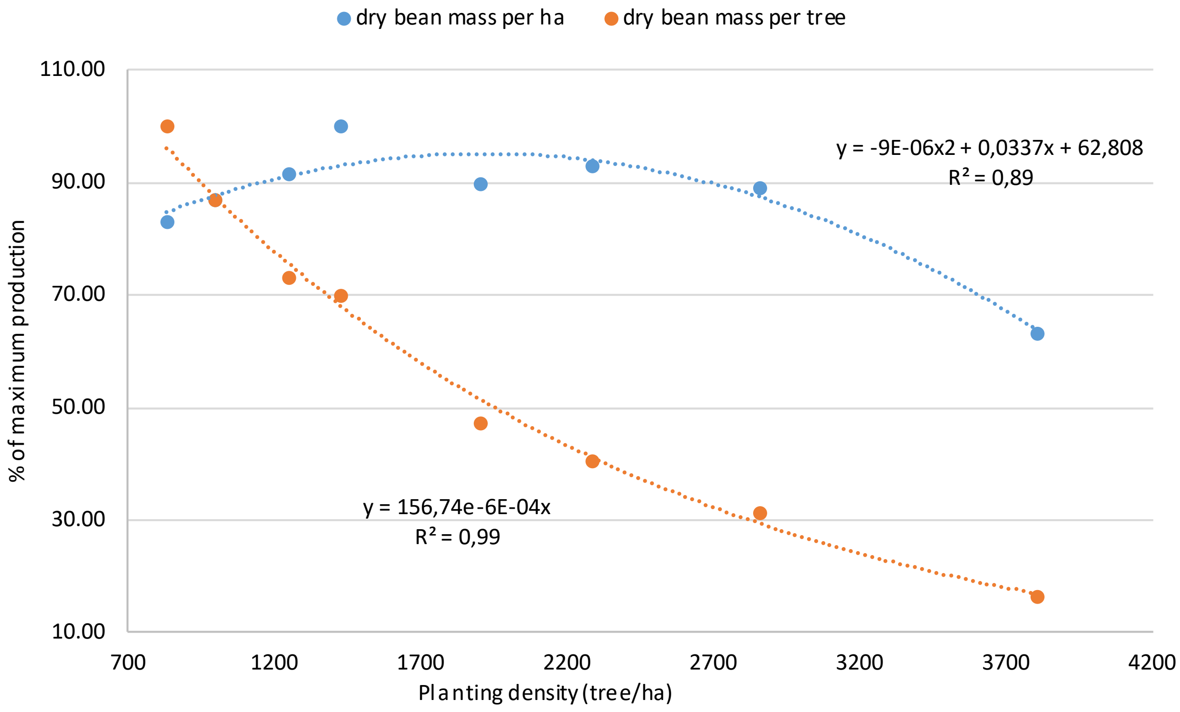

Figure 59: Predicted effect of Cocoa planting density on dry bean production at tree and orchard level.

Actual varieties planted on the common rootstock “Parazinho” show a vigorous growth. Even with a density of 1200 trees/ha, trees of cultivars such as CCN51 or Salobrinho 03 closed the rows after 2-4 years. This clearly shows the limitation of densification with the actually available rootstocks and cultivars.

Other plantation models, such as high-density plantations of trees with one main branch, are possible. However, currently their efficiency is unknown.

Due to the natural behaviour of its development the tree architecture has to be determined in the nursery. No plantation of poorly preformed trees should take place. Nowadays, it takes between 4 to 5 months to prepare the rootstock. After being planted, the seedlings need to remain in the nursery between 30 and 50 days. Instead of keeping the seedlings in small containers in the nursery for only 2 months, they shall be raised there for about 5 months prior planting them in the field. To do so, a bigger container is necessary for proper development of the root system and plants need to be replanted in containers of about 5 liters (Figure 60). First experiences have shown very good results by keeping plants in the nursery for a longer period.

Figure 60: Small containers (left) are suited to keep plants for about 2 months. Afterwards they need to be planted in containers of 3-5 litres (right).

Nurturing the seedling at the nursery for a longer time period does result in increased costs and practitioners do suggest that plant’s soil contact develops better in the field, although the latter has already been falsified. Nevertheless, it will be more advantageous to have a stronger seedling (Figure 61, Figure 62 and Figure 63) with a preformed architecture than a weak, non-preselected seedling (Figure 63).Tree shapes are described in Figure 63.

Figure 61: Tree with two main branches trained in the nursery.

