Smallholder oil palm: space for diversification?

WaNuLCAS model-based exploration of the environmental and economic impact of intercropping scenarios for Indonesian smallholders

MSc Thesis Plant Production Systems

Dienke Stomph
January 2017

WAGENINGEN
UNIVERSITY & RESEARCH

World
Agroforestry
Centre

Smallholder oil palm: space for diversification?

MSc Thesis Plant Production Systems

Name Student:	*Dienke Stomph*
Registration Number:	*930507808100*
Study:	*MSc Organic Agriculture – Specialization Agroecology*
Chair group:	*Plant Production Systems (PPS)*
Code Number:	*PPS-80436*
Date	*January, 2017*
Supervisors:	*Meine van Noordwijk* *Ni'matul Khasanah* *Tom Schut*
Examiner:	*Maja Slingerland*

Disclaimer: this thesis report is part of an education program and hence might still contain (minor) inaccuracies and errors.

Correct citation: Stomph, D., 2017, Smallholder oil palm: space for diversification?, MSc Thesis Wageningen University, 78 p.

Contact office.pp@wur.nl for access to data, models and scripts used for the analysis

ACKNOWLEDGEMENT

Firstly, I would like to express my sincere gratitude to supervisors Meine van Noordwijk and Ni'matul Khasanah for their continuous support, assisting me, challenging me and allowing for independence. I would also like to thank Tom Schut for his helpful remarks, which were of considerable support in improving the structure of this final report. Furthermore, the fruitful discussions with people in my close surroundings at Wageningen University and the World Agroforestry Centre scientists are gratefully acknowledged.

FOREWORD

This MSc. thesis report describes the model development and simulation of plot-level diversification scenarios for oil palm cultivation. The study zooms in to the Indonesian oil palm context, with as a focal point smallholders on Sumatra. The report first lists the research aim and objective. After which the contextual components of importance to this study are made explicit. The WaNuLCAS model (van Noordwijk & Lusiana, 1999) is used as a tool to explore these scenarios, with the required inputs and generated output. Then follows a section on the diversification scenarios and the indicators of interest to measure and compare the scenario outcomes. As a last section in the methods, the calibrations and modifications are described that were needed to equip the model to be suitable as an explorative tool. Results of the scenario simulations are summarized and discussed in a broader context of recent developments as well as the impact of this study on future developments.

ABSTRACT

This research aimed at challenging the assumption that oil palm is best suited to monoculture cultivation for smallholders in Indonesia, through a model-based exploration of the short- and long-term feasibility of a range of plot-level diversifications. The global palm oil production has increased over fourfold in the last two decades, by converting forests and agroforests into monocultures, under the assumption that monoculture oil palm cultivation is most productive. This deforestation caused biodiversity losses and environmental degradation and raised social, political and economic concerns. This study hypothesized that intercropping could serve as an integrative answer to several of these concerns. As intercropping can deliver agronomic, economic and environmental system improvements.

Intercropping was explored through simulation of five scenarios in the **Wa**ter, **Nu**trient and **L**ight **C**apture model for **A**groforestry **S**ystems (WaNuLCAS) model. The 5 crops included were: cacao, rubber, cassava, groundnut and mucuna as a cover crop. The scenarios were simulated for a 25-year period, for four typical Indonesian oil palm weather and soil conditions. The prices of the farm inputs (e.g. seedlings, labour, fertilizers) and produce were based on those recorded for the Indonesian context. The intercropping scenarios were compared to the monoculture oil palm simulation based on 4 productivity and 6 environmental performance indicators. The model output was generated at plot-level and therewith ignores interactions intercropping could have at farm- or landscape level.

The results showed that considerable economic and environmental system improvements can be achieved through intercropping. With the exception of returns to labour, all indicators showed that performance improvement was obtained. Compared to the monoculture, larger productivity per unit of land, and environmental performance improvements were predicted for all intercropping scenarios. Intercropping with cacao showed to obtain the largest net return to land, a 25% increase compared to the monoculture, and can serve as a risk coping strategy. Including annuals in the first years of oil palm cultivation resulted in the quickest investment recovery. Intercropping rubber performed poorly for the economic indicators, but achieved the largest environmental system improvement. It is therefore argued that diversification has a large potential to improve overall system performance at both plot- and landscape-level. To utilize this potential more insight in smallholders' interest in diversification and suitable incentives to support diversification adoption by smallholder is required.

Table of Contents

INTRODUCTION

The recent global boom in vegetable oil demand drives expansion of oil crop cultivation (Trostle, 2008). Oil palm (*Elaeis guineensis* Jacq.) is one of the main crops to satisfy the growing demand, for it has the highest vegetable oil yield per unit area and labour of all oil crops (Corley & Tinker, 2015; Sheil *et al.*, 2009). Indonesia has responded to this increased demand, turning 10 million ha into oil palm plantations (Direktorat Jenderal Perkebunan, 2015). Within a decade the country became world's largest palm oil producer, accounting for more than 50% of the global market share (FaoStat, 2016). The crops' high profitability can support economic prosperity of rural areas, giving formerly subsistence farmers the opportunity to obtain a substantial income (Belcher *et al.*, 2004). However, this rapid expansion, has not been without controversy, since the oil palm plantations replaced more diverse agroforestry systems and 56% of the expansion was planted after clearance of native forests (Casson, 2000; Basiron, 2007; Koh & Wilcove, 2008). More issues add to the controversy around palm oil production. A shift in farm practices from a diverse system, to a single crop system increases the vulnerability of rural communities, especially since global prices of palm oil have shown to be volatile (Vermeulen & Goad, 2006). Additionally, the currently promoted oil palm farming practices do not allow for intercropping of food crops, which former land uses did (Joshi *et al.*, 2000). Thus, the production of palm oil may come at the cost of farm and regional food security (Sheil *et al.*, 2009).

Additionally, oil palm plantations pose environmental threats, such as biodiversity losses and environmental issues arising from the increased uses of pesticides and fertilizers. The land clearing practices lead to soil quality degradation and related erosion and sedimentation damage (Sheil *et al.*, 2009).

Furthermore, the extent to which smallholders and local communities profit from conversion to oil palm is debated, and practices are disconnected from the local farming context (Casson, 2000; Potter, 2016). Growth of the oil palm industry accelerated with the involvement of large agribusinesses, which through governmental regulation and their established market positions, limited smallholder's independence and negotiation autonomy (Bissonnette, 2016). This large dependence is also due to the large-scale dominated character of Indonesia's palm oil processing industry, imposing smallholders to sell their fresh fruit bunches (FFB) to the single reachable mill (Potter, 2016; Vermeulen & Goad, 2006).

The current palm oil production system thus shows opportunities and pitfalls. In order to benefit from the opportunities oil palm as a crop has to offer, perceptive analyses have to be made on the trade-offs linked to the production. In the advocated production system, it is assumed that oil palm grows best in monoculture. However, it is this monoculture production system that causes the oil palm related issues listed above. Intercropping was coined as a strategy to alleviate similar dilemmas in other regions and showed able to achieve productivity increases and/or address environmental damages (i.a. Godoy & Bennett, 1991; Iijima *et al.* 2003; Yildirim & Guvenc, 2005). In oil palm main reasons underlying the assumption that oil palm performs best as a monoculture, such as easy mechanization, low labour demands, need for large yield to satisfy the processing capacity; are relevant to large agribusinesses, but to a lesser extent apply to the context of smallholders (Corley & Tinker, 2003; Potter, 2016).

Oil palm expansion may have originated from large scale plantations, but in the last two decades an increasing proportion of oil palm is managed by smallholders (Table 1). Smallholders tend to diversify their oil palm systems, however, an agronomic exploration of a range of diversified oil palm systems is missing, despite the current wave of oil palm research from a socio-economic and policy perspective (Drescher *et al.*, 2016; Gatto *et al.*, 2015a,b; Klasen *et al.*, 2016; Li, 2015; Cramb &

McCarthy, 2016). Therefore, gaining insight into which species are favourable to use as an intercrop, and establishing guidelines to support diversification decisions, can play a crucial role to safeguard economic and environmental prosperity, both at farm and regional level. With disappearance of traditional practices, the knowledge of managing these complex systems rapidly declines, thus support is needed (Deb *et al.*, 2009).

Table 1. Oil palm area (ha) by type of ownership in Indonesia, 1980–2010. Source: Direktorat Jenderal Perkebunan (2015).

Year	Smallholders	%	Government estate	%	Private estate	%	Total
1980	6,000	**2**	200,000	**69**	84,000	**29**	290,000
1990	291,338	**26**	372,246	**33**	463,093	**41**	1,126,667
2000	1,166,758	**28**	588,125	**14**	2,403,194	**58**	4,158,077
2010	3,387,257	**40**	631,520	**8**	4,366,617	**52**	8,385,394

Modelling provides a suitable tool to explore such agronomic options, as a model is able to synthesize and integrate experimental and conceptual understanding of a system (Matthews *et al.*, 2002). A model provides the opportunity to explore a wide range of scenarios, against low cost, within a limited timeframe (Mulia & Khasanah, 2012). Several models can be used for oil palm as monoculture crop (Hoffmann *et al.,* 2014; Khamis *et al.*, 2005), but do not allow intercropping. Models suited to explore intercropping include: CropSys (Stockle *et al.*, 1994), STICS (Brisson *et al.*, 1998), WaNuLCAS (van Noordwijk & Lusiana 1999) and the GroIMP modelling platform (appendixrueyer & Infomiatik, 2004).

WaNuLCAS, a model describing Water, Nutrient and Light Capture in Agroforestry Systems, was selected for this study. As it had the potential to combine oil palm with a wide range of annual and perennial intercrops in a realistic and most plausible way. The model required a number of modifications to strengthen the foundation for scenario exploration.

AIM & RELEVANCE

To this end the research aimed at challenging the assumption that oil palm is by definition a monoculture crop, by exploring the feasibility of intercropping options in oil-palm plantations. The specific objectives were to adapt WaNuLCAS to enable quantification of short- and long term effects of oil-palm intercropping and to compare five scenarios with respect to agronomic, environmental and socio-economic aspects. It is hypothesized that the productivity of oil palm cultivation can be improved through plot-level diversification, while maintaining or enhancing environmental performance.

The scenarios consisted of five realistic intercrop options: cacao, rubber, groundnut, cassava and mucuna (legume cover crop). These species represent a diverse range, in terms of agronomical performance and demand (e.g. profitability and light-, nutrient-, and labour requirements), while being available to the Indonesian smallholder. The model simulates plot-level performances of diversification. But in Indonesia smallholders manage an area of 3.4 million ha of oil palm. Their practices are thus also of relevance to larger spatial analysis scales.

Sumatra serves as the focal area for this study, as it is illustrative of general trends observed in Indonesia, but in its most widespread form (McCarthy & Cramb, 2009). The model simulations accounted for a range of four modelled environments, to represent part of the existing diversity in Indonesia's oil palm planting environments.

BACKGROUND

Sumatran oil palm context

The present oil palm production system is complex and is therefore best seen in its economic, environmental and socio-political context, as well as with consideration of precedent land-uses. Sumatra is taken as focal area for this analysis, because Sumatra is the main oil palm producing island of Indonesia, having 66% of the total oil palm area, and 81% of the area under smallholder production (Direktorat Jenderal Perkebunan, 2015; Potter, 2016).

The Sumatran environment

Sumatra is the most western island of the Malay Archipelago. It stretches from the northwest to southeast, with a latitude ranging from 5°51' N to 5°59' S, thus its midline is crossed by the equator. The entire island is classified as Af (equatorial, fully humid) according to the Köppen Climate Classification System (Kottek *et al.*, 2006). The majority of Sumatra is classified as 'wet' (>200mm/month) for more than 7 months per year, with less than two consecutive dry months (<100 mm/month). The most pronounced wet area is along the Island's west coast, here precipitation exceeds 400mm for at least two consecutive months. The very northern tip of the island, as well as the South-eastern part are distinguished by more pronounced dry seasons of 2-3 months, and are characterized as wet for less than 6 consecutive months (Oldeman *et al.*, 1978; Appendix 1).

As the sixth largest Island on earth Sumatra has a large diversity in soil types. A main distinction can be made by the division in mineral and peat soils. The peat soils are estimated to cover 25% of the island (Miettinen & Liew, 2010) and are mainly located alongside the east coast (Appendix 1). Currently the peat soils are subject to a large range of studies because of the large carbon stocks present, the risk of environmental damage by peat fires, and the complications for agricultural management. This study includes scenarios for mineral soils only because reports of oil palm performance on peat soils are scarce.

The island's forests are characterized by high floral and faunal biodiversity, containing over 10,000 plants species, 201 mammal species, and 580 avifauna species (Kementerian Kehutanan, 2003; Whitten *et al.,* 2000 in Margono *et al.*, 2012). However, this diversity is in decline (Wilcove & Koh 2010).

A landscape in transition

From early 20th century, at the time of the first transition, decrease of Sumatrans natural forest cover began (Therville *et al.*, 2011). This land cover change started by introduction of rubber seedlings by farmers into their swidden systems. Overtime systems evolved into 'jungle rubber': a productive system in terms of ecological functions, soil protection and water regulation, however at current monetary desires these systems decreasingly meet farmer's expectations. Stimulated by governmental efforts, some of these rubber agroforests have gradually been transformed to "improved" monoculture plantations (Joshi *et al.*., 2003). Since 1990 a new actor has gained ground, large agribusinesses, supported by the local and national authorities, have introduced various schemes to gain access to farmland. The majority of the land owned by these agribusinesses did not originate from land with prior cultivation, but from secondary or primary forest. This caused 40% of Sumatran's tropical forests to be cleared within two decades (Figure 1), of which most is replaced by large-scale monocultures of rubber, oil palm and *Acacia mangium Willd*. (Margono *et al.*, 2012; Therville *et al.*, 2011).

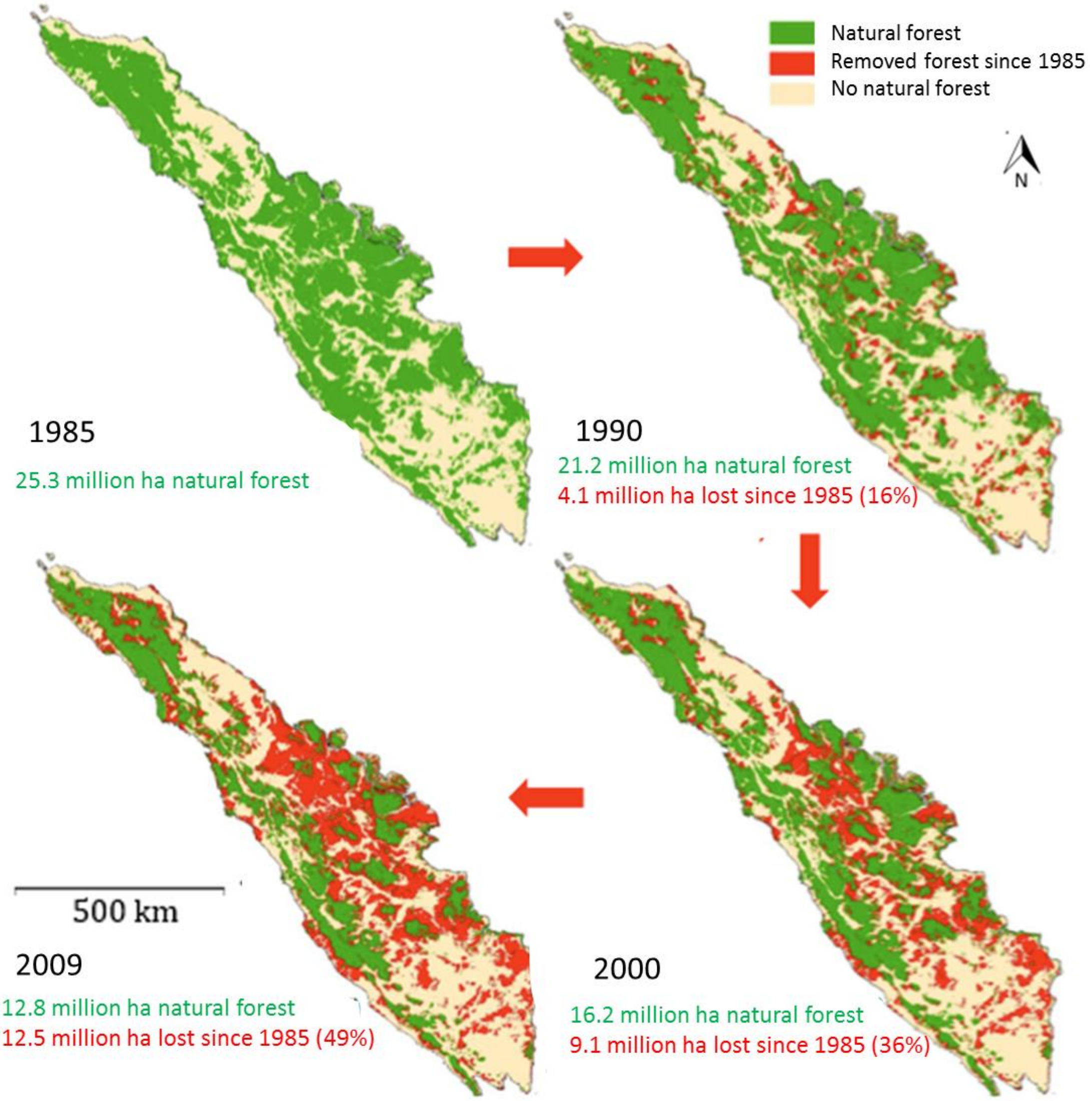


Figure 1: Four maps showing the declining forest cover of Sumatra from 1990-2010 (Margono et al., 2012).

The Sumatran smallholder

The Directorate Jenderal Perkebunan (2015), estimates that 2.2 million smallholder households are managing 4.6 million hectares of oil palm (Table 1). This illustrates the small average size, especially when compared to private estates, with sizes of 5,000 up to 50,000 ha. The group listed as smallholder is highly diverse in their level of dependence.

The first group of smallholders were those stimulated by Governmental and World Bank funded schemes (1978-1999), to become part of Nucleus Estates and Smallholders (NES). Within this group, various degrees of independence and working conditions exist, depending on the associated estate, and individual agreements between farmers and estates (Cramb & McCarthy, 2016). In 1995 these schemes were replaced by "*KKPA*" schemes (Primary Cooperative Credit for Members). This scheme is funded through private companies and therewith differs from the NES schemes. In both programs, generally, the smallholders are responsible for the quality of the management and resulting palm oil yield. However, their management practices are restricted to the procedures as defined by the estate.

Another group classified as smallholder is those in a 'joint-venture scheme' (JV). In such a JV, a company develops and manages a plantation on land owned by a farmer, in return the farmer receives an area based monthly rent (Cramb & McCarthy, 2016). This scheme is independent of governmental funding, however it is much assisted by the government through continued law-revisions, guarantying availability of land and length of tenure. For instance, in 2007, the Indonesian government reformulated their Plantation Law on investment (No. 25/2007) to change the initial plantation lease time to 60 years with possibility of further extension (Potter, 2016).

A third group of smallholders is classified as independent, meaning self-managed, self-funded, thus independent in terms of production. In terms of income, however, they often still dependent upon the willingness-to-buy and price-setting of a nearby plantation or mill (Cramb & McCarthy, 2016, Figure 2). About half of the Indonesian smallholders is independent (Potter, 2016). Recently, in major oil palm producing provinces as Riau and Jambi, these farmers, sometimes assisted by local NGO's, started to organize themselves into groups. This, in order to improve their negotiation position and access to inputs, knowledge and processing mills. The independent smallholders are mostly former rubber plantation and jungle rubber farmers. Once transport and processing infrastructures were in place, and rubber prices showed unreliable, smallholders were attracted to plant oil palm. Most of these smallholders are limited by investment capital and thus adopt a strategy of stepwise intensification to gradually intensify their production (Cramb & McCarthy, 2016; Rival & Levang, 2014).

Figure 2: For processing of their fresh fruit bunches smallholders depend on the presence and willingness of private mills or estate mills to buy their harvest. Which makes them dependent on haulers, as mills do not permit them to transport their own fruit (Potter, 2016). Picture by D. Stomph (2016).

Mis(sing)-information

Currently smallholders, especially those independent of larger estates, are less productive than private estates. A main driver is the lack of access to high-quality inputs, as with appropriate levels of access to inputs and infrastructure, farmers were able to reach comparable, and even higher yields than private estates (Cramb & McCarthy, 2016; Cramb & Sujang, 2013; Hartemink, 2005). Similarly, Molenaar *et al.* (2013) found that only 50 percent of the independent smallholders use hybrid planting material, which strongly decreases their yield potential. Additionally, the study mentions, that farmers located in remote areas face a main limitation of getting the palm fruit to the mill on time (within 48h after harvest, Corley & Tinker, 2003). The lower productivity is thus mainly resulting from differences in access, between private estates and smallholders. These access issues persist, as the current policy orientation continues to support expansion of large-scale agribusiness at the expense of smallholder systems, despite the promised political commitment to support smallholders and implementation of associated institutional reforms (Bissonnette, 2016).