Figure 62: Trees with one, two and multiple branches in Macacos, Ceará – Brazil planted with a density of 2200 trees/ha.

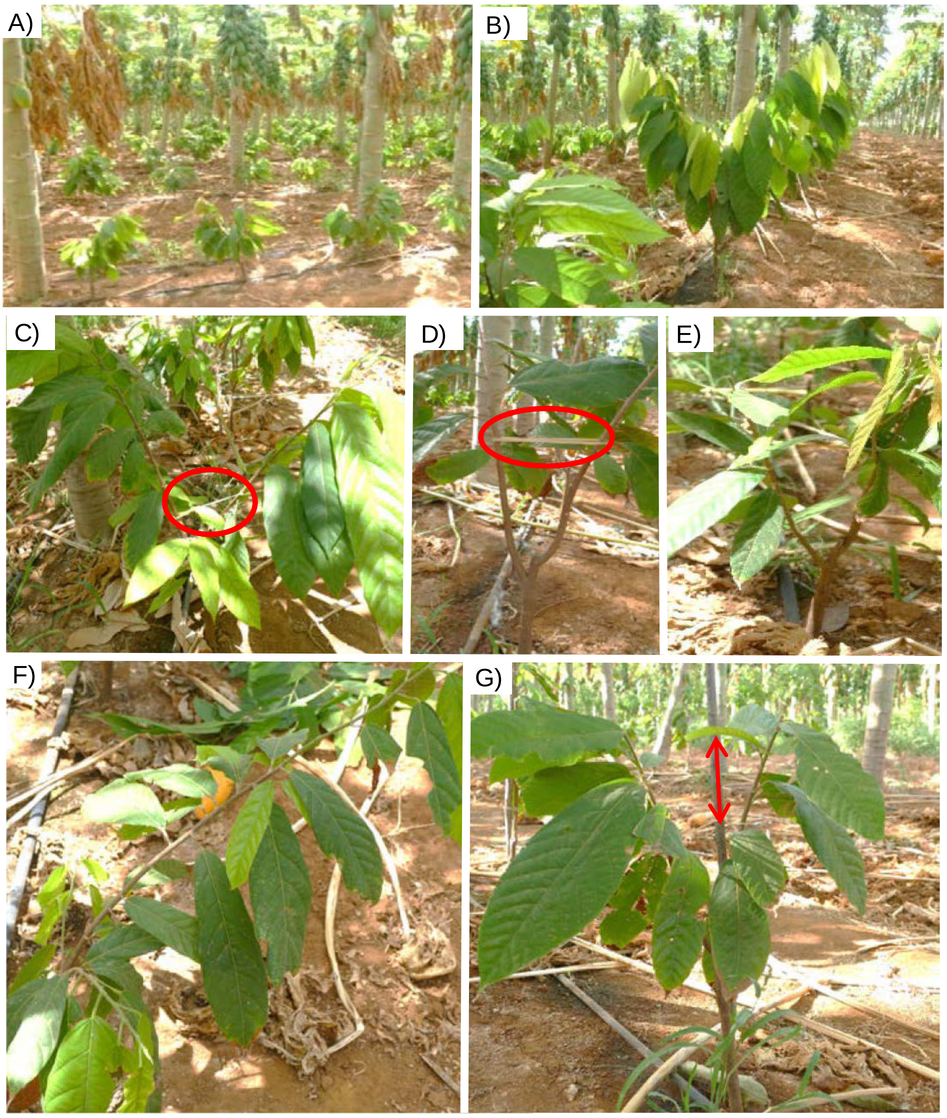

Figure 63: First experimental orchard with both tree shapes (double and single stem, respect. A) - E) and F) - G) at different planting densities, i.e. 1420 - 2850 trees/ha. Papaya shading resulted in an optimal light microclimate A) and good overall management resulted in fairly homogeneous initial growth. Differences in tree habit according to cultivars required adapted pruning and support to initiate the shaping of balanced primary structures. Some plants produced 2 elements naturally well balanced with the right angle B) while others needed to be supported with a rubber band (red circle) C). Pruning and supporting both young shoots (red circle) D) was sometimes necessary to avoid extreme bending. Although young Cocoa trees generally produced shoots with equivalent vigour when their number did not exceed 2, it was not easy to find the right solution in case of unequal vigour such as in picture E). Most plantlets intended to be trained as single stem trees don't grow the adapted vertical direction F) and required pruning and support by a little wooden stake (red arrow) G).

7.4 Protection of young trees from excessive sunlight

Young trees are sensitive to direct sunlight especially in combination with an exposure to wind, high temperatures and low air humidity. Several field tests in the semi-arid climate showed, that trees have to be well protected during the first two growing years. After two years, the plants reached their adult status and are able to build a layer of leaves for self-shading. Papaya (*Carica papaya*) seems to be a well suited crop for shading in the first two years. It's long stem and the umbrella-like crown creates an ideal shadow for young Cocoa plants (Figure 64). As shown, planting papaya about 50 cm outside the row of Cocoa with a planting distance in the papaya row of 1-3 m works well. Shading is also possible using bananas (*Musa acuminata*) or cassava (*Manihot esculenta*). In the case of banana the control of these strong growing plants as well as their removal may be challenging. To facilitate their removal, banana should be planted outside the Cocoa row. This also makes repeated cutting by hand or by means of mulching machines possible. A distance of 3 m between the banana trees is recommended.
The combination of two crops can result in extra income and in some cases favour the protection of the environment.

Advantages of Papaya:

- Rapid growth.
- Planting 2 months before Cocoa seedlings.
- Life cycle of 2 to 3 years.
- Consumes less water than other temporary crops.
- Easy removal.
- Creates a very nice shadow.

Disadvantages of Papaya:

- Sensitivity to viruses.

Advantages of Banana:

- Rapid growth.
- Planting 4 months before Cocoa seedlings.
- Life semi-perennials.

Disadvantages of Banana:

- Difficult to keep under control and to remove.
- Competition for water and nutrients.

Figure 64: Papaya and banana can be used to provide shade for young trees. Instead of a double row such as in the image, a single row of banana is sufficient to protect Cocoa.

8 Digital innovation for knowledge creation and decision support in agriculture

To date, hardly any crop or environmental data is used for the management of Cocoa. Quantifying the plants growing conditions and behaviour will enable a much better refinement of the cropping system. Sensor networks provide the potential to improve future cropping systems.

8.1 Agronomeet – cloud based platform for precision agriculture

To serve the requirements of the Cocoa trials and allow future commercial application by the farmers, the project partner EnvEve SA developed a novel cloud-based digital platform: Agronomeet. Today, Agronomeet is a state-of-the-art agricultural management system, used and validated by many customers. This learning showcase offers insight into an agricultural cropping system and unlocks its potential, for instance with regard to pest control and disease prediction or irrigation modelling. Agronomeet is a cloud software available as web interface and APP on Google Play. Different users (cooperatives, agriculture extension services, farmers, agronomists, agri-researchers, agri-experts, corporate users) can upload their data onto the Agronomeet cloud to store, process, share agronomic data, and receive decision support.
Agronomeet is interoperable with any Internet of Things sensor or weather station. By combining advanced crop, irrigation and pest models, Agronomeet is designed to attract researchers and agronomists to use Agronomeet as a platform for modelling and integrated data processing within their own projects. Beside farmers, these experts are an important pillar for the adoption of Agronomeet. The two showcases pest management of apples and the automated irrigation system for Cocoa are the commercially available outcome of Agronomeet, which is easily extendable to any other crop.

8.2 Sensor systems – integrating hardware and “human sensors”

Interoperability of the Agronomeet digital platform, meaning easy integration of different sensor types and brands, allowed creating fully integrated data sets at reasonable costs. Existing infrastructure was integrated in a short time. Subsequently, the following sensors (Table 3) were installed at the various test locations and integrated in the digital platform Agronomeet.

Table 3: Sensors used for monitoring the Cocoa field in Juazeiro.

Sensor	**Parameter**
Sensirion SHT75, Sensirion, Stäfa, CH	Temperature and air humidity
Apogee SP212, Apogee, Logan, USA	Pyranometer, solar radiation
Davis 6410 Anemometer, Davis, Hayard, USA	Wind speed and direction
Watermark, Irrometer, Riverside, USA	Soil moisture content
Megatron, MSLPT 25, Megatron, Allinges, FR	Dendrometer, stem diameter
Arad SF15, Arad, Dalia, IR	Flow meter for Irrigation water
Solenoides, Arad	Electrical valve to control irrigation
DavisRain DS3_, SB104-0, Rain Collector, Hayard, USA	Rain quantity (mm)

In addition, data were collected manually via an easy to use APP, working with an offline option, also feeding into the single digital platform. This manually collected data is considered as “human sensor” data, which perfectly complements the automatically captured data from sensors installed within the cropping system (Figure 65 and Figure 66). It is possible to follow the growth of the plant with the use of the dendrometer sensor that sends the data to the cloud. Figure 67 shows an example, of how this kind of processed data can be viewed on the platform. Figure 68 further shows systems used for automatic irrigation.