Certification trend within smallholder context

Recently, research institutes and NGOs have become increasingly aware of socio-environmental damage resulting from the rapidly expanding oil palm sector. Through scientific and media reporting oil palm criticism continued to spread, which urged investigation of more sustainable palm oil production practices (Comte *et al.*, 2012; Rist *et al.*, 2010). Oil palm plantations often replaced landscapes which provided important ecosystem services. Plantations eliminated ecosystems characterized by their large carbon stocks and degraded biodiversity. Simultaneously, increasing the risk of flooding and degrading variety of rural food and income resources. Furthermore, the techniques used for land conversion have led to emission of large amounts of greenhouse gasses (Ivancic & Koh, 2016; Winarni & Sutrisno, 2014).

In response to these trends, the international non-profit 'Roundtable on Sustainable Palm Oil' (RSPO), developed a scheme in 2008, for Certified Sustainable Palm Oil (CSPO). With this certification RSPO aimed to limit environmental damage from cultivation practices and rainforest clearance for oil palm plantations. Within 7 years 18% of the global palm oil has been CSPO certified, including 9% that is produced by Indonesia (Roundtable on Sustainable Oil Palm, 2016). Nevertheless, the certification developments and the role of RSPO has been criticized, which drives re-consideration of sustainability standards and assessments. One of the critiques concerns the limited extent to which these programs reach out to smallholders (SNV, 2016). Achieving certification is complex and can be costly, which favours the large-scale plantations with access to knowledge and capital. Whereas in theory smallholders have a large potential to achieve certification because most smallholdings of oil palm are not farming on recently deforested land (Potter, 2016). The struggle by smallholders, to engage in sustainable practice program and access supportive funds, is increasingly recognized. Giving rise to new initiatives, such as the RSPO Smallholder Support Fund (RSSF) endorsed in 2013 (Roundtable on Sustainable Palm Oil, 2014).

The potential of sustainability initiatives to serve smallholders and explore sustainable practices, is recognized. Currently these initiatives are mainly seen to slowdown innovation and exploration of contextual farming practices by smallholders (Potter, 2016). The criteria of CSPO are strict and allow for little diversity in management. In order to include smallholders in sustainability programs the CSPO criteria should consider the unique characteristics of this farm type (Potter, 2016).

Smallholders and diversification

Indonesian smallholders have a long standing tradition in managing complex agroforestry systems and thus tend to experiment allowing other species considered valuable to be included into their system (Joshi *et al.*, 2000). This plot-level diversification is practiced through three main strategies: (i) a planned intercropping, planting based upon a determined pattern (Figure 3 a,b,c,d), (ii) secondary gap filling, where unforeseen spaces, resulting from i.a. underproductive planting material or suboptimal spacing, are filled by planting additional species (Figure 3 e), (iii) a strategy originating from rubber agroforests named '*sisipan*', can be seen as a third strategy (Box 1) (Figure 3 f). *Sisipan* is used as a rejuvenation strategy, replacing old trees (Joshi *et al.*, 2000). This study's scenario exploration only considers the first type of diversification, as this was most suited to be explored in the current model version.

BOX 1: *Sisipan (Joshi et al., 2000)*

Sisipan or interplanting into existing vegetation is a complement to *tanam*, with refers to planting after land clearing. *Sisipan* is used to describe transplanting of productive rubber seedlings to fill gaps or replace old trees in existing agroforests. This smallholder-developed strategy is increasingly adopted by farmers as a solution to the economic constraints associated with abrupt conversion. Independent smallholders are seen to incorporate this strategy in their oil palm management. Using it as a strategy to step-by-step convert from one crop to another by replacing individuals. With *sisipan* a permanent land cover is maintained, which would prevent environmental damages and fertility losses related to mechanical field-clearance and slash-and-burn techniques.

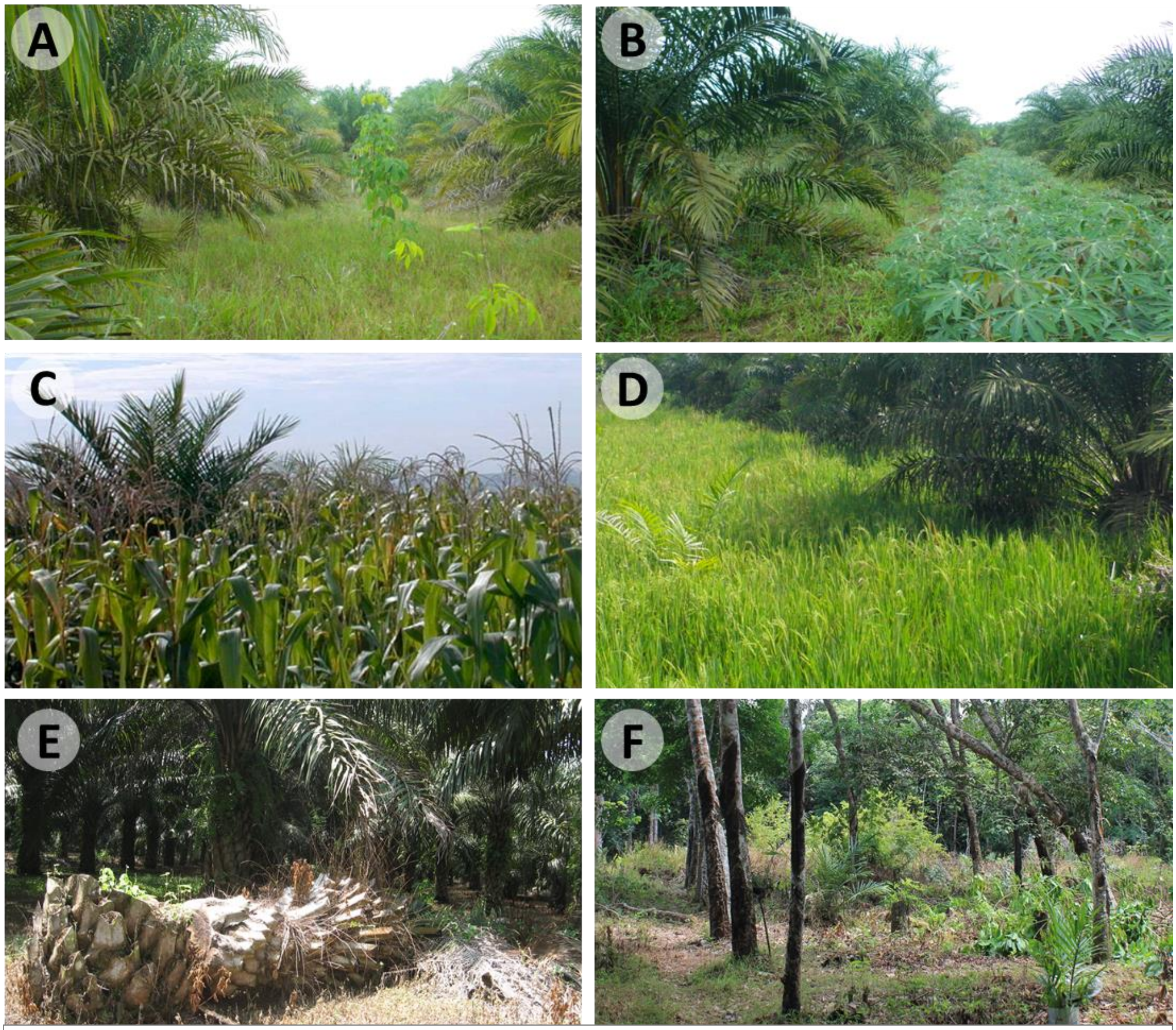


Figure 3: Field examples of diversified oil palm intercropped with: (a) young rubber; (b) cassava; (c) maize; (d) paddy rice; (e) diversification opportunity through 'secondary gap filling'; (f) *sisipan* strategy oil palm rubber system. Pictures by A:E) M. van Noordwijk, F) D. Stomph (2016).

Oil palm cultivation[1]

The oil palm is monoicous and therefore sex determination of its inflorescences is an important determinant of the number of fruit bunches. Meaning that the fruit yield level will decline when the ratio female:male inflorescences reduces. Cultivation of oil palm in less suitable climates can induce a lower ratio of female:male inflorescences (Adam *et al.*, 2011; Legros *et al.,* 2009a,b), mainly relating to a larger number of sequential dry days per year. These drought-induced occurrences of male inflorescences can potentially be alleviated by improved hydraulic lift. Recently, experiments have been laid out to explore the possibility of intercropping small trees, which do not compete for light, but with their roots may accommodate the palms' water uptake (M. van Noordwijk, personal communication, 26 January 2016).

---

[1] Additional description of the oil palm and its common management practices can be found in the appendix 2.

One of these is an ongoing study in Tome-Acu (Brazil) showing that, at least in the early years, intercropping trees with oil palm supports cultivation in areas with less suitable climates. By showing that the climate induced female:male ratio reduction, could be reversed through planting the palms in an intercrop with trees (M. van Noordwijk, personal communication, May 2016). The functionality of hydraulic lift and long term palm yield effects will need to be explored further, since questions remain regarding: the timespan for which this hydraulic lift functionality is beneficial and the suitable tree species and the environmental context required for the beneficial interaction to occur. The WaNuLCAS model is so far the only model known to have incorporated oil palm into an existing agroforestry model. The model is continuously improved in-line with data on oil palm performance in diversification experiments by education and research institutes (i.a. Göttingen University, Brawijaya University, World Agroforestry Centre).

Oil palm is generally grown at a 138 palms ha^{-1} density. Fertilizer is applied in a circle around the tree, this circle is generally kept free from weeds. The extent to which the surrounding soil is weeded varies largely per owner. In well-managed plots the first oil bunches can be harvested from 24 months after planting (Corley & Tinker, 2015; van Noordwijk *et al.*, 2016). Labour requirements for oil palm plantations are most intensive in the year of field preparation and planting. The following 25 years, main labour costs come from bunch harvesting, pruning, fertilization and weeding. Four years after planting a hectare of oil palm requires typically 40 person-days per year.

MATERIALS & METHODS

In this section the data used in the simulations and specifics of the WaNuLCAS model are described. Based on the model specifics and the Sumatran context, a range of sensible scenarios to be modelled are presented. Thereafter, follows a brief description of how the scenarios were translated into model input and which criteria were used to analyse the model output. In the final section, the model modifications that were required to prepare the model for the defined scenarios are listed.

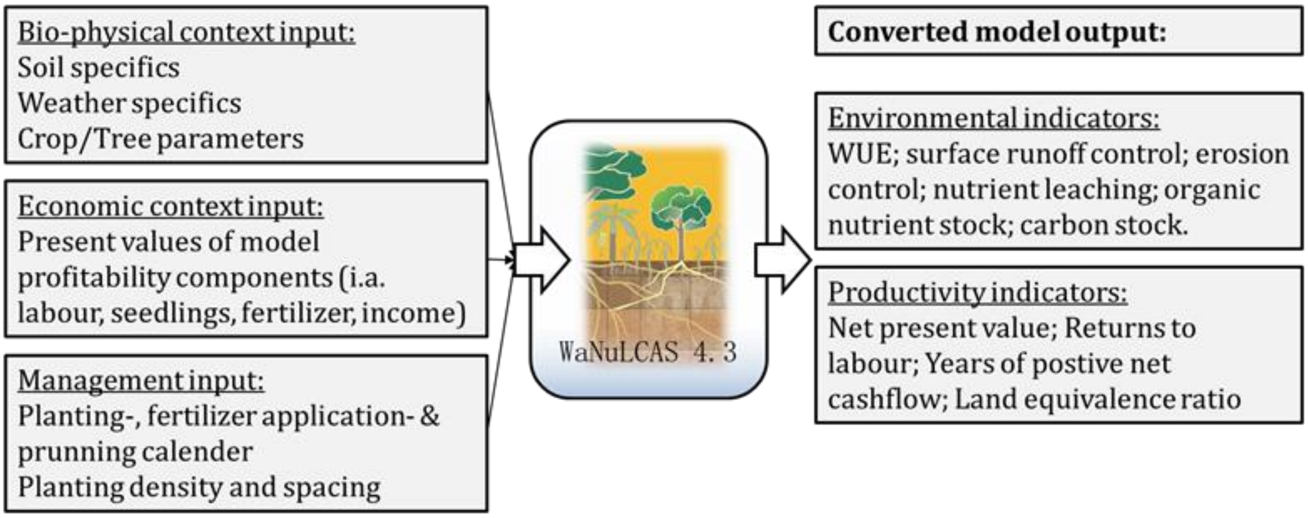


Figure 4: On the left-side the required bio-physical, economic and management inputs. On the right-side the generated and translated model outputs serving as environmental and productivity indicators to evaluate scenario performance.

Data input & model description

The version 4.3 of WaNuLCAS (van Noordwijk & Lusiana, 1999; van Noordwijk *et al.,* 2011) was used to analyse and explore agronomic options for diversification of oil palm production systems. The model is a generic model for water, nutrient and light capture in agroforestry systems. Through the integration of well-established modules (Appendix 3a) the model aims to predict complementarity and competition of plant-plant interactions. The model is able to analyse generic performance criteria for context specific data, therewith making quantitative predictions which were validated with the use of experiments (Appendix 4). The model lists a number of tree-soil-crop interactions, with a strong focus on their core relations (Appendix 3b). Figure 4 lists the required input and output components.

Model input for spatial field arrangement

To describe the below ground interactions the model distinguishes between four layers with a specified soil depth and four zones with a specified zone width (Figure 5). The same principle applies to the above ground interaction, the canopy shape and thus interaction is specified for four layers. Thus, both the belowground and aboveground interactions between the crop and tree species can be specified for each of the 16 cells (4 layers x 4 zones) below ground and above ground.

The model simulates a row-planting pattern for the trees, as well as for the crops. Within a row however, a number of different crop or tree species may be planted. For trees there is a maximum of three species which may alternate each other. For crops each zone has a maximum of five crop species which may alternate each other. The simulated field size is one hectare.

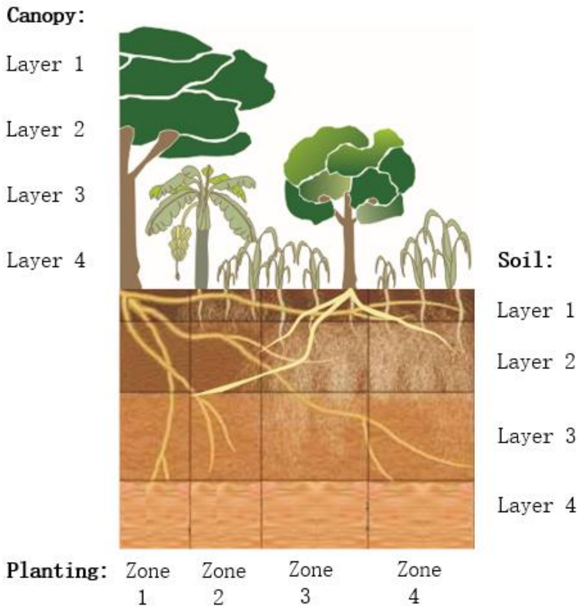


Figure 5: Configuration of the models planting zones, canopy layers and soil layers.

Parameterization

As a first step the model has to be parameterized for the specific climate and soil data. The daily weather data serving as a climate input are: rainfall, soil temperature and potential evapotranspiration. Data for parameterization were provided by colleagues from Brawijaya University working in South Sumatra, listed in Appendix 6. Soil conditions are considered to be typical for the lowland peneplain zone of Sumatra. The climate has the pronounced dry season typical of the southern quarter of Sumatra (see also Figure 2 in van Noordwijk *et al.*, 2016). The parameterization of the soil used the sampled physio-chemical soil characteristics: texture, bulk density, organic carbon content, pH and the CEC, which were included for each of the soil layers. Detailed description of the collection methods can be found Khasanah et al, (2015).

As described in the WaNuLCAS manual, from these soil characteristics the soil hydraulic properties could be obtained through the pedotransfer function for tropical soils by Hodnett & Tomasella (2002). These properties served to describe the relations between soil water content, pressure head and hydraulic conductivity on the basis of the van Genuchten equation (Genuchten, 1980). The saturated conductivity was used to calculate infiltration capacities of both soil types.

The initialization data of soil nutrient content was obtained through randomized field sampling, therefore the input of nutrient contents across zones were identical. The layer-specific nutrient content for the four soil layers was calculated, to represent the gradient in nutrient content with soil depth. The concentrations of mobile and sorbed P were calculated based on a two-surface Langmuir equation (Holford *et al.,* 1974).

Diversification scenarios

The selected diversification scenarios represent a range of management requirements, anticipated environmental and economic benefits resulting from the different crops and their interactions when grown in intercropping. Thus, the options for diversification in palm oil production included intercropping with perennials and/or, marketable, and/or non-marketable annuals, of which the latter was used as a cover crop (Table 2). Each of the scenarios where simulated for four soil and climatic conditions, determined by two soil types and two rainfall regimes (Appendix 6).

Table 2: The list of the simulated diversification scenarios and a brief characterization of crop type, planting densities, the fertilizer application and years of intercropping. The fertilizer application per palm in monoculture and intercrop were identical, therefore additional fertilizer, is the fertilizer specifically applied to the intercrop.

Scenario	Crop type	Intercrop species	Oil palm, tree density	Additional fertilizer: N, P	Years of intercrop
0	Control	-	138 | n.a.	No, no	0
1	Annual	Mucuna	138 | n.a.	No, no	4
2		Groundnut	138 | n.a.	No, yes	2.5
3		Cassava	138 | n.a.	Yes, yes	2
4	Perennial	Cacao	100 | 308	Yes, yes	25
5		Rubber	111 | 200	Yes, yes	25

Annual intercrops

Annual intercropping at normal palm densities is restricted to the first 2-3 years after palm planting, because at this time light availability has not yet become too limited. Furthermore, after oil palm starts to produce harvestable bunches the management requires field accessibility and space for palm frond stacking (appendix 2), which complicates the combination with intercrop management. Three scenarios include an annual intercrop during the first 2 to 4 years after oil palm field planting:

(1) *Mucuna bracteata DC.* was intercropped at a 2-meter distance from the palm. Mucuna is mainly used as a cover crop to improve soil management through minimizing soil erosion and maintain soil fertility and the recycling of pruned palm biomass (Comte *et al.*, 2012). The relative groundcover is modelled to decline with age of the oil palm, from 77% in the year of establishment, until 33% in year 3 after establishment, in the fourth the mucuna cover is no longer maintained. This represents the actual field situation, where increased competition for light the leguminous groundcover is slowly replaced by more shade-tolerant species (Appendix 2).

(2) Groundnut, *Arachis hypogaea L.,* is one of the marketable annuals. Groundnut is traditionally present in the smallholder systems, as it was cultivated during the first years after planting rubber agroforests (Bagnall-Oakeley *et al.*, 1996; Budiman & Penot, 1997). Groundnut is an herbaceous legume, and if planted in suitable areas with the proper Rhizobium strain, it can fixate most of its nitrogen requirements. The time from planting till maturity can range from 100-150 days, which is a relatively short season, allowing for two harvests per year. Within this time the crop reaches a height of 15-60 cm. These characteristics make groundnut a low competitive-crop for

nitrogen and light. However, due to its low competitiveness the crop requires relatively high labour input, to prevent weed infestation (Putnam *et al.*, 1991).

In the model for the groundnut intercrop scenario the oil palm spacing was adjusted to support establishment of groundnut in a 6 m wide strip, relative to a 9 m palm to palm row distance (66% of the simulated field). Leaving a distance of 1m from the palm planting row and a 1m wide path, in between the palm rows, for field management activities. The groundnut was planted twice per year during the first 2.5 years, amounting to five harvests in the 25-year simulation. The groundnut was fertilized at an application rate of 8 kg^{-1} season^{-1} for the 6 m wide planting strips, corresponding to 5.28 kg ha^{-1} season^{-1}.

(3) Cassava, *Manihot esculenta Crantz,* was the second marketable annual intercrop. Mainly because it is another crop commonly cultivated by mixed system smallholders, and it differs from groundnut by various characteristics (Belcher *et al.*, 2004; Rao *et al.*, 1998). Cassava is cultivated to provide income, food or fodder. Indonesia is the world's second largest consumer and third largest producer, of which most by smallholders (FaoStat, 2016). Cassava has a flexible cropping season length, from 6 months up to 2 years. The cassava plant may reach a height of 250 cm within 9 months, and has an extensive rooting system (Grace, 1977; Streck *et al.*, 2014). This rapid growth is related to high nutrient requirements and can result in rapid soil exhaustion. This makes cassava a relatively competitive crop. In the model it was cultivated during the first two years after planting, the spacing arrangements were the same as for groundnut. Fertilizer was applied to the cassava strips at the rate of 18 kg N ha of cassava^{-1} season^{-1} (= 11.88 kg N ha^{-1} season^{-1}) and 4 kg P ha of cassava^{-1} season^{-1} (= 2.64 kg P ha^{-1} season^{-1}).

Perennial intercrops

Perennial intercropping is not limited to a certain oil palm phase, like annual intercropping, but allows permanent diversification. Establishment of permanent intercropping requires spatial re-arrangements (Appendix 7). The re-arrangements were so as to provide field access allowing maintenance and harvesting, and to balance competition and facilitation. Therefore, the planting density of oil palm for these scenarios had to be reduced.