Figure 65: Left: Weather station: Wind direction and speed, pluviometry, pyranometer, temperature and air humidity and RF-Antenna. Right: Modem and Internet connection.

Figure 66: Dendrometer Megatron (linear potentiometer, fixation constructed by Agroscope).

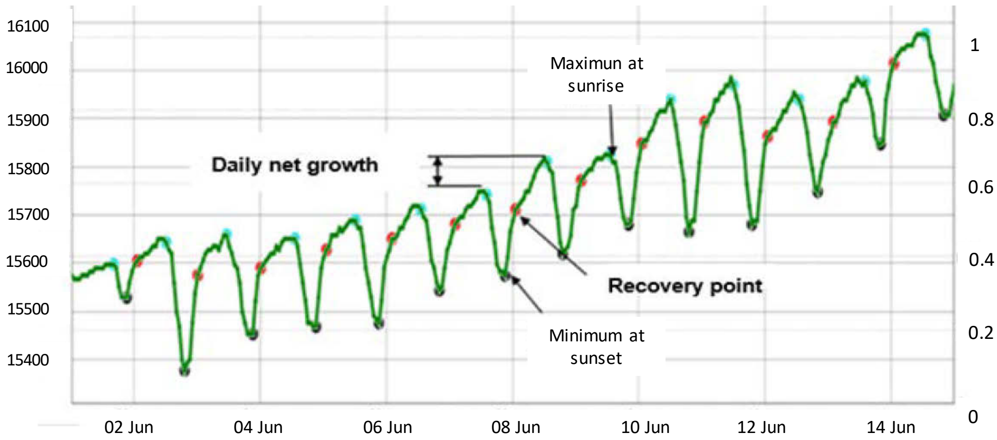

Figure 67: The graph provided by the platform highlights the crucial phases of the growth at scale of the day. The daily shrinkage is "blue" – "black" and the Daily Net Growth is "blue" – "blue of previous day".

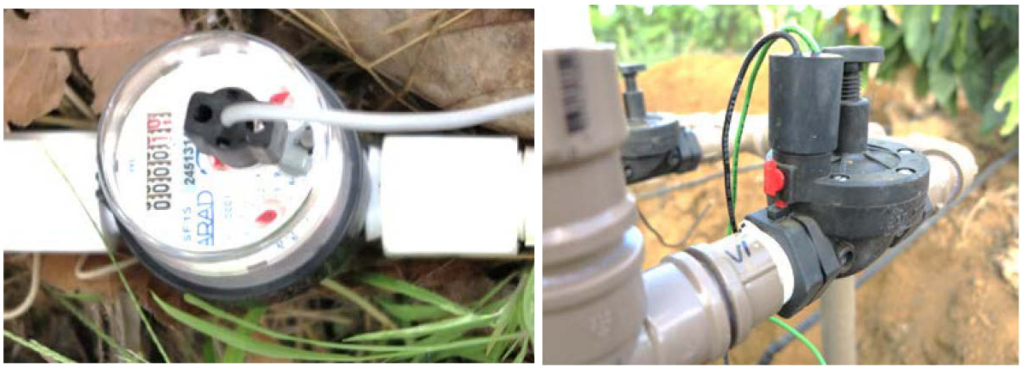

Figure 68: Flow meter and electric valves for automated irrigation.

8.3 Real-time data improve decision support, management and knowledge sharing

Plant behavioural insights gained through real-time digital data collection e.g. monitoring weather, soil moisture, plant growth and respiration have proven to be crucial for the improvement of Cocoa growing systems in the new growing context. Desktop and mobile applications offered access to crop performance at any time and provide the foundation for improvements of irrigation practices, saving great amounts of water and yield performance (Figure 69). Flow meters and solenoids were used to control and automate irrigation (Figure 68). Experiences during the three year project revealed, that this technology provided substantial potential to save water, as excess of water is visually not easy to recognize.

Dendrometers allow the measurement of stem growth and can indicate stresses of trees. They allowed an insight into the growth rhythms of the plant. As dendrometers are very sensitive and need a lot of maintenance, they are mainly used for research. Dendrometers still need further development for a broad use on farms. However, once handling and data analysis are more standardized, these tools provide the potential to optimize farm management.

Solid data output requires rigorous data validation before data series are created. For Agronomeet, the incoming heterogeneous data follow an automatized step by step process:

- Data gathering (field - Human or Sensor).
- Data upload to cloud.
- Raw data is generated and updated automatically.
- Agronomist can set automatic rules and plausibility checks to create the data series used and presented on Agronomeet. They can go back to the raw data at any time for individual plausibility checks.
- The data series is created from the raw data, using the filters set by the agronomist. If no filters are set, then the raw data will be equal to the corresponding data series.

Digital technologies can enable innovation in Agriculture. Agronomeet combines interoperability of sensors with advanced data analytics and modelling. The platform offers decision support and allows to share best practice knowledge of crop management. The current project demonstrates that automated monitoring of soil moisture and automation of irrigation allow to save a considerable amount of water, which is critical in semi-arid regions. This can prepare agronomic systems for droughts predicted with climate change. In addition, the project showed that combing different data sources (Figure 70), such as dendrometers, soil moisture and weather stations, analysed with machine learning methods, will allow for optimized crop management.

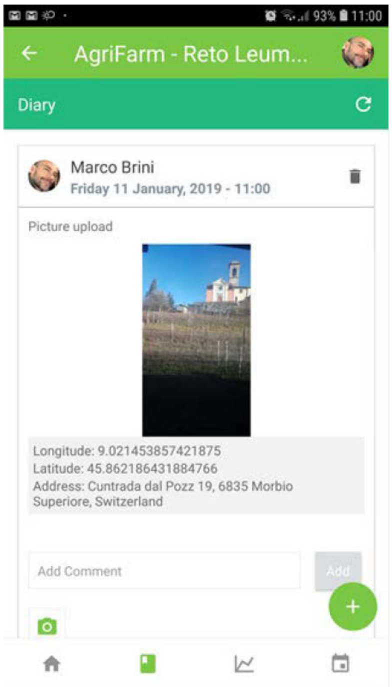

Figure 69: Offline function of Agronomeet smartphone app. 1. In the field without Internet connection data are downloaded to a smartphone by means of an app. 2. As soon as Internet connection is given again, the smartphone sends the data to the server.

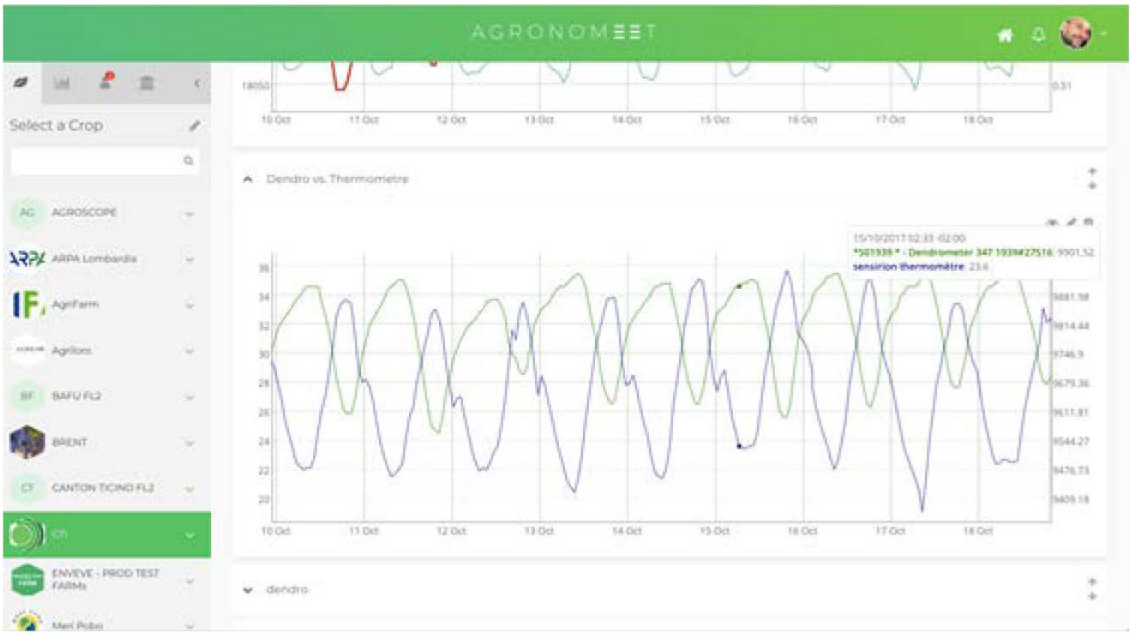

Figure 70: Agronomeet is a validated platform for digital agriculture providing real-time data collection and advanced analytics for decision support.

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10 Figures

11 List of tables

12 References

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