(4) Cacao, *Theobroma cacao L.,* is a crop of the humid lowland tropics and suitable for the vast majority of Sumatra's agricultural land. Cacao is commonly integrated within smallholder agroforestry systems, growing below the semi-shade. On average Indonesian cacao smallholder are more productive (pods ha^{-1}) and effective[1] (pods input Rp.$^{-1}$) than large scale plantations and government estates (Rice & Greenberg, 2000). Which illustrates how cacao tree performance can benefit from the level of site-specific practices by smallholders. The cacao trees in cultivation are usually pruned to maintain a canopy height of around 3-5 meter. If the cacao develops well the first cocoa pods can be harvested 2-3 years after planting (FAO, 1970; Smiley & Kroschel, 2010). A main cocoa yield limiting factor is pest occurrence; thus it should be noted that the simulations do not consider specific pest related palm-cacao interactions. Common cacao planting densities in Indonesia range from 1,000 to 1,200 trees ha^{-1} (Smiley & Kroschel, 2010; Souza *et al.*, 2009). The scenario simulated a double-row system with 100 palms ha^{-1} and 308 cacao trees ha^{-1}. Fertilization rate for cacao was 1.31 kg N tree^{-1} year^{-1} and 1.15 kg P tree^{-1} year^{-1}.

(5) Rubber, *Hevea brasiliensis M.A.,* is as mentioned before often the precedent crop to oil palm cultivation for Sumatran smallholders. Rubber trees require about 7 to 10 years to reach tappable girth size (Schwarze *et al.*, 2015). Once tappable, one hectare of rubber requires regular labour inputs,

---

[1] The number of harvested pods relative to the amount of money (Rp.) spend on inputs both labour and goods (fertilizer, pest-control, seedlings, etc.).

as trees can be tapped every 2 days and tapping of 600 trees requires about 1 person-day of labour (Budiman & Penot, 1997). In matured smallholder gardens the rubber canopy height can reach 20-40 meter (Beukema *et al.,* 2007). In monoculture stands rubber may be planted at densities of 600-700 trees ha^{-1} (Budiman & Penot, 1997). In the double-row system the densities were reduced to 111 palms ha^{-1} with 200 rubber trees ha^{-1}. The average per tree fertilization rate was 0.12 kg P $year^{-1}$ and 0.12 kg N $year^{-1}$.

Decision criteria

To interpret the performance of the diversification scenarios quantifiable indicators for decision making were selected. These indicators were part of a hierarchical group of assessment tools, named, Principle-Criterion-Indicator analysis (Van Cauwenbergh *et al.,* 2007).

The selected criteria were: sustainable land management and farm viability. A criterion however, is not a direct measure of performance. Therefore, the criteria were made specific and measurable by ten indicators[1]. These indicators were divided into productivity indicators and environmental indicators[2]. This because, the productivity indicators are expected to be most decisive in smallholder diversification appreciation. Most environmental indicators are not of primary interest to the smallholder, but are of major importance for other stakeholders. Local communities, NGOs and authorities, as well as palm oil users/buyers will have an interest in reducing negative environmental impacts. The links between spatial stakeholder at different spatial scales and indicators are summarized in Table 3.

Productivity indicators

Economic performance is conventionally expressed in relation to one of the production factors land, labour or capital, with the other factors accounted for at standard prices. Thus, the various indicators are not independent of each other and do not indicate how the allocation of net benefits to those providing land, labour or capital will (or should) be made.

Within the model relatively simple cost benefit flows were calculated, from these flows meaningful economic parameters were calculated using the model output, but outside the modelling environment.

$$\text{NPV}= \sum_{y=1}^{25} NFV_y * \left(\frac{1}{(1+r)^y}\right)$$

Eq. 1: Net Present value (NPV) as a function of the net future value (NFV), the discount rate (r) and year (y).

(1) The **Net Present Value** (NPV) or returns to land. Since the scenario is a prediction for a future value with a 25-year timespan the annual returns have to be discounted, to represent their present value. For Indonesia various discount rates between 4% and 20% have been used in studies (Van Beukering *et al.*, 2003; Grieg-Gran, 2008; Papenfus, 2000; Siregar *et al.*, 2007), for this study 15% was assumed. The extent to which this value represents the actual discount rate remains debatable. Nevertheless, since the discount rate is identical for each scenario the ability to estimate their relative performance will remain valid. Through a simple equation (1) annual 'present values' (FV) could be calculated. The future value was, prior to the discounting,

---

[1] Indicators, as described by Hammond *et al.* (1995, p1) "*provide a clue to a matter of larger significance or makes perceptible a trend or phenomenon that is not immediately detectable*". The values the scenarios have for the chosen indicators thus reflect the relative functioning of the scenario within the context of the sustainability and agility principles.

[2] For all indicators higher values are deemed preferable to ease comparison indicators between the scenarios, each indicator was translated into the system performance as aimed for by the criteria. E.g.: nutrient leaching is defined as 'limiting nutrient leaching', years to positive cash flow, to 'years of positive cash flow' during the 25-year cycle.

adjusted for any annual interest fees. Since these NPV is calculated on a one-hectare basis its value represents returns to land.

(2) Another way of analysing the economic performance is through the **Returns to Labour** (RTL). In this metric all net benefit is attributed to labour (equation 2). As the scenarios demand different intensities of labour input, performance ranking in terms of RTL will differ from that based on NPV. RTL is calculated by adjusting the wage rate until the NPV reaches zero. This converts the profit into the maximum possible wage rate. If this wage rate is below the regionally determined minimum wage rate (43,000 IDR/person-day for Sumatra), the system is not considered to be attractive. RTL is relevant as an indicator for farmer's resilience to changing labour markets, furthermore it can serve as a predictor for the extent to which a farmer has off-farm activities and the extent to which the farm depends on family labour (Cramb & McCarthy, 2016).

$$\text{RTL}= Wage + \left(\frac{NPV}{\sum_{y=1}^{25} Labour_y}\right)$$

Eq. 2: Returns to Labour (RTL) as a function of the wage rate per personday (=43,000), the NPV (at year 25) and the cumulative labour input over 25 years.

(3) **Years of positive cash flow**, is the complement of 'years till positive cash flow' in a fixed accounting period. The latter represents the required smallholder capacity to access capital to recover establishment costs as well as the premature phase of the palms. While companies, managing large scale plantations, often own multiple enterprises, can obtain profit elsewhere to cover the premature phase and establishment costs. For smallholders the situation is different, they tend to depend on the land as their main source of income. Therefore, when considering their economic impact, also the years of positive cash flow can serve as an important indicator for a smallholder to value the different scenarios. Note: Each scenario describes at 25-year cycle, year of positive cash flow is thus for each scenario the difference between 25 and the years of neutral or negative cash flow.

(4) **Land Equivalent Ratio** (LER) is an indicator to compare the performance of a mixed system with that of a combination of sole crops (Mead & Wiley, 1980). The LER is a relevant decision criterion where there is land scarcity, e.g. because of societal relevance of conserving remaining forests. If the LER exceeds the value of 1, relative yield gains can be obtained through intercropping. If the LER is lower than 1, or not significantly different from 1, a farmer may still choose to grow the two species on his farm, but temporally, or spatially separated. The LER as defined here, is purely yield biomass (DM) based.

To serve as a reference, 25-year monoculture yields were simulated for both soil types and precipitation distributions. In these simulations the fertilization rates per tree corresponded to those in the scenarios, and the densities represented the species specific common density. For the double row tree scenarios, the relative densities close to 1 (Appendix 7), therefore the scenarios can be seen as a replacement.

For the annual intercrop, the crops do not replace palms but make use of the immature phase of the plantation. For all scenarios LER was calculated with use of equation 3, for the mucuna scenario the yield of the diversification species was nil. Note: Y crop intercrop was the yield for 2 years of intercropped cassava, divided by a 25-year sole crop yield, and 2.5 years of intercropped groundnut, divided by a 25-year sole crop yield.

Eq. 3
$$LER = \frac{\sum_{y=1}^{25} palm\ oil_y(intercrop)}{\sum_{y=1}^{25} palm\ oil_y\ (sole\ crop)} + \frac{\sum_{y=1}^{2\ or\ 2.5} intercrop_y\ (intercrop)}{\sum_{y=1}^{25} intercrop_y\ (sole\ crop)}$$

Additional to these four indicators, the variability in economic performance was tested through a **sensitivity analysis**. The analysis enabled quantification of the effects of fluctuations in discount rate, labour wages, and prices on the economic performance. The analysis allowed prices and rates to fluctuate from 50% below to 100% above their observed present values.

Environmental indicators

The environmental impact indicators that were selected include:

(1) **Water uptake efficiency** (WUE) was chosen as a main indicator for the systems water use performance. The term can have various components depending on the complexity of the system it describes and the levels of analysis (Pereira *et al.*, 2012). In general, as any efficiency, it is a tool to describe the ratio used:available (Equation 4). For this study WUE was calculated at plot level, and only consisted of the tree and crop water uptake and the precipitation, since none of the scenarios included irrigation.

$$\text{Eq. 4:}\quad WUE = \frac{Crop\ water\ uptake}{Precipitation}$$

The WUE summarized the effect of the water balance relates processes. Included in the indicator is the amount of precipitation that was able to infiltrate, versus the amount lost at plot level through run-off and evaporation. Of the infiltrated fraction, the amount of soil water which the tree and crop roots were able to take up was differentiated from the water which was lost by deep percolation. Deep percolation losses may at catchment level not be an actual loss, for instance by replenishing groundwater. The environmental detriment which may result from deep percolation is considered in the nutrient leaching indicator. Evaporation is lost to the sky and can only return to the system through precipitation and dew, however, the loss is not related to further damage. WUE does not distinguish between the character of the type of water losses, therefore an additional indicator was used to account for the damages related to surface run-off.

(2) **Surface run-off control** is listed as an indicator, because overland flow may damage systems downstream, as well as causing losses at the farm field level. Runoff can transport high levels of nutrients, sediments and agricultural chemicals, with the threat of environmental damage downstream (Higgins *et al.*, 1993). Furthermore, run-off decreases the residence time of water within a system, creating larger river peak discharge rates, therewith increasing the risk and/or intensity of floods. Since many of the risks posed by run-off are linked to the transportation of soil particles and agrochemicals this was another indicator.

(3) **Soil erosion control**: The scenarios varied considerable in terms of percentage of soil cover and rooting, especially in the earlier phases. Therefore, the erosion rate will be influenced by diversification. The extent to which a scenario promotes or reduces erosion is calculated. Erosion is an important indicator because it is a major cause of soil quality degradation and quality degradation of aquatic ecosystems. Furthermore, sedimentation may cause stream obstruction, therewith reducing river discharge rate and increased risk of flooding (Comte *et al.,* 2012).

(4) Preventing **nutrient leaching**: The output of N, and P losses through leaching were used as an indicator. The amount of leaching relates directly to nutrient losses and thus system inefficiencies. These losses are economical losses, but also inflict environmental treats by driving degradation of groundwater quality. The leached nutrients which are transported to surface waters through lateral subsurface flows, may deteriorate aquatic ecosystems (Tung *et al.*, 2009).

(5) **Organic nutrient stock**: The soil's organic matter nutrient stock serves as an indicator for the extent to which a scenario triggers soil quality degradation (Reeves, 1997). The stability of the nutrient stock over the 25-year cycle was therefore analysed to gain insight in the scenarios performance. The initial OM nutrient stocks for the scenarios were identical.

(6) **Carbon stock**: The soil's carbon content is an indicator for soil quality. The soil's capacity to allow infiltration, to retain nutrients and water, and to support soil organisms is related to the amount of carbon in the soil (Comte *et al.*, 2012; Manns & Berg, 2014). Additionally, the potential of land to act as a net C-sink is of importance when considering the ecosystem services that soils can provide through sequestering of GHGs (Lal, 2004).

Spatial levels and stakeholders

The selected indicators represent a wide range of objectives aimed at by various stakeholder categories (Table 3). These stakeholders are included because, even though the smallholder is the final decision maker, the political, economic and social context he/she acts in will influence decisions. Stakeholders other than the smallholders, may shape the smallholders' context to favour the objectives the stakeholder aims at. Therefore, more than only the smallholders' primary objectives were included in the analysis.

Table 3: Indicators, concerned stakeholders and the spatial level of analysis (see: Appendix 12)

Indicator	**Stakeholder**
	Productivity indicators
NPV	Farm household; Local community; Region; External
RTL	Farm household; Local; Region; External
Years of positive cashflow	Farm household;
LER	Local community; Region;
	Environmental Indicators
WUE	Local community; Region; External
Run-off control	Local community; Region; External
Soil erosion control	Local community; Region; External
Nutrient leaching	Local community; Region; External
Organic nutrient stock	Local community; Region; External
Carbon stock	Local community; Region; External

Model preparatory steps

The agronomic diversification options were chosen to match the abilities of the WaNuLCAS model. Nevertheless, model modifications were required to obtain model outputs which can be assumed to describe the crop interactions at a sufficient level of credibility to allow comparisons between them. For these modifications, aligned with the PhD research of N. Khasanah, the following three activities were carried out in cyclic iteration: (i) model parameterization, calibration and validation, (ii) model performance evaluation, comparing measured and simulated data, (iii) simulation of the diversification scenarios.

First the main modifications and additions are briefly mentioned, after which the revision is discussed in more detail.

A. *Oil palm calibrations*

(1) Vegetative & generative palm performance calibration
(2) Palm planting density calibration
(3) Palm fertilization calibration
(4) Profitability module calibration

B. *Oil palm module modifications*

(5) Oil palm drought sensitivity
(6) Palm trunk as a growth reserve
(7) Age-dependent yield dynamics

C. *Core-module modifications*

(8) Root density and distribution
(9) Soil initialization
(10) Light module

Parameterization, calibration and validation requirements

Competition between two species may result from differences in their ability: (1) to acquire available soil water and nutrients, (2) to use acquired water and nutrients more efficiently in producing biomass, or (3) to allocate assimilates in way that maximizes survival and growth (Nambiar & Sands, 1993). Therefore, the modelled abilities of each species will not only influence their individual performance, but also the performance of the species with which they are intercropped. In order to be confident that the predicted outcomes of the scenarios resulted from the interaction between the two species and their management, and not from faulty described abilities to acquire and allocate resources, different responses of oil palm growth had to be examined. When intercropping oil palm, the planting density, fertilizer application and spacing will be altered. This will influence both inter- and intraspecific competition for nutrients, light and water (Nambiar & Sands, 1993). Therefore, firstly the simulation of the intraspecific competition had to be accurate before the various scenarios could be run.

(1) Vegetative & generative oil palm calibration

Five output variables were used to optimize the models' functioning. After each addition or modification, statistical criteria for model performance evaluation, as described by Loague & Green (1991) were calculated to evaluate the predicted palm growth and yield (Appendix 4). The data used for the calibration came from a dataset of 25 plantations and from Brawijaya University research sites in Sumatra and Kalimantan (Brawijaya University, personal communication, May 2016; Khasanah, 2015a). These plantations provided annual data for: trunk height, trunk diameter, number of palm fronds, frond length and FFB yield. The dataset enabled the model to have a trustworthy description of the vegetative processes, as well as for fruit yield. Data allowing a more detailed calibration of the generative part, i.e. inflorescence sex ratio and bunch weight, was not yet available.

(2) Planting density calibration

One of the simulation outputs which had to be analysed and compared was that of the responsiveness to changes in density. Optimal planting densities are mainly dependent on leaf area and light interception (Smith *et al.*, 1996; in Corley 2003). Therefore, planting conditions and planting material determine the optimum as both of these will influence the leaf area per palm. The values listed as an optimal planting density were based on the optimal LAI for oil yield, which was considerably below the optimal LAI for maximum total biomass accumulation (Corley, 1973). Additionally, costs and profit, related to the planting, maintenance and harvesting, combined with the complications the planting pattern might pose to the management practices, determine the optimum at farm level. The common oil palm planting density in Indonesia is 138 trees ha^{-1}, corresponding to a 9 m triangular planting pattern (Prévôt & Duchesne, 1955; in Corley & Tinker, 2003). This density is low compared to calculated optimal densities from a palm yielding perspective. Which can be explained by consideration of the management and economic constraints mentioned above.

The yield response to density variation (Figure 6), described a similar trend as the yield data of density experiments from comparable environments in Papua New Guinea (Breure, 1996) and Malaysia (Corley, 1973). The influence density alterations had on vegetative and generative growth were assumed to be comparable.

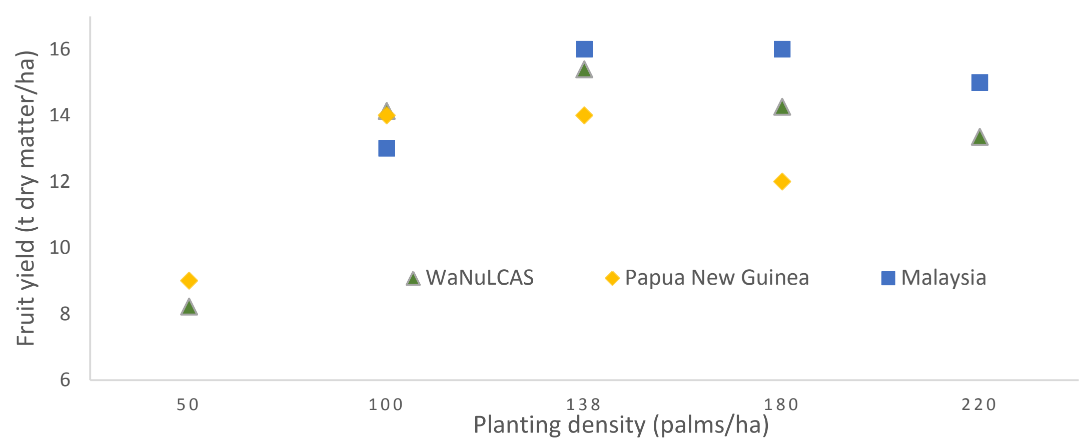


Figure 6: Yield data of average fruit yield (t DM/ha) for the productive years. The planting densities were: 50, 100, 138, 180 and 220 palms/ha. Data from sites in Papua New Guinea and Malaysia are compared with modelled output for corresponding density treatments.

(3) Fertilizer response calibration

As a common practice urea and Triple Superphosphate (TSP) are applied as sources of nitrogen and phosphorus respectively. The usual timing and corresponding fertilization rates were obtained from Pahan (2008) (Appendix 5). Since the 1920s fertilization and the palm's response to different regimes have been subjects to study. Most of these studies had the objectives to find economic optima in terms of fertilizer composition, dosage and timing. Some studies included minimizing environmental impact as an objective.

It has to be considered that quantitative predictions of yield response to fertilization, are to a high degree dependent on the contextual management and environmental conditions (Goh & Po, 2005; Corley & Tinker, 2015). For this reason, it seemed most accurate to consider a number of studies and extract from these a general trend. Most studies showed a relatively steep yield increase for the first amounts of N or P supplied compared to a zero level. After this first increase the responsiveness levels off. The relationship can be described by different models: linear response and plateau, quadratic, Mitscherlich or Michaelis-Menten (Corley & Tinker, 2015). Simulating a range of fertilizer inputs showed a similar responsiveness.

To have quantitative reference for the yield response: adding phosphorus at a rate of 0.6 kg/palm showed to result in a 45% to 80% FFB yield increase (average yield increase for 4 to 18 years after planting, see: Appendix 8) (Pushparajah, 1990). The yield increase varied over soil type and palm age. In general palm's responsiveness to phosphate showed to increase with palm age, from 12-18 years after planting 110% increases in FFB yield were obtained. A recent study by van Noordwijk *et al.* (2016), with sample locations in Sumatra and Kalimantan, showed a relation between FFB yield with N application, where yield increased up to 10 t ha^{-1} yr^{-1} for a fertilization ranging from 50 kg ha^{-1} yr^{-1} to 250 kg ha^{-1} yr^{-1}. Furthermore, a study by Akbar *et al.* (1976) on per palm fruiting response showed an interaction between combined and single N and P application rates and fruit yield. For a given N- or P-fertilization rate, the resulting yield increase was larger if the other nutrient was applied as well. These trends served as a benchmark for testing the models' responsiveness to different fertilization regimes. In these ranges of fertilizer application, the model performs reasonable.

(4) Profitability module

Analysing the economics of the different scenarios required defining the various sources of costs and incomes as well as their prices. The costs originate from inputs of materials (planting material and fertilizer) and labour (field preparation, planting, weeding, pruning and harvesting). Income is obtained through selling of the produce. Labour wages were assumed to be constant over time and per activity with a value of 43,000 IDR/person/day (Cramb & McCarthy, 2016; Mundlak *et al.,* 2002). For each of the crops or trees specific labour demand per activity were listed based upon crop specific studies (Anuebunwa, 2000; Manivong & Cramb, 2008; Meier, 2013; Perdew, & Shively, 2009; Remesh, 2010; Schwarze *et al.*, 2015; Tully, 1988). Fertilizer was priced 5,000 IDR/kg of N and 13,500 IDR/kg of P (Pahan, 2008), these prices were assumed to remain constant over time. The labour for field preparation prior to planting was estimated to be 30 working person days (Corley & Tinker, 2015). For every marketable output the Indonesian 5-10-year average farm-gate price was taken from FAOSTAT (2016).

Furthermore, the farming context had to be simplified by making informed assumptions. Firstly, for each of the scenarios the labour availability was assumed to be unlimited. This is based upon the fact that the number of Indonesian regions where agriculture is labour-limited has seen a steep decline. This trend was mostly driven by the governmental transmigration programs which brought in large groups of Javanese and Balinese migrants seeking jobs (Papenfus, 2000).

Secondly, loans were assumed to be available to the farmer. The initial investment for an agricultural field is considerable, especially for trees and palms, mainly due to a delayed return on investment. Therefore, the scenarios have a negative net present value (henceforth: NPV) for the first year(s). The annual interest rate taken into account, for these loans was estimated to be 7% based upon a ten-year Indonesian average (2005-2016) (Bank of Indonesia, 2016).

(5) Palm's responsiveness to drought

Simulation of oil palm for the earlier mentioned rainfall regimes of 15 and 60-day consecutive drought had no effect on palm growth and yield. Testing for limiting factors to palm growth showed that water barely limited palm growth, which required re-examining the oil palms characteristics used during the initialization of the palm in WaNuLCAS. This showed that the mentioned water requirement for biomass production, 300 litre of water transpired per kg of dry matter plant biomass, which seemed to be an underestimation when compared with reported values. Although literature on the topic is limited, a detailed study on oil palm water requirements by Henson (1993) finds a water use for a productive oil palms to be 400 litre kg^{-1} of dry matter[1]. With the updated value the palms showed the anticipated drought response. Drought stress primarily affected generative growth, mainly due to a decreased female:male inflorescences ratio and therewith yield decline.

(6) Palm growth reserves

The oil palm trunk serves as the main carbon transitory photosynthate reservoir to sustain growth and fruiting during periods of scarcity (Legros *et al.*, 2009). The reservoir forms a buffer for source-sink imbalances. The photosynthetic rate of oil palm is not responsive to sink strength. Therefore, during periods of abundance, carbon and to certain extent nutrients can be stored for later periods of physiological drought. The presence of these growth reserves are known to play an important role on the sex determination of the inflorescence (Adam *et al.* 2011). Hence the flow of transitory surpluses[2] to the storage pool, as well as the role reserves play in next gender determination, had to be incorporated in the model. The following rules were made explicit: (i) the flows to the transitory photosynthate reservoir only occurs if the demands of both vegetative growth and generative growth are satisfied, (ii) a fraction of these transitory photosynthate reserves can become available, on a daily time step, to suffice carbon requirements.

The relation between female:male ratio and the size of the growth reserves was dynamic. Meaning that the size of the palm's growth reserve pool, relative to the overall palm biomass, should suffice the demand threshold in order for the inflorescence to become female.

---

[1] The water use here only includes the water that is taken up by the tree roots. All other water losses/uses are accounted for in other model sections.

[2] The growth of the oil palm vegetative and generative organs can be satisfied, meaning they are bound by a maximum.

(7) Age-dependent yield dynamics

Phyllochron dynamics

Simulation of the first four years after planting, showed that the model underestimates the palms potential to yield harvestable fruit bunches (bunch weight >5 kg). New measurement data became available during the modelling process, this listed various vegetative and generative development processes (Brawijaya University, personal communication, September 2016). The data showed that the phyllochron time in the earlier stages was much lower than the previously noted values of 17-days. Altering the phyllochron time required a reconstruction of the oil palm routines to allow for age-dependent phyllochron time (Appendix 9). The updated potential phyllochron time was adjusted according to the level of nutrient and water stress experienced by the palm, to calculate the actual phyllochron time (Broekmans, 1957; Gerritsma & Soebagyo, 1999; Rafii *et al.*, 2013).

A number of processes had to be aligned accordingly, including the ripening of the fruit bunches. For fruit ripening, 22 phyllochron time steps were assumed based upon the 8 time steps required from anthesis till pollination, follow by 14 time steps from pollinated till ripened (Corley & Tinker, 2015). With these adjustments an improved establishment of yield during the early phase of production was obtained.

Management related yield losses

A second trend observed when plotting palm oil yields over time is a decline that sets in approximately 10-15 years after planting. However, research has not yet traced any physiological process which could explain this trend, especially not for the first 25 years after planting (Corley & Tinker, 2003). Until now the most likely explanation is that the yield decline originates from two harvesting related causes. Firstly, with increasing palm trunk height, the oil palm bunch harvesting becomes increasingly challenging increasing the likelihood of bunch damage when harvested. The common practice of cutting and then dropping the bunch down results in increased fruit damage and thus yield loss, with increasing age (Corley & Tinker, 2003). Secondly, the average bunch size increases with age (Chan & Chiew, 1998). The larger fruit size, especially combined with the increased trunk height, complicates the mean ripeness estimation of the fruit bunches (Corley & Tinker, 2003). Resulting in lower oil level at harvest time per kg of bunch.

Since the management related yield decline has a large impact on fresh fruit bunch (FFB) yields per hectare the trend of increased yield loss as a function of palm trunk height had to be integrated in the model to improve yield prediction.

(8) Root density and distribution

The rooting pattern was included in a descriptive manner. Therefore, the rooting pattern was fairly rigid and was too sensitive to alterations in zone width. Therefore, the module describing root growth and the format of the initial input data had to be altered.

Growth rates and root-shoot ratios of the rooting systems seemed to be up to date, but the maximum obtainable root densities had to be revised. Based on field measurements, maximum root densities per zone and layer were loaded into the model. Therefore, the spacing and zonation of the trees and crop in monoculture and intercrop needed to be considered carefully. Each tree should be planted in the centre of its zone to accurately represent its rooting pattern. Additionally, the planting zone has to be accounted for within the rooting module, meaning that the zone of planting was the zone where root development was initialized and where highest root density was obtained.

Competition between species showed to be influenced by zone sizes, thus this had to be compensated for. This could be done with the use of field measurement data. Data on rooting density variation with soil width and depth was retrieved from experiments in Sumatra and Kalimantan (D. D. Saputra, personal communication, August 2016; Brawijaya University, personal communication, August 2016). For oil palm, rubber and cassava the studies listed root densities (g/cm^3) for intercrop and monocrop systems. The data on cocoa, groundnut and legume cover was only available for monocrop systems.

The following assumptions were made for intercropping oil palm with cocoa and rubber. (1) The oil palm planting zone had the same rooting density as the observed density in the mono stand. (2) The zone in between the two oil palms was similar to the zone in between the oil palms in the mono stand. (3) The zone in between rubber and cocoa had the same total root length, but a lower root density, meaning that the palm roots stretched further than assumed based on the mono stand. This can be seen as a compensation for the difficulty of measuring root densities. The total amount of roots observed in the zone in between the two oil palms can originate from either one of the palms. In the monoculture the root is assumed to originate from the palm closed to the measurement point. This assumption is legitimate in a monoculture when looking at field level performance. However, this may underestimate the palms ability to expand its rooting system horizontally, decreasing its ability to compete with the intercropped tree for nutrients and water. Therefore, for the perennial species, the spatial extent of the roots was slightly increased, the root-density was lowered accordingly and thus the total root length per tree remained unchanged.

(9) Soil initialization

The initialization of both the clay loam and sandy loam soils showed to result in unstable organic matter pools, resulting in high mineralization in the first years after planting. Therefore, an initialization period was run prior to each scenario, during this initialization weed infestation was allowed. A period of 20 year showed to be sufficient to stabilize the relative sizes of organic matter carbon and nutrient pools in the soil. As described in the WaNuLCAS manual, the model includes a distinction of organic matter pools as described in the Century model (five pools: 'metabolic', 'structural', 'active', 'slow' and 'passive'). The Century equation is used to distribute the initial organic matter and any organic matter input, over these pools. Therewith it is the main driver behind fluxes in pool sizes. The equation used to derive the organic matter transformations is a function of clay content, soil temperature and soil water content. The 20 year weed simulation resulted in an initialization of the C stock of 37 t C^{-1} ha^{-1} (sandy loam) and 38 t C^{-1} ha^{-1} (clay loam). Which were comparable to the measured values of the soil organic matter C-stock under oil palm, of 40 t C^{-1} ha^{-1}, with a C:N ratio of 8, and a N:P ratio of 10 (Khasanah et al, 2015b).

Running a weed scenario as an initialization method was a temporary solution, which was an effective but inefficient measure. This part of the model has to be revised in a future version.

(10) Light module

The canopy configuration and competition for light included were detailed and from comparison of LAI fractions per zone the canopy configuration response to intercropping could be observed.

The palm and tree canopy are the main determinants of competition. In the 4.2 version of WaNuLCAS light was coming in from a 90^0 angle. Meaning that a species could only shade another when the canopy expanded until directly above the other. This only represents the competition of the canopy close to the equator, for a few days per year, at mid-day. Therefore, a new element had to be included in the light module describing lateral light capture. The conditions were designed to allow for distinguishing between cloudy (incl. haze) or clear days. For both conditions a simple rule described that the canopy in one zone could be shaded by the canopy of the neighbouring zone, as a function of the relative height of the canopy in both zones and the angle of the sun relative to the surface. Figure 7 depicts how the light is reallocated over the different zones depending on their height and the solar angle. If zone 2 is larger than zone 3 than zone 2 shades zone 3 and vice versa. If zone 3 is larger than zone 4 than zone 3 shades zone 4 and vice versa. The shade zone 2 poses upon zone 3 ('x' in Figure 7), is *extra* incoming irradiance to zone 2.

The azimuth angle ‘α’ and the declination angle of the sun with respect to the equator ‘δ’, were included into the model, using the equations (5 & 6) of Goudriaan & van Laar (1994). The input to the equations were ‘λ’ (degree of latitude) and day of year. Since the model runs with daily time steps, the incoming angle depending on time of day was only implicitly included into the calculations, by describing the average amount of energy coming in at a given angle.

In the model version used for calibration, clear sky conditions were assumed for all days. The cloud module is still *work in progress*. For the clouded or hazed conditions additional rules describing overcast as a function of time have to be added. This requires an input dataset describing the cloud-haze cover as a function of location on earth and time of year.

Equations 5 & 6 (Goudriaan & van Laar, 1994):

$$\sin \delta = -\sin(\pi * 23.45/180) * \cos(2\pi * (\text{day of year} + 10)/365)$$

$$\alpha = \sin(\lambda) - \sin \delta$$

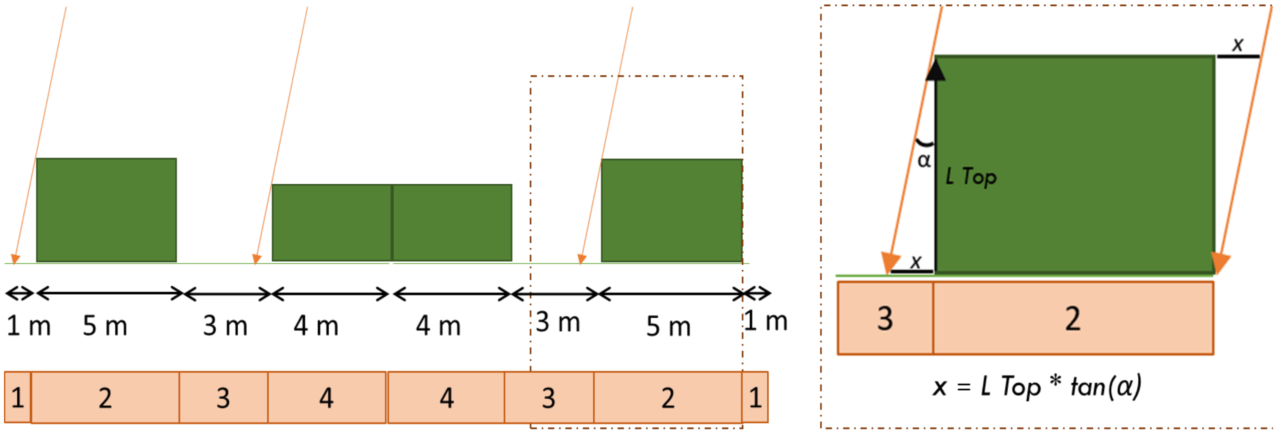


Figure 7: An illustrative example, showing spacing and top of canopy height (green box) for oil palm cocoa double row planting. The orange arrow represents incoming radiation. Light distribution over the different zones is calculated by the given formula: relative height (L top) multiplied by the tangent of the incoming irradiance angle (α). In the enlarged fragment of the figure ‘x’ represents the coming irradiance captured by the right side of the canopy of zone 2, this causes an equal amount of incoming radiation being prevented from reaching zone 3 (shading).

RESULTS

The results section consists of four paragraphs: (i) the performance of each diversification scenario for the productivity and environmental indicators relative to the oil palm monoculture; (ii) the outcomes of the sensitivity analysis; (iii) scenario performance comparison over the four treatments of soil type and length of consecutive drought and (iv) spatial upscaling of the results and the summarized scenario suitability.

Performance levels for diversification scenarios (I)

The **cacao** oil palm intercrop was the most profitable scenario in terms of NPV over the 25-year cycle (Table 4). The scenario required the largest investment resulting in a negative NPV of between -10 and -13 million Rp. during the first three years after planting (Figure 8). The recovery of the investment was completed in year five when the palms and trees started to yield substantially. The required labour inputs for the scenario were around 115-140% larger than for the monoculture, which resulted in decreased returns to labour. The LER exceeds 1, illustrating that yield levels per hectare were increased by intercropping.

Table 4: Productivity performances[1] for each of the diversification scenarios. The listed values are the averages of the four simulated soil-precipitations conditions.

	NPV (Rp. ha^{-1})	RTL (Rp. person-days^{-1})	Years of positive cash flow (#)	LER
Oil palm	53,641,039	**80,494**	20	1.00
+ Cacao	**68,818,497**	64,324	20	**1.18**
+ Rubber	5,126,306	43,609	12	**1.21**
+ Mucuna	53,230,981	**80,242**	20	1.01
+ Groundnut	63,528,614	78,904	**23**	1.16
+ Cassava	59,122,107	74,788	**23**	1.05

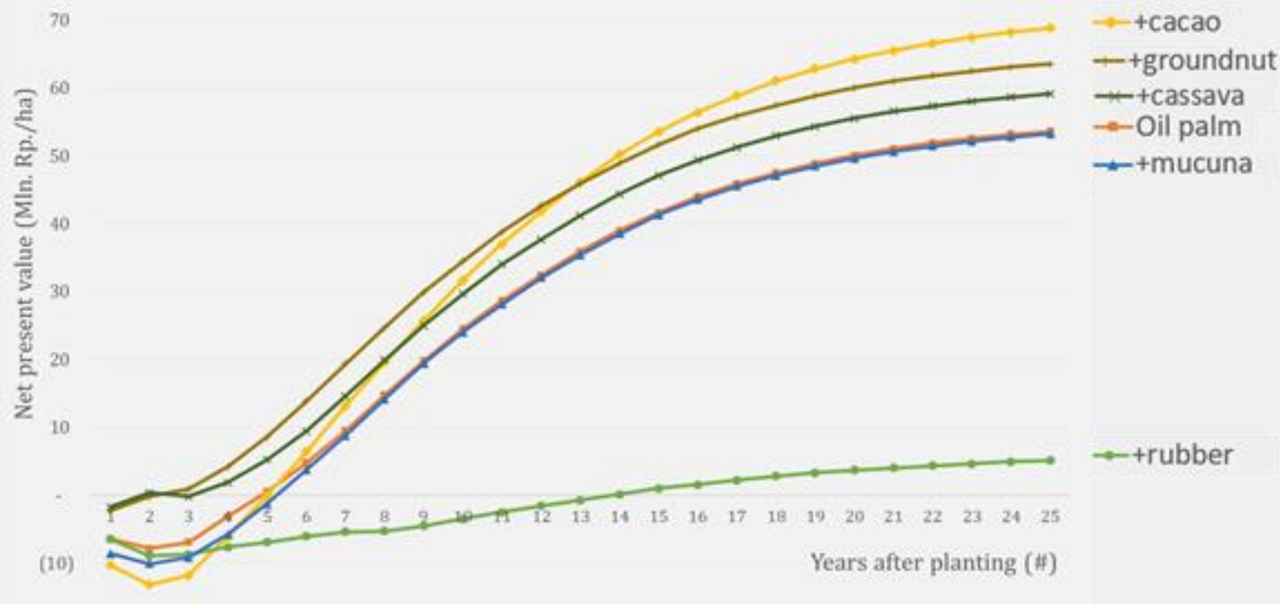


Figure 8: Net present value dynamics for the 25-year cycle in Million Rp. per hectare for each of the diversification scenarios. The values are the averages of the four soil and drought treatments.

Rubber intercropping showed to have the weakest economic performance. Both palm oil yield levels per hectare and per palm decreased substantially with 55-60% and 44-50% respectively. Compared to the oil palm monoculture scenario the required labour inputs increased with 475-512%. This resulted in a relatively short period of positive cashflow of 13 years and a low final NPV of less than 10% of the monoculture. Since rubber yields per tree substantially increased, the scenario did have a LER exceeding 1.

The scenario with **mucuna** as a cover crop was in performance most similar to the monoculture, NPV and RTL decreased by less than 1%. The cumulative oil yield was increased between 1-2% (Appendix 13), but this was not expressed in the NPV since labour requirements for the scenario also increased with 1%. As shown in Figure 8 the mucuna scenario in the first year requires slightly larger investments, these were compensated for within approximately 5 years after planting.

Groundnut and **cassava** intercropping during the first 2 years after oil palm planting were comparable in terms of indicator performances and thus will be discussed jointly. Compared to the monoculture oil palm, the scenarios gave 19% (groundnut) and 11% (cassava) larger NPVs at the end of the 25 year cropping cycle. To establish and maintain the intercrops an additional labour input of 24-31% was required. Which explains the reduced RTL for both scenarios (Table 4). The annual

---

[1] The productivity in terms of cumulative yield level is listed in Appendix 13

intercropping with groundnut and cassava showed to have the quickest return on investment, within 2 years after plating, and the largest NPV for the first 13 and 9 years, respectively (Figure 8). Also the obtained LER levels were greater than 1. Overall, the scenarios achieved a performance improvement for three of the four economic indicators relative to the oil palm monoculture.

Performance levels for diversification scenarios (II)

Compared to the oil palm monoculture, both perennial intercropping scenarios, **cacao** and **rubber**, improved the environmental performance on all indicators with the exception of WUE (Table 5). The scenarios increased the organic nutrient and carbon stocks in the soil, while reducing runoff, erosion and N-leaching. Rubber performed better on these environmental performance indicators than any other tested scenario. The largest environmental improvement was obtained for N-leaching control, rubber reduced N-leaching with 66%, whereas N-inputs were 15% larger than in the monoculture scenario.

The **mucuna** cover crop scenario performed fairly similar to the oil palm monoculture, in terms of surface runoff and soil carbon stock (Table 5). Nevertheless, it was able to reduce erosion and maintain larger organic nutrient stocks. N-leaching increased slightly, these losses mainly occurred after the mucuna intercropping phase, 4-6 years after planting.

Groundnut and **cassava** intercropping scenarios performed similar in comparison to the oil palm monoculture, for each of the environmental indicators (Table 5). The most significant improvements were those of erosion control and organic nutrient stocks. Whereas WUE, runoff control, carbon stock and nitrogen leaching control were only slightly different from that of the oil palm monoculture.

Table 5: Environmental performances of each of the diversification scenarios relative to the oil palm monoculture scenario. The listed values are the averages of the four soil-precipitation conditions, over the 25 year cropping cycle.

	WUE	Surface runoff control	Erosion control	N-leaching control	Organic nutrient stocks	Carbon stock
Oil palm	-	-	-	-	-	-
+ Cacao	-3%	9%	12%	16%	6%	4%
+ Rubber	-12%	27%	57%	66%	15%	37%
+ Mucuna	6%	3%	39%	-5%	11%	1%
+ Groundnut	4%	-2%	38%	-3%	14%	1%
+ Cassava	5%	-2%	36%	-1%	3%	-

Sensitivity analysis

The sensitivity analysis showed that the relative performances of the diversification scenarios, in terms of NPV, were sensitive to fluctuations in wage rate (Figure 9b) and oil palm prices (Figure 9c). This is mainly due to the relative sensitivity of cacao to fluctuation in wage rate and insensitivity of cacao scenario to oil palm prices (Box 2). Therefore, the relative performance of cacao compared to groundnut and cassava varied, if the wage rate increases with more than 50%, and 75% respectively groundnut and cassava showed most profitable. Similarly, if oil palm price increases more than 25% or 50% respectively groundnut and cassava showed most profitable. Relative to the oil palm monoculture, diversification with cacao, groundnut and cassava intercropping showed to be more profitable per unit of land with any rate or price fluctuation within the -50% and +100% range. Profitability of adding mucuna remained comparable to the oil palm monoculture, at any tested price or rate change. The perennial intercropping with rubber showed to be less profitable than the oil palm monoculture at any tested price or rate change.

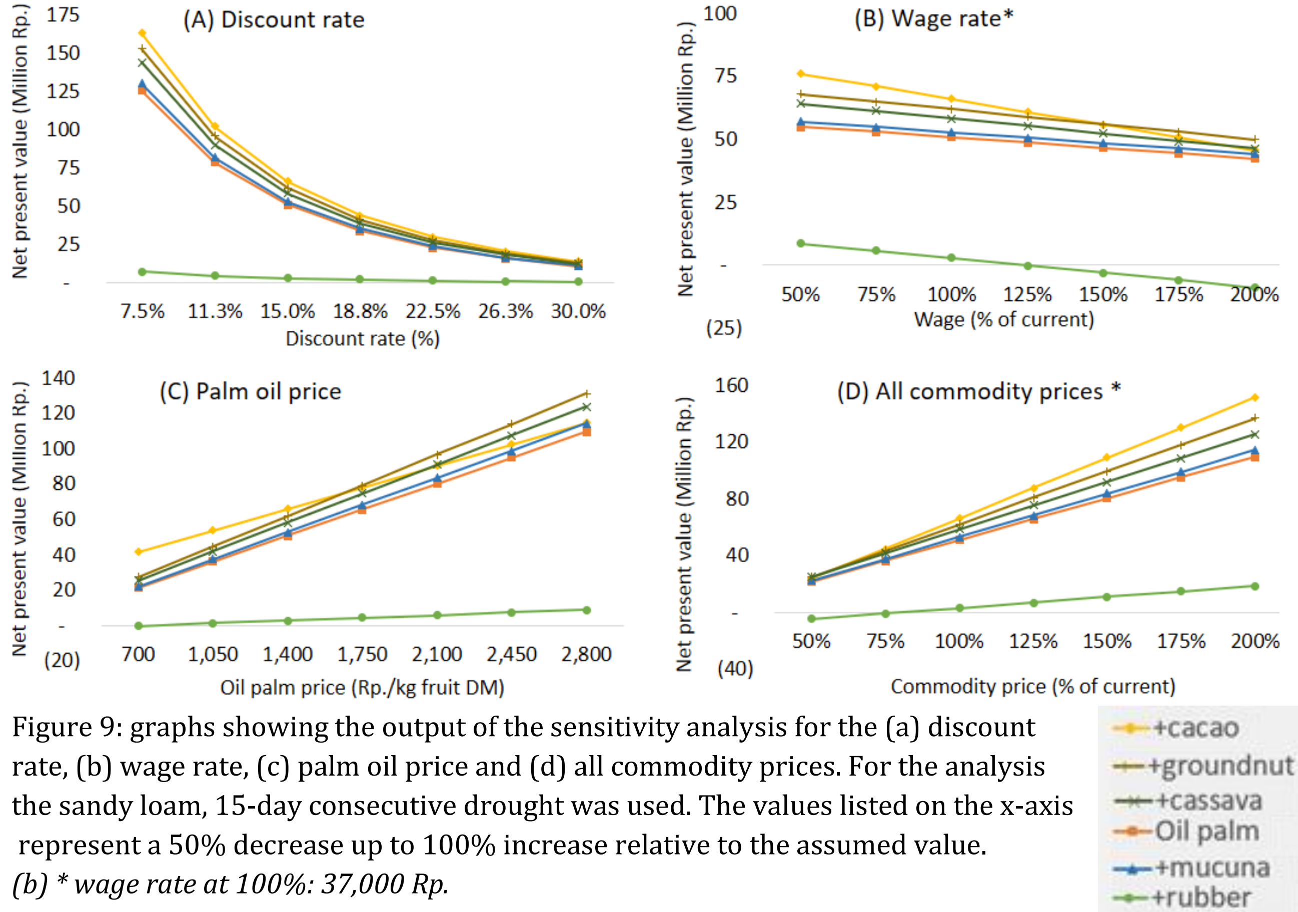


Figure 9: graphs showing the output of the sensitivity analysis for the (a) discount rate, (b) wage rate, (c) palm oil price and (d) all commodity prices. For the analysis the sandy loam, 15-day consecutive drought was used. The values listed on the x-axis represent a 50% decrease up to 100% increase relative to the assumed value.
*(b) * wage rate at 100%: 37,000 Rp.*
*(d) * commodity prices at 100% as listed in Appendix 11.*

BOX 2: Sensitivity of the cacao intercrop scenario, relative to monoculture scenario.

(i) Sensitivity to wage rates

Monoculture trendline: NPV = **-2.1***10^6 * Wage rate + 57.0*10^6
Cacao trendline: NPV = **-5.1***10^6 * Wage rate + 81.1*10^6

(ii) Sensitivity to palm oil prices

Monoculture trendline: NPV = **3.2***10^6 * Palm oil price + 1.4*10^6
Cacao trendline: NPV = **2.6***10^6 * Palm oil price + 6.3*10^6

Performance levels for soil types and drought length

For each of the simulated scenarios, the relation between scenario and the four simulated combinations of length of dry period and soil type proved similar. The relation can be described by three trends:

(I) Lengthening of the number of consecutive dry days showed to decrease the performance for each of the productivity indicators and in 94% of the cases for the environmental indicators.

(II) The relative responsiveness to the consecutive drought length was larger for the sandy loam soil, than for the clay loam.

(III) The highest productivity levels were reached for the clay loam soil. For environmental indicators the clay loam also performed better than the sandy loam soil, with the exception of erosion control. Higher erosion rates were observed on the clay loam soil.

These three trends showed the same for each diversification and the monoculture scenarios. Within no significant interactions were observed between indicators and soil type or drought length. There were two exceptions the cacao scenarios which had higher erosion rates, compared to the monoculture for the clay loam, but lower erosion rates for the sandy loam (Appendix 10). The other exception was the performance of the mucuna cover crop scenario, the performance varied for the productivity indicators LER, NPV and RTL depending on the soil type and length of drought (Appendix 10). Nevertheless, the indicator performances were in general similar to the oil palm monoculture.

Upscaling from plot to farm

In Table 6 the diversification scenario performances relative to the monoculture are summarized. An indication is given of how these performances relate to farm-level context and farmers' objectives. The analysis showed that scenario suitability is farmer-context specific, this implies that different farmers would likely select different diversification strategies.

Table 6: The summarized scenario performances at plot- and farm-level. Listing the advantages & disadvantages, relative to the performance of monoculture oil palm, and a description of a suitable farm-context.

Scenario		Advantages	Disadvantages	Performance improvement *if the farmer...*	
				Context related	Objective related
1	+ Mucuna	Increased soil organic nutrient stocks; erosion control; RTL similar to oil palm;	Slightly higher costs in the first 3 year;	Is able to cover the costs of extra labour input in the first 3 years; Farms a plot with a sloped surface;	Is focussed at maximum RTL instead of largest NPV;
2	+Groundnut	Supports food security during intercropping years; increased NPV; positive NPV after year 2;	Reduced RTL; N-leaching slightly increased;	Has limited access to external funding (off-farm income, subside, loan); Farms a plot with a sloped surface;	Is focused at quick investment recovery;
3	+ Cassava	Support food security during intercropping years; increased NPV; longest period of positive cashflow;	Reduced RTL;	Has limited access to external funding (off-farm income, subside, loan); Farms a plot with a sloped surface;	Is focused at quick investment recovery;
4	+ Cacao	Largest NPV; environmental performance improved;	Reduced returns to labour; large costs of establishment;	Has an additional source of funding (off-farm income, subside, loan) to cover the establishment costs;	Aims to reduce the impact of oil palm price volatility;
5	+ Rubber	Largest environmental performance improved;	Reduced returns to labour & land; shortest period of positive cash flow;	Is supported by external funders who appreciate the environmental prosperity the farmer can maintain; Has access to labour at low prices;	Aims to reduce negative environmental impacts;

DISCUSSION & RECOMMENDATIONS

This study aimed to explore the feasibility of a range of diversification options for smallholder oil palm production systems. In line with the hypothesis (the productivity of oil palm cultivation can be improved through plot-level diversification, while maintaining or enhancing environmental performance) the model results showed that the productivity of oil palm systems per unit land, can be improved through plot-level diversification. The second part of the hypothesis, stated that diversification could furthermore assist in enhancing or maintaining of environmental performance. Diversification showed to achieve the hypothesised effects. The labour-demand however, was increased for all of the scenarios, therewith reducing the returns to labour. Each of the diversification scenario showed to have a unique balance of productivity and environmental farm indicator performances. This illustrates the complexity of decision making and defining a farming practice as 'best practise' or 'the most sustainable option'. The main complication is the relative weighing of performance indicators. This relative weighing is the product of: the spatial scale of analysis, farming styles[1] and external incentives (primarily: policies and agribusiness schemes) (Binswanger & Deininger, 1997; Feder *et al.,* 2004; Feintrenie *et al.,* 2010; Van der Ploeg, 1994).

Each scenario is linked to performance improvement at a particular set of indicators. For instance, if a smallholder seeks to obtain an early yield and early positive net returns, the simulation showed that the choice of an annual intercrop is preferred. Whereas, if a smallholder aims at obtaining largest returns to land and a risk coping strategy throughout the production cycle, perennial intercropping with cacao is preferred. While, if aiming at enhanced environmental system performance, rubber intercropping showed most suitable. A smallholder focussed at maximizing returns to labour, while alleviating some of the environmental damages caused by an oil palm monoculture, the groundcover scenario is preferred. When the farmer is solely focussed on maximizing returns to labour, the oil palm monoculture shows the best strategy.

Thus, to gain insight of indicators weighing by oil palm smallholders, to assess suitability of diversification strategies for their farming system, insight in the present farming styles and role of external incentives is required. This insight can be obtained through farm questionnaires and decision making games, to create interactive learning (Dobbins *et al., 1995;* Franzel *et al.,* 2001; Villamor & van Noordwijk, 2011). The anticipated diversity in intercropping suitability may result in adoption of a diversity of intercropping practices dependent on the farm and regional context. On a landscape level, this diversity would result in the establishment of a landscape mosaic. Thus there is a synergy between plot- landscape-level aims for diversification. Because a diversity in plot-level diversification would at a landscape level create more diversity in habitat, as well as a diversity in marketed commodities.

With the implemented model improvements, the scenario exploration was able to simulate the relevant complexity at an acceptable reliability level. The model developments have contributed to the establishment of a model able to integrate oil palm and useful other annual and perennial species, allowing further investigation of a wider range of options, in a specified range of environmental contexts. Studies of interest include: diversification performance in variable economic and weather contexts (simulating annual weather and price fluctuations), regeneration strategies (*sisipan*), possibility to combine short- and long-term benefits through combining oil palm with both annual and perennial intercropping. Nevertheless, any anticipated scenario exploration with the aim to explore other cropping options and/or in other environment will require parameterization and calibration of

---

[1] 'Farming styles represent a specific unity of farming discourse and practice, (...) entailing a specific structuration of the labour process, (...) resulting in a particular organization of the process of production.' The prevailing styles of farming 'represent specific connections between economic, social, political, ecological and technological 'dimensions'. Van der Ploeg (1994)

the model. Besides these specific scenario-based preparatory steps, general modules of interest on which continued work is required remain. So to say, the model is *work in progress* which requires continuous efforts to improve reliability and allow for a larger range of explorations.

Zooming into the scenario performances: All diversification scenarios were more productive from a land-equivalence perspective (LER > 1). Except for rubber intercropping, all intercropping scenarios achieved larger returns to land. However, each of the marketable intercropping scenarios required considerable increased labour input, therewith reducing the returns to labour (RTL). This increased labour demand is not necessarily a negative system feature, as the majority of the oil palm smallholders is not labour-limited (Schwarze *et al.,* 2015; Vermeulen & Goad, 2006). Due to the small plot size and low demand of labour the smallholder can satisfy his demand with family labour (*ibid*.). Smallholders employ their excess labour through working as a labourer on other farms as an important source of household income (Feintrenie *et al.,* 2010; Schwarze *et al.,* 2015). The labour prices accounted for in de simulations were at the high-end of the current labour market prices (Feintrenie *et al.,* 2010; McCarthy & Cramb, 2015). On a regional level this indicates that increased availability of well-paid employment through intercropping, could assist smallholders to stabilize their household income.

Rubber intercropping scenario combined the poorest economic performance with the best environmental performance and largest LER[1], pointing out that LER as sole indicator, does not necessarily reveal the best scenario. The poor economic performance has three main causes: (1) the rubber tree outgrows the oil palm, therewith severely reducing palm oil yields (Corley & Tinker, 2003; Hartley, 1988) (2) rubber prices are too low to compensate for the palm oil yield losses and (3) the wage rates in rubber cultivation are generally lower than those for oil palm, whereas the study assumed wage rates to be independent of activity (Belcher *et al.,* 2004). The scenario thus showed unfeasible in terms of profitability. In-line with these outcomes oil palm is seen to replace much of the plantation rubber in Indonesia (Basiron, 2007; Fitzherbert *et al.,* 2008; Koh & Wilcove, 2008; Rist *et al.* 2010). Nevertheless, large areas under rubber cultivation remain and mixed oil palm rubber systems are the prevailing type of intercropping, resulting from the interaction of farming-styles and external incentives (see also: Cramb & McCarthy, 2015; Potter, 2016; Wibawa *et al.,* 2005).

In terms of environmental performance, rubber intercropping outperformed any other scenario, this confirms concern about the environmental impact of the widespread conversion of rubber towards oil palm (Koh & Wilcove, 2008; Wijaya & Glasbergen, 2016). This illustrates the conflict between environmental and economic incentives. The cacao scenario illustrated that considerable economic performance improvements can be achieved jointly with at least some level of environmental impact improvement.

Model assumptions

The modelled scenarios assumed a homogenous plot and farming context. In reality, farming and the performance of a scenario will be widely heterogeneous. Scenario exploration should be seen as an initial assessment of relevant farm field experiments. The follow-up experiments are essential to see how the modelled performance is translated to the heterogeneous context of farm fields. This heterogeneity is fourfold. (1) The socio-economic context: the model assumed sales of FFB against 'fair' and stable prices, and access to good quality planting material, investment capital, labour and fertilizer. However, the extent to which these assumptions are correct will vary, depending on the socio-economic farm context. (2) The environmental context included solely four soil-precipitation

---

[1] The larger LER mainly resulted from the increased rubber production per tree, nevertheless, tapping these trees was labour intensive and the rubber was sold at low prices.

combinations. This range of soil and precipitation combination includes the prevailing soil types and the most extreme weather conditions. Nevertheless, the Indonesian oil palm production, knows a larger diversity in i.a. field slope, soil type (mineral soils) and fertility. The environmental context will largely determine the environmental priorities linked to a region. The context may also have an impact on the relative performances of the scenarios, especially in extreme situations (i.a. steep slopes, mineral soils). (3) Plot-level homogeneity: the modelled scenarios consisted of distinct rows under predefined treatments and variation in plot qualities was levelled out over the field. Whereas a smallholder's field has more chaotic nature, and intercrops may be used in various manners as secondary gap filling or rejuvenation. This was not included in the modelled scenarios. (4) The scenarios in this study ignored pest and disease-occurrences, but diseases and pests can have large yield reducing effects. Additionally, the occurrence of pest and diseases is influenced by field conditions and farm management. Relative performances of scenarios in disease prone conditions are likely to be different from those simulated.

Future perspective

Objectives of smallholders and other stakeholder will vary and are dependent on: their spatial scale of analysis, farming styles and external incentives. Contextual constraints determine farmers' ability to adopt favourable diversification strategies. Environmentally, the range of simulated context did not show to influence the performance of the scenarios. Nevertheless, socio-economic conditions, such as limit freedom of decision-making, lack of access to high quality inputs, knowledge and capital, does limit the current ability of famers to adopt favourable diversification scenarios.

Farm assistance and sustainability schemes currently show not to be capable to appreciate diversified oil palm systems and include them into their funding schemes. In order for sustainability schemes to be inclusive to smallholders they need to acknowledge the mixed system tradition of the smallholder and its potential, meaning that certification criteria need to be more flexible. The presented results support opportunities for farmers to engage in diversifying their systems, further exploration and context-specific suitability analysis is recommended.

CONCLUSION

Based on the scenario analyses, I conclude that there is space for economic and environmental performance improvement through diversification of smallholder oil palm production systems. The performance varied over the set of indicators, but was independent of the tested soil type and number of consecutive dry days. The only indicator at which an oil palm monoculture showed superior to any diversification scenario was the low labour demand and therefore high relative returns to labour. The labour-wage returned by the intercrop systems was, however, highly competitive at present labour markets. Therefore, the lower RTL are not considered a main constraint to intercropping. At all other indicators performance improvement was obtained. Diversification through intercropping with marketable annuals showed most suitable when considering early yield and returns to land, while slightly improving the environmental impacts. Intercropping with perennials will require considerably more labour, but will be able to achieve the largest LER. If the commodity has a competitive price compared to palm oil, such as cocoa, it will deliver profits and serve as a risk-coping strategy.

Insight in smallholders' interest in intercropping, and the suitability of incentives to support adoption of diversification by smallholders are required to utilize and upscale the performance improvements plot-level diversification offers.

References

Adam, H., Collin, M., Richaud, F., Beulé, T., Cros, D., Omoré, A, & Tregear, J. W. (2011). Environmental regulation of sex determination in oil palm: current knowledge and insights from other species. *Annals of botany*, *108*(8), 1529-1537.

Agamuthu, P., Chan, Y. K., Jesinger, R., Khoo, K. M., & Broughton, W. J. (1981). Effect of differently managed legumes on the early development of oil palms (Elaeis guineensis Jacq.). *Agro-Ecosystems*, *6*(4), 315-323.

Agamuthu, P., & Broughton, W. J. (1985). Nutrient cycling within the developing oil palm-legume ecosystem. *Agriculture, ecosystems & environment*, *13*(2), 111-123.

Akbar, U., Tampubolon, F. H., Amiruddin, D., & Ollagnier, M. (1976). Fertilizer experimentation on oil palm in north Sumatra. *Oleagineaux*, *31*(7), 305-316.

Anuebunwa, F. O. (2000). A bio-economic on-farm evaluation of the use of sweet potato for complementary weed control in a yam/maize/egusi/cassava intercrop in pigeon pea hedgerows in the rain forest belt of Nigeria. *Biological agriculture & horticulture*, *18*(2), 95-102.

Azhar, B., Lindenmayer, D. B., Wood, J., Fischer, J., Manning, A., Mcelhinny, C., & Zakaria, M. (2013). The influence of agricultural system, stand structural complexity and landscape context on foraging birds in oil palm landscapes. *Ibis*, *155*(2), 297-312.

Bagnall-Oakeley, H., Conroy, C., Faiz, A., Gunawan, A., Gouyon, A., Penot, E., & Anwar, C. (1996). Imperata management strategies used in smallholder rubber-based farming systems. *Agroforestry Systems*, *36*(1-3), 83-104.

Bank of Indonesia. (09/2016). Indonesia Interest Rate 2005-2016 [Database]. Retrieved from: http://www.tradingeconomics.com/indonesia/interest-rate

Basiron, Y. (2007). Palm oil production through sustainable plantations. *European Journal of Lipid Science and Technology*, *109*(4), 289-295.

Belcher, B., Imang, N., & Achdiawan, R. (2004). Rattan, rubber, or oil palm: cultural and financial considerations for farmers in Kalimantan. *Economic Botany*, *58*, S77-S87.

Beukema, H., Danielsen, F., Vincent, G., Hardiwinoto, S., & Van Andel, J. (2007). Plant and bird diversity in rubber agroforests in the lowlands of Sumatra, Indonesia. *Agroforestry Systems*, *70*(3), 217-242.

Beukering, van P. J., Cesar, H. S., & Janssen, M. A. (2003). Economic valuation of the Leuser national park on Sumatra, Indonesia. *Ecological economics*, *44*(1), 43-62.

Binswanger, H. P., & Deininger, K. (1997). Explaining agricultural and agrarian policies in developing countries. *Journal of Economic Literature*, *35*(4), 1958-2005.

Bissonnette, J. F. (2016). Is oil palm agribusiness a sustainable development option for Indonesia? A review of issues and options. *Canadian Journal of Development Studies/Revue canadienne d'études du développement*, 1-20.

Breure, C. J. (1996). Desarrollo de las hojas en la palma de aceite (Elaeis guineensis) y determinación de la tasa de apertura de las hojas. *Revista Palmas*, *17*(4), 45-49.

Brisson, N., Mary, B., Ripoche, D., Jeuffroy, M. H., Ruget, F., Nicoullaud, B., & Richard, G. (1998). STICS: a generic model for the simulation of crops and their water and nitrogen balances. I. Theory and parameterization applied to wheat and corn. *Agronomie*, *18*(5-6), 311-346.

Budiman, A. F. S., & Penot, E. (1997). Smallholder rubber agroforestry in Indonesia. In *International Rubber Conference, IRC*.

Casson, A. (2000). *The hesitant boom: Indonesia's oil palm sub-sector in an era of economic crisis and political change* (No. CIFOR Occasional Paper no. 29, p. 50p). CIFOR, Bogor, Indonesia.

Cauwenbergh, van N., Biala, K., Bielders, C., Brouckaert, V., Franchois, L., Cidad, V. G., & Sauvenier, X. (2007). SAFE—A hierarchical framework for assessing the sustainability of agricultural systems. *Agriculture, ecosystems & environment*, *120*(2), 229-242.

Chan, K. W. L., & Chiew, K. (1998). Bunch components studies over the past two decades. In *International Conference on Oil and Kernel production in oil palm. A global perspectiveSeptember 27-28Kuala Lumpur, Malasia* (No. L-0372). PORIM.

Chew, P. S., & Khoo, K. T. (1976). Growth and yield of intercropped oil palms on a coastal clay soil in Malaysia. *International Agronomy Oil Palm Conference*

Colchester, M. (Ed.). (2011). *Oil palm expansion in South East Asia: trends and implications for local communities and indigenous peoples*. Forest Peoples Programme.

Comte, I., Colin, F., Whalen, J. K., Grünberger, O., & Caliman, J. P. (2012). 3 Agricultural Practices in Oil Palm Plantations and Their Impact on Hydrological Changes, Nutrient Fluxes and Water Quality in Indonesia: A Review. *Advances in Agronomy*, *116*, 71.

Corley, R. H. V. (1973). Effects of plant density on growth and yield of oil palm. *Experimental Agriculture*, *9*(02), 169-180.

Corley, R. H. V., & Mok, C. K. (1972). Effects of nitrogen, phosphorus, potassium and magnesium on growth of the oil palm. *Experimental Agriculture*, *8*(04), 347-353.

Corley, R.H.V. & Palat, T. (2013) Maximising lifetime yield for greater economic sustainability. Paper presented at Int. Palm Oil Congr. 'Green opportunities from the golden crop', Kuala Lumpur, 19–21.

Corley R.H.V. & Tinker P.B. (2003). *The Oil Palm.* Fourth edition. Blackwell Publishing.

Corley R.H.V. & Tinker P.B. (2015). *The Oil Palm*. Fifth edition. Blackwell Publishing.

Cramb, R., & McCarthy, J. F. (Eds.). (2016). *The Oil Palm Complex: Smallholders, Agribusiness and the State in Indonesia and Malaysia*. NUS Press.

Cramb, R. A., & Sujang, P. S. (2013). The mouse deer and the crocodile: oil palm smallholders and livelihood strategies in Sarawak, Malaysia. *The Journal of Peasant Studies*, *40*(1), 129-154.

De Groot, R. S., Wilson, M. A., & Boumans, R. M. (2002). A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecological economics*, *41*(3), 393-408.

Deb, S., Arunachalam, A., & Das, A. K. (2009). Indigenous knowledge of Nyishi tribes on traditional agroforestry systems. *Indian Jour Trad Knowledge*, *8*, 41-46.

Direktorat Jenderal Perkebunan (2015). Kelapa Sawit: Directorate General of Estate Crops. *Tree Crop Estate Statistics of Indonesia, Oil Palm, 2014–2016*. December 2015. Jakarta: Ministry of Agriculture (Indonesia).

Dobbins, C. L., Boehlje, M., Erickson, S., & Robert, T. (1995). Using games to teach farm and agribusiness management. *Review of Agricultural Economics*, *17*(3), 247-255.

Drescher, J., Rembold, K., Allen, K., Beckschäfer, P., Buchori, D., Clough, Y. & Irawan, B. (2016). Ecological and socio-economic functions across tropical land use systems after rainforest conversion. *Phil. Trans. R. Soc. B*, *371*(1694), 20150275.

FaoStat. Cassava consumption by country & Production of Cassava: top 10 producers (2013-2014). Viewed November, 2016, retrieved from: http://faostat.fao.org/beta/en/#data

Feder, G., Murgai, R., & Quizon, J. B. (2004). Sending farmers back to school: The impact of farmer field schools in Indonesia. *Applied Economic Perspectives and Policy*, *26*(1), 45-62.

Feintrenie, L., Schwarze, S., & Levang, P. (2010). Are local people conservationists? Analysis of transition dynamics from agroforests to monoculture plantations in Indonesia.

Fitzherbert, E. B., Struebig, M. J., Morel, A., Danielsen, F., Brühl, C. A., Donald, P. F., & Phalan, B. (2008). How will oil palm expansion affect biodiversity? *Trends in ecology & evolution*, *23*(10), 538-545.

Food and Agriculture Organization of the United Nations (1970). Better farming series (No. 22). *African Institute for economic and Social Development*.

Franzel, S., Peters, G. H., & Pingali, P. (2001). Use of an indigenous board game,'bao', for assessing farmers' preferences among alternative agricultural technologies. In *Tomorrow's agriculture: incentives, institutions, infrastructure and innovations. Proceedings of the Twenty-fourth International Conference of Agricultural Economists, Berlin, Germany, 13-18 August 2000.* (pp. 416-424).

Gatto, M., Wollni, M., & Qaim, M. (2015a). Oil palm boom and land-use dynamics in Indonesia: the role of policies and socioeconomic factors. *Land Use Policy*, *46*, 292-303.

Gatto, M., Wollni, M., Rosyani, I., & Qaim, M. (2015b). *Oil palm boom, contract farming, and village development: Evidence from Indonesia* (No. 10). Collaborative Research Centre 990" EFForTS, Ecological and Socioeconomic Functions of Tropical Lowland Rainforest Transformation Systems (Sumatra, Indonesia)", University of Goettingen.

Genuchten, van M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil science society of America journal*, *44*(5), 892-898.

Godoy, R., & Bennett, C. P. (1991). The economics of monocropping and intercropping by smallholders: The case of coconuts in Indonesia. *Human Ecology*, *19*(1), 83-98.

Goh, K. J., Chew, P. S., Teo, C. B., & Chee, K. H. (1994). Maximising and maintaining oil palm yields on commercial scale in Malaysia. In *Proc. Int. Planters' Conf. on Managing Oil Palm for Enhanced Profitability. Incorp. Soc. Planters, Kuala Lumpur* (pp. 121-141).

Goh, K. J., & Po, S. B. (2005). Fertilizer recommendation systems for oil palm: Estimating the fertilizer rates. In *Proceedings of MOSTA Best Practices Workshops-Agronomy and Crop Management.*

Goudriaan, J., & Van Laar, H. H. (1994). Radiation in crops. In *Modelling Potential Crop Growth Processes* (pp. 95-119). Springer Netherlands.

Grace, M. R. (1977). *Cassava processing*. Rome: Food and Agriculture Organization of the United Nations.

Grieg-Gran, M. (2008). The cost of avoiding deforestation: Update of the report prepared for the Stern Review of the Economics of Climate Change.

Hartemink, A. E. (2005). Plantation agriculture in the tropics: Environmental issues. *Outlook on Agriculture*, *34*(1), 11-21.

Hartley, C.W.S. (1988) *The Oil Palm*. Third edition. Longman.

Henson, I. E. (1993). Carbon assimilation, water use and energy balance of an oil palm plantation assessed using micrometeorological techniques. In *PORIM International Palm Oil Congress: Update and Vision (Agriculture) 22-25Kuala Lumpur, Malaysia* (No. L-0314). PORIM.

Higgins, M. J., Rock, C. A., Bouchard, R., & Wengrezynek, B. (1993). Controlling agricultural runoff by use of constructed wetlands. *Constructed wetlands for water quality improvement. CRC Press, Boca Raton*, 359-367.

Hodnett, M.G. & Tomasella J., (2002). Marked differences between van Genuchten soil water-retention parameters for temperate and tropical soils: a new water-retention pedotransfer functions developed for tropical soils. Geoderma 108:155–180

Hoffmann, M. P., Vera, A. C., Van Wijk, M. T., Giller, K. E., Oberthür, T., Donough, C., & Whitbread, A. M. (2014). Simulating potential growth and yield of oil palm (Elaeis guineensis) with PALMSIM: Model description, evaluation and application. *Agricultural Systems*, *131*, 1-10.

Holford, I. C. R., Wedderburn, R. W. M., & Mattingly, G. E. G. (1974). A Langmuir two-surface equation as a model for phosphate adsorption by soils. *Journal of Soil Science*, *25*(2), 242-255.

Iijima, M., Izumi, Y., Yuliadi, E., Sunyoto, Afandi, & Utomo, M. (2003). Erosion control on a steep sloped coffee field in Indonesia with alley cropping, intercropped vegetables, and no-tillage. *Plant production science*, *6*(3), 224-229.

Ivancic, H., & Koh, L. P. (2016). Evolution of sustainable palm oil policy in southeast Asia. *Cogent Environmental Science*, (just-accepted).

Joshi, L., Wibawa, G., Beukema, H., Williams, S., & van Noordwijk, M. (2000). Technological change and biodiversity in the rubber agroecosystem of Sumatra. *Tropical Agroecosystem*, 133-155.

Kementerian Kehutanan Indonesia (Ministry of Forestry) 2003. Tropical Rainforest Heritage of Sumatra. *(available at http://whc.unesco.org/uploads/nominations/1167.pdf)*

Khamis, A., Ismail, Z., Haron, K., & Mohammed, A. T. (2005). Nonlinear growth models for modelling oil palm yield growth. *Journal of Mathematics and Statistics*, *1*(3), 225-233.

Khasanah, N., van Noordwijk, M. & Ningsih, H. (2015a). Aboveground carbon stocks in oil palm plantations and the threshold for carbon-neutral vegetation conversion on mineral soils. Cogent Environmental Science 1: 1119964

Khasanah, N., van Noordwijk, M., Ningsih, H. & Rahayu, S. (2015b). Carbon neutral? No change in mineral soil carbon stock under oil palm plantations derived from forest or non-forest in Indonesia. Agric. Ecosyst. Environ 211: 195–206.

Klasen, S., Meyer, K. M., Dislich, C., Euler, M., Faust, H., Gatto, M., & Pérez-Cruzado, C. (2016). Economic and ecological trade-offs of agricultural specialization at different spatial scales. *Ecological Economics*, *122*, 111-120.

Knierueyer, O., & Infomiatik, L. P. (2004). Rule-based modelling with the XL/GroIMP software. In *The Logic of Artificial Life: Abstracting and Synthesizing the Principles of Living Systems; Proceedings of the 6th German Workshop on Artificial Life, April 14-16, 2004, Bamberg, Germany* (p. 56). IOS Press.

Koh, L. P., & Wilcove, D. S. (2008). Is oil palm agriculture really destroying tropical biodiversity?. *Conservation letters*, *1*(2), 60-64.

Kottek, M., Grieser, J. , Beck, C., Rudolf, B., & Rubel, F. (2006). World Map of the Köppen-Geiger climate classification updated. *Meteorol. Z.*, 15, 259-263.

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *science*, *304*(5677), 1623-1627.

Larson, D. F., & Butzer, R. (2002). *Determinants of agricultural growth in Indonesia, the Philippines, and Thailand* (Vol. 2803). World Bank Publications.

Legros, S., Mialet-Serra, I., Clement-Vidal, A., Caliman, J. P., Siregar, F. A., Fabre, D., & Dingkuhn, M. (2009a). Role of transitory carbon reserves during adjustment to climate variability and source–sink imbalances in oil palm (Elaeis guineensis). *Tree physiology*, *29*(10), 1199-1211.

Legros, S., Mialet-Serra, I., Caliman, J. P., Siregar, F. A., Clement-Vidal, A., Fabre, D., & Dingkuhn, M. (2009b). Phenology, growth and physiological adjustments of oil palm (Elaeis guineensis) to sink limitation induced by fruit pruning. *Annals of botany*, *104*(6), 1183-1194.

Letchumanan, A. L., Nazeeb, M., & Wood, B. J. (1990). Underplanting as a means to shorten the Non-productive period of oil palm. In *1989 PORIM International Palm Oil Development Conference. Agriculture. 1989. September 5-9, Kuala Lumpur, Malaysia* (No. L-0076). PORIM.

Li, T. M. (2015). *Social impacts of oil palm in Indonesia: A gendered perspective from West Kalimantan* (Vol. 124). CIFOR.

Loague, K. & Green, R.E. (1991). Statistical and graphical methods for evaluating solute transport models: Overview and application. Journal of Contaminant Hydrology 7:51–73.

Manivong, V., & Cramb, R. A. (2008). Economics of smallholder rubber expansion in Northern Laos. *Agroforestry Systems*, *74*(2), 113-125.

Manns, H. R., & Berg, A. A. (2014). Importance of soil organic carbon on surface soil water content variability among agricultural fields. *Journal of Hydrology*, *516*, 297-303.

Margono, B. A., Turubanova, S., Zhuravleva, I., Potapov, P., Tyukavina, A., Baccini, A., & Hansen, M. C. (2012). Mapping and monitoring deforestation and forest degradation in Sumatra (Indonesia) using Landsat time series data sets from 1990 to 2010. *Environmental Research Letters*, *7*(3), 034010.

Matthews, R., Stephens, W., Hess, T., Middleton, T., & Graves, A. (2002). Applications of crop/soil simulation models in tropical agricultural systems. *Advances in Agronomy*, *76*, 31-124.

McCarthy, J. F., & Cramb, R. A. (2009). Policy narratives, landholder engagement, and oil palm expansion on the Malaysian and Indonesian frontiers. *The Geographical Journal*, *175*(2), 112-123.

McCarthy, J. F. (2010). Processes of inclusion and adverse incorporation: oil palm and agrarian change in Sumatra, Indonesia. *The Journal of peasant studies*, *37*(4), 821-850.

Mead, R., & Willey, R. W. (1980). The concept of a 'land equivalent ratio' and advantages in yields from intercropping. *Experimental Agriculture*, *16*(03), 217-228.

Meier, E. (2013). The wood database.

Miettinen, J., & Liew, S. C. (2010). Status of peatland degradation and development in Sumatra and Kalimantan. *Ambio*, *39*(5-6), 394-401.

Molenaar, J. W., Persch-Orth, M., Lord, S., Taylor, C., & Harms, J. (2013). Diagnostic study on Indonesian Oil Palm Smallholders: developing a better understanding of their performance and potential. *International Finance Corporation, World Bank Group*.

Mulia, R. & Khasanah, N. (2012). Introduction to Agroforestry modeling. WaNuLCAS model training Hanoi- Vietnam, 07-2012. ICRAF-SEA, Bogor, Indonesia.

Mundlak, Y., Larson, D. F., & Butzer, R. (2002). *Determinants of agricultural growth in Indonesia, the Philippines, and Thailand* (Vol. 2803). World Bank Publications.

Nambiar, E. S., & Sands, R. (1993). Competition for water and nutrients in forests. *Canadian Journal of Forest Research*, *23*(10), 1955-1968.

Namkoong, G., Boyle, T., El-Kassaby, Y. A., Palmberg-Lerche, C., Eriksson, G., Gregorius, H. R., & Young, A. (2002). Criteria and indicators for sustainable forest management: assessment and monitoring of genetic variation. *Forest genetic resources working paper FGR E*, *37*.

Nazeeb, M., Loong, S. G., Wood, B. J., Hassan, A. H., Chew, P. S., & Pushparajah, E. (1988). Trials on reducing the non-productive period at oil palm replanting. In *Proceedings of the 1987 international oil palm/palm oil conference. Progress and prospects. I. Agriculture.* (pp. 372-390). Palm Oil Research Institute of Malaysia.

Noordwijk, van M., Khasanah, N., & Dewi, S. (2016). Can intensification reduce emission intensity of biofuel through optimized fertilizer use? Theory and the case of oil palm in Indonesia. GCB Bioenergy. Doi: 10.1111/gcbb.12398.

Noordwijk, van M., & Lusiana, B. (1999). WaNuLCAS, a model of water, nutrient and light capture in agroforestry systems. In *Agroforestry for Sustainable Land-Use Fundamental Research and Modelling with Emphasis on Temperate and Mediterranean Applications* (pp. 217-242). Springer Netherlands.

Noordwijk, van M., Lusiana, B., Khasanah, N. & Mulia, R. (2011). WaNuLCAS version 4.0, Background on a model of water nutrient and light capture in agroforestry systems. Bogor, Indonesia. World Agroforestry Centre – ICRAF, SEA Regional Office. 224p.

Obidzinski, K., Andriani, R., Komarudin, H., & Andrianto, A. (2012). Environmental and social impacts of oil palm plantations and their implications for biofuel production in Indonesia. *Ecology and Society*, *17*(1).

Oldeman, L.R., Darwis, S.N. & Las, I. (1978) Central Research Institute for Agriculture, Bogor, Indonesia.

Pahan, I. (2008). *Kelapa Sawit: Manajemen Agribisnis dari Hulu hingga Hilir [Palm Tree: Agribusiness Management from Upstream to Downstream].* Jakarta: Penerbit Swadaya.

Papenfus, M. M. (2000). Investing in oil palm: an analysis of independent smallholder oil palm adoption in Sumatra, Indonesia. *Southeast Asia Policy Research Working Paper*, *15*, 1-20.

Perdew, J. G., & Shively, G. E. (2009). The economics of pest and production management in small-holder cocoa: lessons from Sulawesi. *Bulletin of Indonesian Economic Studies*, *45*(3), 373-389.

Pereira, L. S., Cordery, I., & Iacovides, I. (2012). Improved indicators of water use performance and productivity for sustainable water conservation and saving. *Agricultural Water Management*, *108*, 39-51.

Ploeg, van der J. D. (1994). Styles of farming: an introductory note on concepts and methodology. *Born from within: Practice and perspectives of endogenous rural development*, 7-30.

Potter, L. M. (2016). Alternative Pathways for Smallholder Oil Palm in Indonesia: International Comparisons. *The Oil Palm Complex: Smallholders, Agribusiness and the State in Indonesia and Malaysia*, 155.

Prévôt, P., & Duchesne, J. (1955). Densités de plantation pour le palmier à huile. *Oléagineux*, 10, 117-122.

Pushparajah, E., Cnah, F., & Magat, S. S. (1990). Phosphorus requirements and management of oil palm, coconut and rubber. *Phosphorus requirements for sustainable agriculture in Asia and Oceania*, 399-425.

Putnam, D. H., Oplinger, E. S., Teynor, T. M., Oelke, E. A., Kelling, K. A., & Doll, J. D. (1991). Peanut. Alternative Crops Manual.

Rao, M. R., Nair, P. K. R., & Ong, C. K. (1998). Biophysical interactions in tropical agroforestry systems. In Directions in Tropical Agroforestry Research (pp. 3-50). Springer Netherlands.

Reeves, D. W. (1997). The role of soil organic matter in maintaining soil quality in continuous cropping systems. *Soil and Tillage Research*, *43*(1), 131-167.

Remesh, B. P. (2010). Dynamics of Rural Labour: A Study of Small Holding Rubber Tappers in Kerala. Concept Publishing Company.

Rice, R. A., & Greenberg, R. (2000). Cacao cultivation and the conservation of biological diversity. *AMBIO: A Journal of the Human Environment*, *29*(3), 167-173.

Rist, L., Feintrenie, L., & Levang, P. (2010). The livelihood impacts of oil palm: smallholders in Indonesia. Biodiversity and conservation, 19(4), 1009-1024.

Rival, A., & Levang, P. (2014). *Palms of controversies: Oil palm and development challenges.* CIFOR.

Roundtable on Sustainable Palm Oil. (2014). RSPO Smallholder Support Fund (RSSF) Governance Policy.

Roundtable on Sustainable Palm Oil. (2016). About us: History & milestones. Author. Retrieved October, 2016, from: http://www.rspo.org/about

Samedani, B., Juraimi, A. S., Anwar, M. P., Rafii, M. Y., Awadz, S. A. S., & Anuar, A. R. (2012). Competitive ability of some cover crop species against Asystasia gangetica and Pennisetum polystachion. *Acta Agriculturae Scandinavica, Section B–Soil & Plant Science*, *62*(7), 571-582.

Samedani, B., Juraimi, A. S., Abdullah, S. A. S., Rafii, M. Y., Rahim, A. A., & Anwar, M. P. (2014). Effect of cover crops on weed community and oil palm yield. *Int. J. Agric. Biol*, *16*, 23-31.

Sanchez, P. A. (1987). Soil productivity and sustainability in agroforestry systems. *Agroforestry: A decade of development*, 205-223.

Schwarze, S., Euler, M., Gatto, M., Hein, J., Hettig, E., Holtkamp, A. M., & Moser, S. (2015). GOEDOC-Dokumenten-und Publikationsserver der Georg-August-Universität Göttingen.

Sheil, D., Casson, A., Meijaard, E., Van Noordwjik, M., Gaskell, J., Sunderland-Groves, J. & Kanninen, M. (2009). *The impacts and opportunities of oil palm in Southeast Asia: What do we know and what do we* *need to know?* (No. CIFOR Occasional Paper no. 51, p. 67p). Center for International Forestry Research (CIFOR), Bogor, Indonesia.

Silva-Castañeda, L. (2012). A forest of evidence: third-party certification and multiple forms of proof—a case study of oil palm plantations in Indonesia. *Agriculture and Human Values*, *29*(3), 361-370.

Siregar, U. J., Rachmi, A., Massijaya, M. Y., Ishibashi, N., & Ando, K. (2007). Economic analysis of sengon (Paraserianthes falcataria) community forest plantation, a fast growing species in East Java, Indonesia. *Forest Policy and Economics*, *9*(7), 822-829.

Smiley, G. L., & Kroschel, J. (2010). Yield development and nutrient dynamics in cocoa-gliricidia agroforests of Central Sulawesi, Indonesia. *Agroforestry systems*, *78*(2), 97-114.

Smith, B.G., Donough, C.R. & Corley, R.H.V. (1996). Relationship between oil palm clone phenotype and optimal density. *D. Ariffin (Ed.), et al., Proceedings of the 1996 PORIM Int. Palm Congr. Competitiveness for the 21st century, Palm Oil Res. Inst. Malaysia, Kuala Lumpur,* 76–86.

SNV (formerly: Stichting Nederlandse Vrijwilligers) (2016). Smallholder palm oil farmers can farm sustainably, but external support is necessary [Website article]. Retrieved on October 2016 from: http://www.snv.org/update/smallholder-palm-oil-farmers-can-farm-sustainably-external-support-necessary

Souza, C. A. S., Dias, L. A. D. S., Aguilar, M. A. G., Sonegheti, S., Oliveira, J., & Costa, J. L. A. (2009). Cacao yield in different planting densities. *Brazilian Archives of Biology and Technology*, *52*(6), 1313-1320.

Stockle, C. O., Martin, S. A., & Campbell, G. S. (1994). CropSyst, a cropping systems simulation model: water/nitrogen budgets and crop yield. *Agricultural Systems*, *46*(3), 335-359.

Streck, N. A., Pinheiro, D. G., Junior Zanon, A., Gabriel, L. F., Rocha, T. S. M., Souza, A. T. D., & Silva, M. R. D. (2014). Effect of plant spacing on growth, development and yield of cassava in subtropical environment. *Bragantia*, *73*(4), 407-415.

Therville, C., Feintrenie, L., & Levang, P. (2011). Farmers' perspectives about agroforests verconvesion to plantations in Sumatra. Lessons learnt from Bungo District, Jambi. *Forests, Trees and Livelihoods*, *20*(1), 15-33.

Thornley, J. H., & Johnson, I. R. (1990). *Plant and crop modeling: a mathematical approach to plant and crop physiology*. Oxford University Press, New York.

Trostle, R. (2008). *Global agricultural supply and demand: factors contributing to the recent increase in food commodity prices*. Washington, DC, USA: US Department of Agriculture, Economic Research Service.

Tully, D. (1988). *Culture and Context in Sudan: the process of market incorporation in Dar Masalit*. SUNY Press.

Tung, P. G., Yusoff, M. K., Majid, N. M., GohKah, J., & GanHuang, H. (2009). Effect of N and K fertilizers on nutrient leaching and groundwater quality under mature oil palm in Sabah during the monsoon period. *American Journal of Applied Sciences*, *6*(10), 1788-1799.

Vermeulen, S., & Goad, N. (2006). *Towards better practice in smallholder palm oil production*. Iied.

Villamor, G. B., & van Noordwijk, M. (2011). Social Role-Play Games Vs Individual Perceptions of Conservation and PES Agreements for Maintaining Rubber Agroforests in Jambi(Sumatra), Indonesia. *Ecology and Society*, *16*(3), 27.

Whitten, T., Damanik, S. J., Anwar, J., & Hisyam, N. (2000). The Ecology of Sumatra. The Ecology of Indonesia Series, vol. 1. *Periplus Editions, Hong Kong*.

Wibawa, G., Hendratno, S., & van Noordwijk, M. (2005). Permanent smallholder rubber agroforestry systems in Sumatra, Indonesia. *Slash-and-burn agriculture: the search for alternatives*, 222-231.

Wijaya, A., & Glasbergen, P. (2016). Toward a New Scenario in Agricultural Sustainability Certification? The Response of the Indonesian National Government to Private Certification. *The Journal of Environment & Development*, 1070496516640857.

Wilcove, D. S., & Koh, L. P. (2010). Addressing the threats to biodiversity from oil-palm agriculture. *Biodiversity and Conservation*, *19*(4), 999-1007.

Winarni, R. R., & Sutrisno, E., (2014). Beyond EU, RSPO and ISPO Sustainability Requirements1. *TuK Paper*, Indonesia.

Yildirim, E., & Guvenc, I. (2005). Intercropping based on cauliflower: more productive, profitable and highly sustainable. *European Journal of Agronomy*, *22*(1), 11-18.

Figures

Forest cover of Sumatra:

Figure 1: B. A. Margono, S. Turubanova, I. Zhuravleva, P. Potapov, A. Tyukavina, A. Baccini, S. Goetz and M.C. Hansen (2012). Mapping and monitoring deforestation and forest degradation in Sumatra (Indonesia) using Landsat time series data sets from 1990 to 2010. Environ. Res. Lett. 7 034010 doi:10.1088/1748-9326/7/3/034010

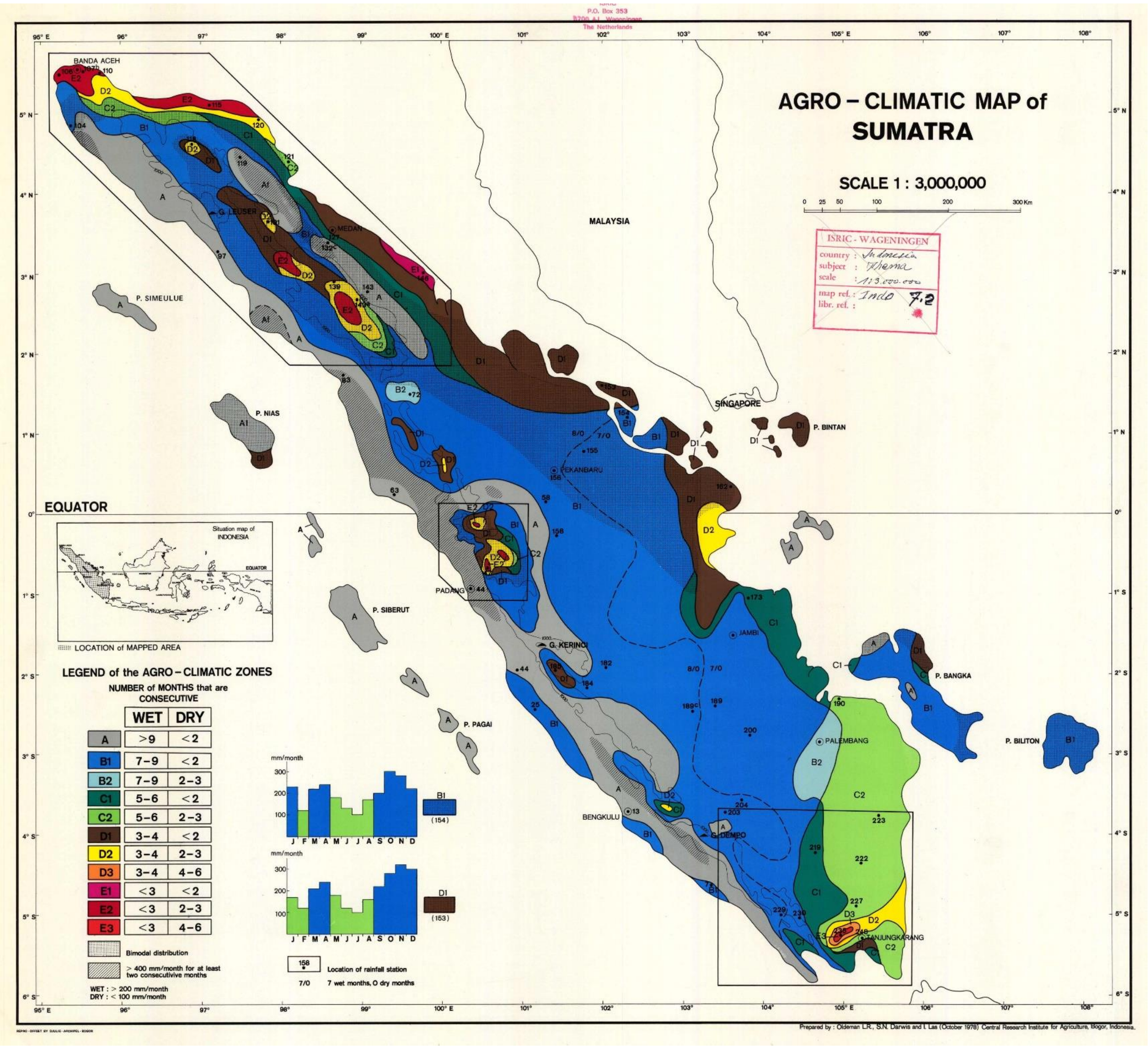
Figure 2: Street side sales of oil palm bunches by independent smallholder in Batanghari Regency, Jambi, Sumatra, Indonesia. (10/26/2016, D. Stomph)

Figure 3: Oil palm diversification in the field. (various dates 2015-2016, M. van Noordwijk)
Sisipan rubber integrating young oil palm. Batanghari Regency, Jambi, Sumatra, Indonesia. (10/26/2016, D. Stomph)

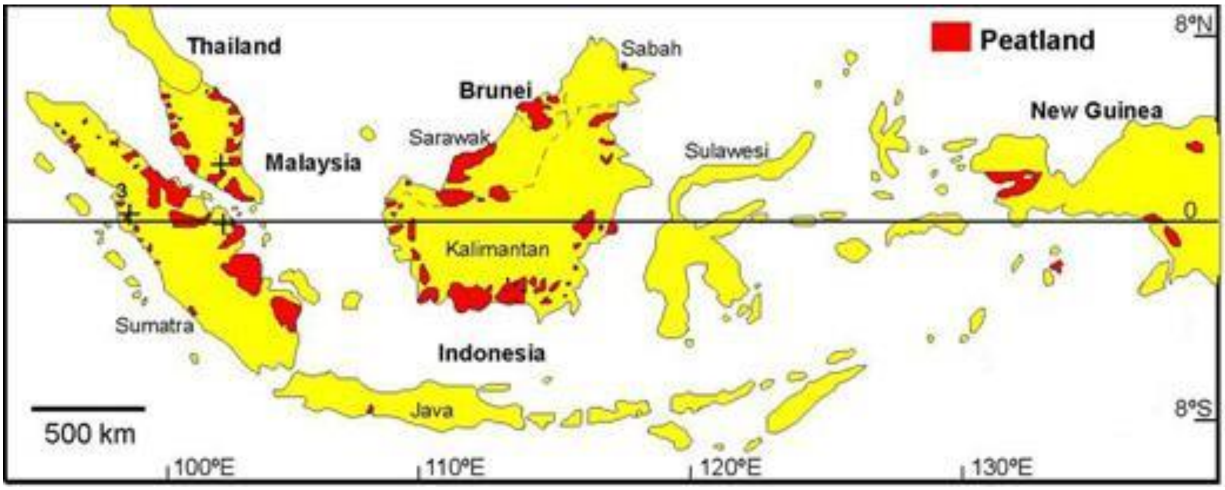
Appendix 2: Frond spreading with legume soil cover, by Pensinee Wongwian retrieved from: http://gb.123rf.com/stock-photo/conserving.html

APPENDIX 1– Sumatran Agro Climatic map & peatland distribution

Source ISRIC - Wageningen, map reference: Indo 7.2



Prepared by: Oldeman, L.R., Darwis, S.N. & Las, I. (1978) Central Research Institute for Agriculture, Bogor, Indonesia.



Vasander, H. 2014. In: Biancalani, R. & Avagyan, A. (eds.), Towards climate-responsible peatlands management. Mitigation of climate change in agriculture series 9: 15-18. FAO, Rome. Tropical peatland

APPENDIX 2 - Common management practices in oil palm cultivation

(For a more detailed description you are referred to: Corley & Tinker, 2015)

Field preparation

Establishment of the field has large implications for the performance of the palms later on. Large differences in field preparation exist due to contextual variations. In terms of socioeconomic conditions availability of capital, labour and land, as well as the political situation and economic stability, determine possibilities and limitations. The environmental conditions require certain preparation practices based up on the soil, slope, field hydraulics and the previous land use (Corley & Tinker, 2015). The importance of careful preparation is illustrated by Goh *et al.*, (1994) showing that poor planting arrangements affect yield establishment mainly through delayed initial growth.

Land clearing is a first preparatory step which either requires heavy machinery, vegetation burning or manual clearing. Mainly due to labour costs and limited labour availability manual land clearing is only practiced on smallholder scale (Corley & Tinker, 2003). Over the last decade the most common practice has shifted from burning to mechanical land clearing. After mechanical clearing the remaining vegetation is left to rot or burned (Comte *et al.*, 2012). The large scale burning has been a main reason for concern as these fires are difficult to manage, release greenhouse gasses and forms a dense haze. Thereby threatening nearby areas, polluting air and causing the loss of valuable nutrients.

After clearing depending on the slope the land may require construction of terraces or bunds. For peat soils drainage systems will need to be installed to lower the water table. The soil should preferably have a profile depth >1m, and a pH ranging from 4 to 6 (depending on soil type). Commonly the oil palm seedlings are transplanted during a relatively wet period, at an age of between 10 months and 20 months (Corley & Tinker, 2015)

Replanting can be done in phases -by replanting under the old stand-, or after land clearing. Independent smallholders are the main practitioners of under planting, having a mixed age system (Azhar *et al.*, 2013). The main reasons for practicing this is the increased income stability in such systems. The large investments of (re)planting can be covered by income from the other palms. Furthermore, systematic removal and replanting can, when practiced well, improve nutrient recycling and has been reported to result in larger cumulative yields (Corley & Palat (2013) and Nazeeb *et al.* (1988) in Corley & Tinker, 2015; Letchumanan *et al.* (1990)).

Weed control

Commonly a circle around each palm is kept weed free. This weed free circle has a diameter of around 4 meters. The method is either through mechanical weeding (most common for smallholders) or by herbicide application (Corley & Tinker, 2003). The latter can be applied with a conventional knapsack sprayer, a controlled droplet applicator or a mist blower. Additional to the planting circle, also the pathways can be kept free of weeds to ease access for maintenance and harvesting.

Additional to allowing accessibility, reducing the population of undesired species in between the palms will decrease the experienced competition. In juvenile plantings this is mainly by limiting the competition for light. In later stages, where the oil palm outgrows the other species, weeds mainly affects palm growth and yield by competing for nutrients and water. As a way of integrated weed management creeping leguminous species can be sown after a preparatory spraying. This way the legumes will be able to outcompete the weed species while providing considerable benefits to the oil palm (more in section: Leguminous creeping cover).

Fertilizer management

Smallholders typically fertilize manually, where fertilizer is applied in a circle around the palm. This placement technique is more efficient than broadcasting, but is currently only feasible when applied manually. However, as labour prices and availability differ per region and vary over time mechanized broadcasting is another option. In Malaysia a trend toward mechanization is observed, whether the same trend will be seen in Indonesia remains uncertain.

As a source of nitrogen urea is favored for is comes at low costs (Corley & Tinker, 2003). Another practice involves the application of ammonium sulfate. The latter is superior to urea in terms of application efficiency, but this advantage does not compensate for the extra costs. Phosphate is mainly applied in the form of Triple superphosphate (TSP) (Pahan, 2008). Potassium is another nutrient essential to oil palm dry matter production and K-limitation is recognized to decrease FFB yields (Corley & Mok, 1972). Due to the high solubility of potassium in the tropical climates suitable for oil palm production it is prone to losses. On forest soils natural K-reserves may be present, but these are certain to decline over time, especially when N fertilizer is applied. This requires a careful dosages and timing of fertilizer application (Corley & Tinker, 2015).

Pruning

The most common practice is to prune the palm up to the first developing bunch. This gives the advantage to clearly observe ripening, which balances out the drawback of not letting natural senescence set in. For the young oil palm, where fruit bunch visibility is not yet too limited, the lower leaves may be left intact to maintain sufficient leaf area. For the mature palms the most desired form is progressive pruning based on the harvest intervals, results in a frond of around 40 leaves. The cut leaves are returned to the soil by stacking them in piles at alternating interlines. Once matured the palms deliver an organic matter in put 9 Mg dry matter ha^{-1} yr^{-1} (Henson 1999c, in Corley & Tinker, 2003). The main objectives of frond stacking are conservation of soil, water and internal nutrient cycling. Whether these objectives are met is debatable. Another method which might be more effective is to spread the frond equally over the soil (figure A1)

Figure A1: Equally spread palm fronds, overgrown by leguminous creeping cover

Harvesting

Assuming good quality planting material and field preparation, oil palm can bear harvestable fruits at the age of 3 years. Fruit bunches are generally harvested with the use of a chisel. As the palm height increases harvesting because increasingly difficult, generally after 5 years a chisel is no longer suited. For mature palms generally a hooked knife on a bamboo pole is used. Timing of harvesting is essential, immature bunches will not have reached their potential oil content, while harvesting of overripe bunches will result in fruit scattering (Corley & Tinker, 2003).

After harvest the fresh fruit bunches are commonly transported by truck. To prevent quality degradation, within 48 hours after harvest the bunches need to arrive at the mill for the abstraction of crude palm oil and kernels. Mills of different capacities exist, but an average commercial mill requires assured supply of a large productive area of at least 5-10 thousand hectares (Cramb & McCarthy, 2016).

Re-planting

The choice to end the production cycle and plant new palms is mainly an economical decision driven the difficulty of the plantation management, the speed of development of improved planting material and planting material-, labour- and oil prices. Currently most oil palm plots are re-planted after 25 years of production. The management difficulties, due to increasing palm height and fruit bunch sizes, have been seen to result in declining yields after 10-15 years (Corley & Tinker, 2003; Cramb & McCarthy, 2016). Making harvesting and overall maintenance more labour intensive. Additionally, oil palm seed material is under continuous development and therefore it is likely that within a 25 years period improved planting material has been developed (Corley & Tinker, 2003).

Leguminous creeping cover

The most common intercrop of oil palm is that with a creeping leguminous crop. The effects of these covers on erosion, nutrient balances and soil water has quiet extensively been cover in research. Reported effects on palm oil yield have been subjected to debate. Differences in legume cover performances may have to do with site specifics (especially soil type), choice of legume species, time of sowing fertilizer schemes and field preparation (Corley & Tinker, 2003; Agamuthu *et al.*, 1981). The use of leguminous covers has been reported to serve multiple benefits: minimizing soil moisture evaporation and runoff losses, reducing soil erosion, improving or maintaining soil fertility levels, stimulating recycling of nutrients and decreasing N losses through leaching (Corley & Tinker, 2003; Samedani *et al.*, 2012; Samedani *et al.*, 2014; Comte *et al.*, 2012). The sum of functions leads (especially in the initial development phase) to increased levels of nutrients in the palm fronts, faster growth rates and an increased FFB yield (Broughton, 1976; Agamuthu *et al.*, 1981). Another factor stimulating the popularity of leguminous covers is its potential to replacement herbicide-use. The driving incentive for this is not necessarily cost saving but public and policy invoked. The increasing concerns about continuous use of herbicides on a large scale, resulting in a growing population of noxious weeds, herbicide resistance, pollution of natural resources, and loss of habitat for pest controlling predators and pollinating insects (Adam *et al.*, 2011; Samedani *et al.*, 2014).

Especially during the first years after planting the soil is left relatively bare, making it prone to erosion, nutrient leaching and weed invasion (Comte *et al.*, 2012). During this phase sufficient water and light is available for biomass production additional to the oil palm development. The main species sown as a cover in South East Asia are: *Mucuna bracteata, Pueraria javanica, Centrosema pubescens, Calopogonium caeruleum, Calapogonium mucunoides* (Corley & Tinker, 2003; Samedani *et al.*, 2012). The species can be planted either in monocultures or in mixture to make use of their different growth patterns. Ideally the cover is sown directly after land clearance and before palm planting (Sanchez, 1987).

An extensive study on nitrogen cycling in an oil palm-legume planting was carried out by Agamuthu & Broughton (1985). They reported atmospheric N-fixation of 150 kg $ha^{-1} yr^{-1}$ and a decrease in N-leaching of 63 kg $ha^{-1} yr^{-1}$. Resulting of a net N-gain of 239 kg $ha^{-1} yr^{-1}$ compared to natural occurring covers. They further state that the re-release of N through legume debris stimulates root-growth and supports general development. Reported values on N-fixation and recycling differ largely between studies, which can be explained by differences in planting conditions.

The legume cover is generally seen to decline with oil palm establishment, this trend arises from the increased competition for light, and to lesser extent competition for nutrients and water. Therefore, after 4 years the undergrowth is likely to be a mixed system of legumes and natural occurring vegetation. The stacking of the palm front is another driving factor of the leguminous cover decline.

The leguminous cover scenario simulated the cover crop for 2 years in 80% of the field, excluding the oil palm planting zone. After 2 years the farmer will most commonly chose to clear the harvesting and maintenance path to ease field access (Corley & Tinker, 2008). Additionally, the front stacking will require space, decreasing the availability of light and space for the cover crop to grow. Therefore, in the simulation, the cover was only maintained up to 4 years after planting, in one third of the field to represent common practices.

Initial-phase intercropping

Alternatively, to a leguminous ground cover, intercropping can be practiced for a limited number of years to optimize light, water and nutrient capture during the phase of establishment. In Indonesia and Malaysia cases of intercropping exist, usually the intercropped products serve to be sold at local markets. The crops of choice are usually groundnut, chilies, vegetables, maize and cassava (Corley & Tinker, 2015). Of these crops only cassava was noted to have a detrimental effect on palm yield by competing for light N and P. However, when the intercropping period was limited to a period of 2 years after planting there was no lasting effect on the yield (Chew & Khoo, 1976).

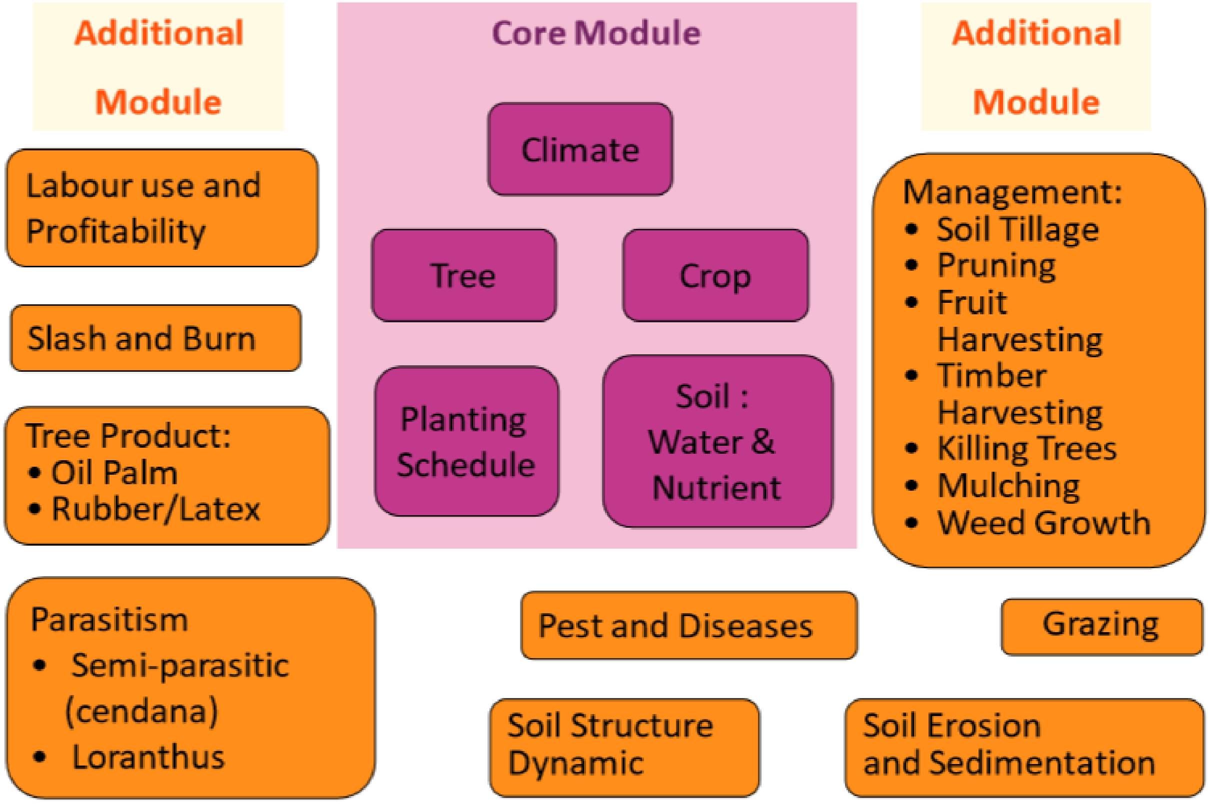
Permanent intercropping

Permanent intercropping of oil palm with trees is not a common practice in Indonesia. The main mentioned constraints to such mixed systems are limitation to mechanize.

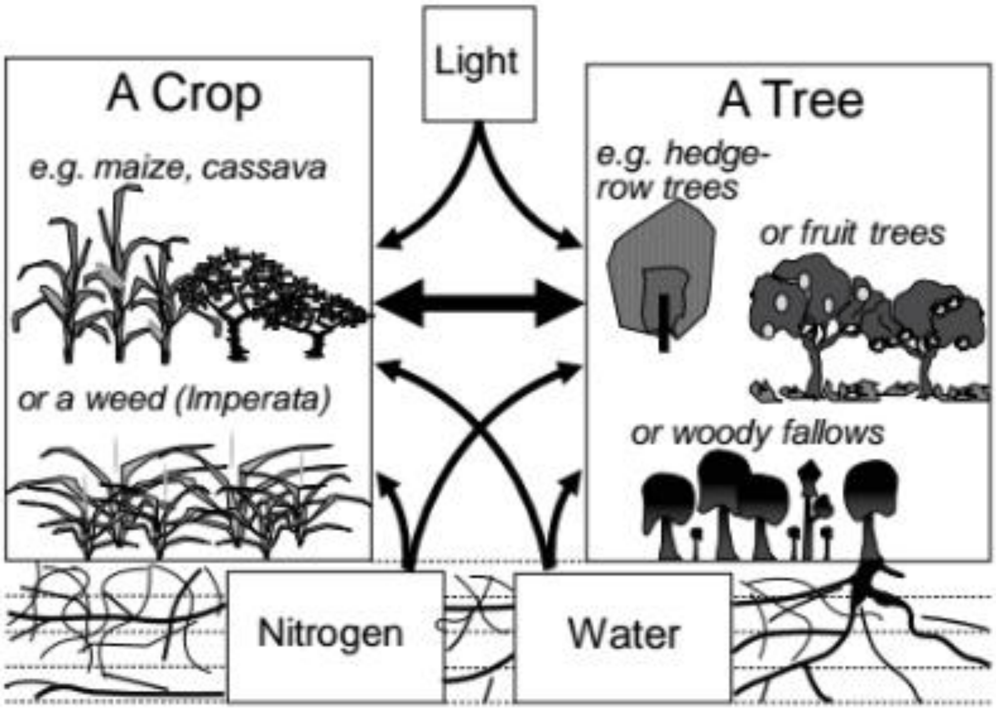
Long-term experiments for palm-tree interactions are relatively limited. Current interest in sustainable farming methods, might alter this, by driving exploration of alternative production methods. Agroforestry combining oil palm with permanent tree crops yielding a well-marketable product is thus-far mainly practiced by small-scale farmers.

APPENDIX 3 – a. Systematic diagram of the core module and the additional modules in WaNuLCAS.

Figures were copied from: Van Noordwijk *et al.*, 2011



3 – b. Figurative diagram of the WaNuLCAS system components and their interactions.



APPENDIX 4 – Calibration: input data, graphs and statistical output

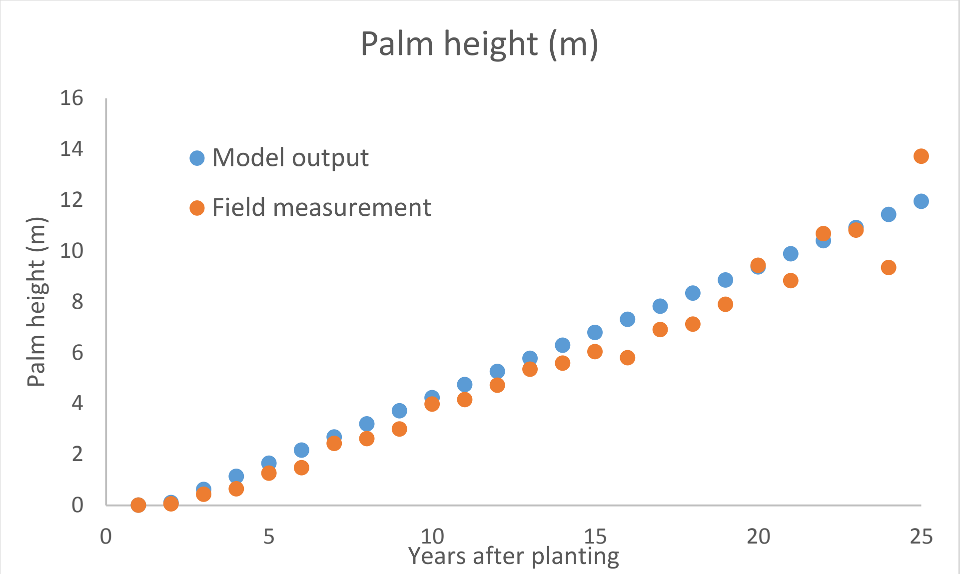
Statistical output of the model performance evaluation of annual FFB yields, trunk diameter, height, front length and leaf number for a 25 year cycles. The simulation was compared to IPOC field data of 25 oil palm plantations (Khasanah *et al.*, 2015) based upon statistical criteria for model evaluation from Loague and Green (1991). The IPOC field data is considered to have business-sensitive aspects and therefore plot-level performances linked to locations cannot be reported. Therefore, the measured values were averaged over de sites. For further details see Khasanah *et al.* 2015a,b; van Noordwijk *et al.*, 2016.

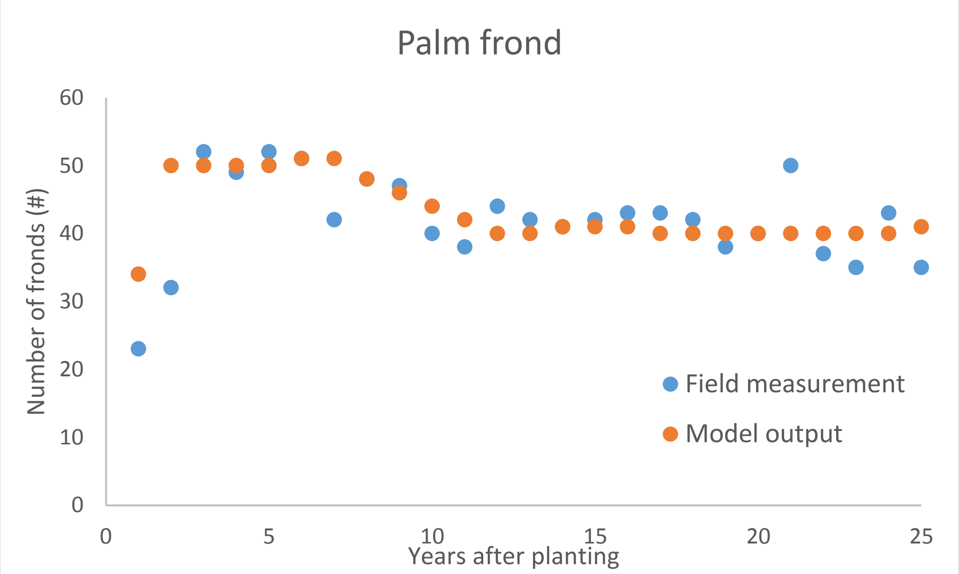
Statistical criteria for model evaluation as presented by Loague and Green (1991). 'P': predicted, "O": observed.

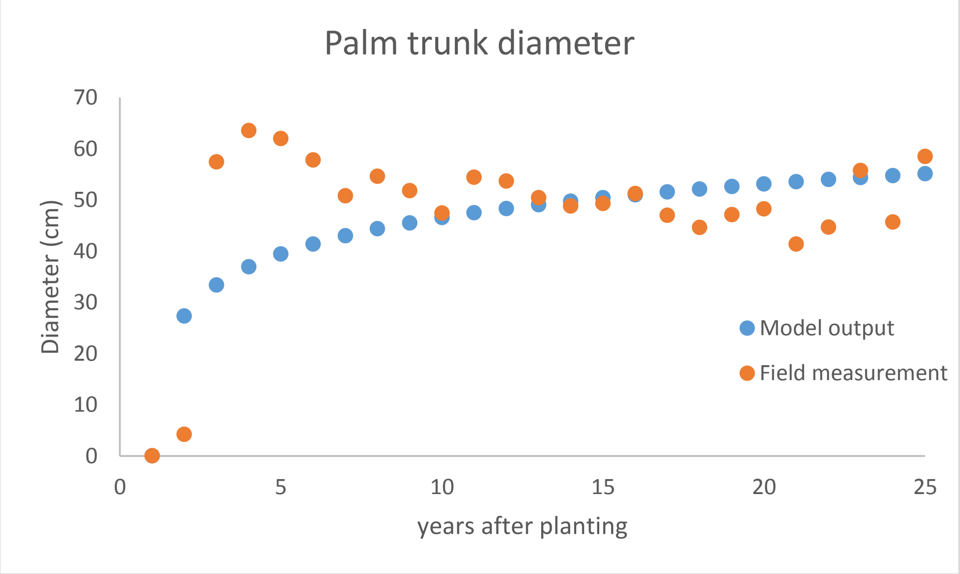
Criteria	**Symbol**	**Calculation formula**	**Range**	**Optimum**
Root mean square	RMSE	$\left(\sum_{i=1}^{n}\frac{(P_i-O_i)^2}{n}\right)^{\frac{1}{2}} x \frac{100}{O_{mean}}$	≥ 0	0
Coefficient of determination	CD	$\frac{\sum_{i=1}^{n}(O_i-O_{mean})^2}{\sum_{i=1}^{n}(P_i-O_{mean})^2}$	≥ 0	1
Modelling efficiency	EF	$\frac{(\sum_{i=1}^{n}(O_i-O_{mean})^2-\sum_{i=1}^{n}(P_i-O_i)^2)}{\sum_{i=1}^{n}(O_i-O_{mean})^2}$	≤ 1	1

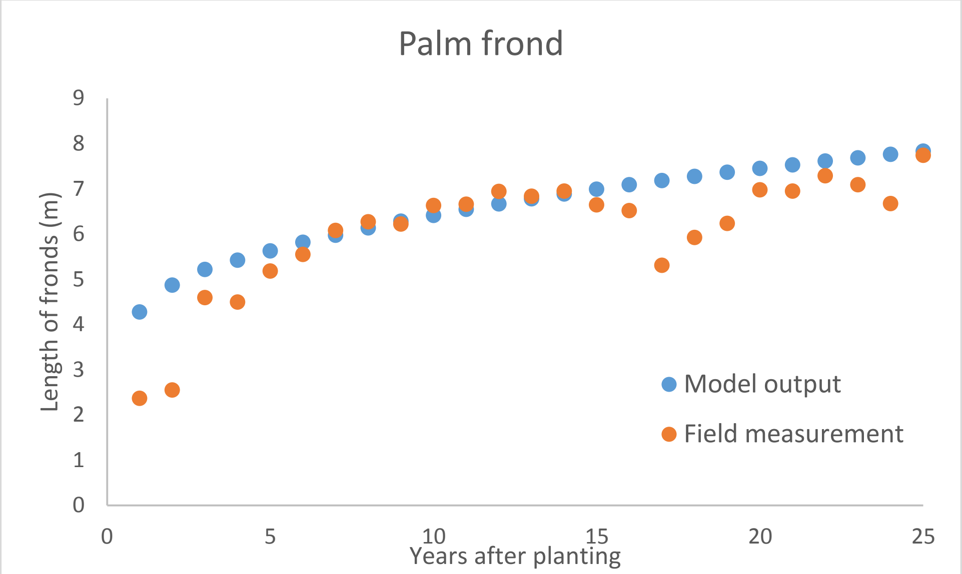
Model performance:

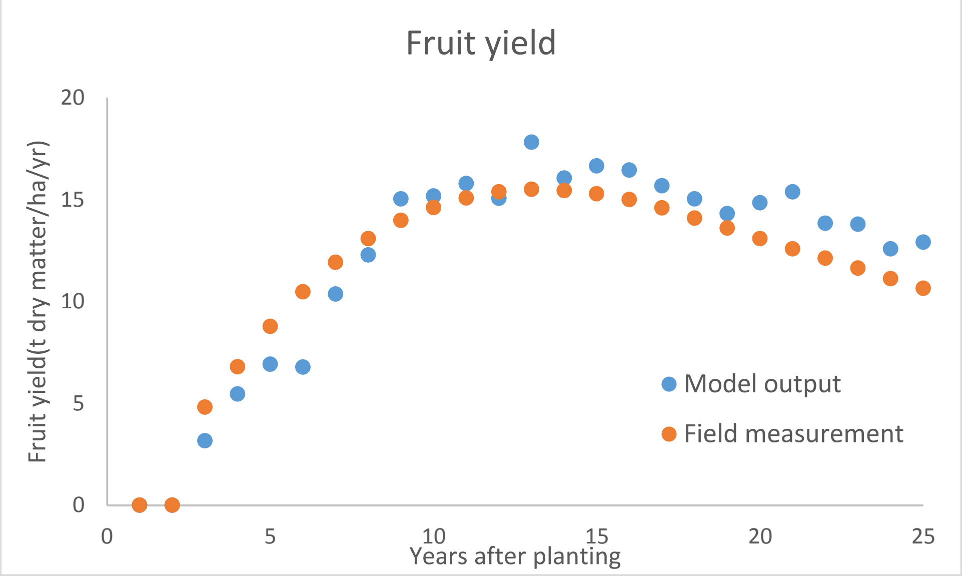
Criteria	**FFB Yield**	**Trunk diameter**	**Trunk height**	**Front length**	**Leaf number**
RMSE	0.158	0.571	0.083	0.088	0.551
CD	1.289	1.24	0.969	1.189	1.214
EF	0.919	0.844	0.952	0.748	0.723


Palm height (m)
Palm height (m)
16
14
12
10
8
6
4
2
0
Model output
Field measurement
0
5
10
15
20
25
Years after planting


Palm frond
Number of fronds (#)
60
50
40
30
20
10
0
Field measurement
Model output
0
5
10
15
20
25
Years after planting


Palm trunk diameter
Diameter (cm)
70
60
50
40
30
20
10
0
Model output
Field measurement
0
5
10
15
20
25
years after planting


Palm frond
Length of fronds (m)
0
1
2
3
4
5
6
7
8
9
0
5
10
15
20
25
Years after planting
Model output
Field measurement


Fruit yield
Fruit yield(t dry matter/ha/yr)
0
5
10
15
20
0
5
10
15
20
25
Years after planting
Model output
Field measurement

APPENDIX 5 – Fertilizer input for oil palm

Table x: TSP (phosphorus) and Urea (nitrogen) application rates, adjusted from Pahan (2008). The minimum application rates served as a reference for the application used in the model.

TSP-Phosphorus

	1	2	3	yr3-5	yr6-15	>15		Palm age		
	1	1	1	2	9	11		Nr. of years		
	138	138	138	138	138	138		palms/ha		
	0.177	0.177	0.177	0.177	0.177	0.177		fraction of application		
	0.36	0.36	0.36	0.36	0.36	0.36		fraction of P in TSP		
	2	2	1	1	1	1		application/yr		
	1.25	0.5	0.75	0.8	1	1		kg TSP/palm/application		
	2.5	1	0.75	0.8	1	1		kg TSP/palm/yr		
MIN	345	138	103.5	110.4	138	138		kg TSP/ha/yr		
	195.3	78.1	58.6	62.5	78.1	78.1		g TSP/m/yr		
	70.3	28.1	21.1	22.5	28.1	28.1		g P/m/yr	=	Model input
	70.3	28.1	21.1	45.0	253.1	309.3		total g/m/phase		
							727	g P/25years cycle		

UREA-Nitrogen

	1	2	3	yr3-5	yr6-15	>15		phase		
	1	1	1	2	9	11		years		
	138	138	138	138	138	138		palms/ha		
	0.177	0.177	0.177	0.177	0.177	0.177		fraction of application		
	0.46	0.46	0.46	0.46	0.46	0.46		fraction of N in Urea		
	2	2	2	2	2	2		application/yr		
	0.5	0.7	0.9	0.9	1	1.5		kg Urea/palm/application		
	1	1.4	1.8	1.8	2	3		kg Urea/palm/yr		
MIN	138	193.2	248.4	248.4	276	414		kg Urea/ha/yr		
	78.1	109.4	140.6	140.6	156.2	234.3		g Urea/m/yr		
	35.9	50.3	64.7	64.7	71.9	107.8		g N/m/yr	=	Model input
	35.9	50.3	64.7	129.4	646.8	1185.8		total g/m/phase		
							2113	g N/25years cycle		373.2624

APPENDIX 6 – Model soil and weather input

The combinations of soil type rainfall regime were:

(1) Sandy loam – 30 days of consecutive drought
(2) Sandy loam – 60 days of consecutive drought
(3) Clay – 30 days of consecutive drought
(4) Clay – 60 days of consecutive drought

Table of the soil characteristics of two soils in Kalimantan, data retrieved from: Brawijaya University

	Layers (cm)	Clay (%)	Silt (%)	Sand (%)	Corg (%)	Bulk density (g/cm^3)	CEC (cmol/kg)	pH	N-mineral (mg/cm^3)	P-mineral (mg/cm^3)
Sandy loam	0-10	12.00	6.00	82	2.6	1.16	5.14	4.31	0.0027	0.0413
	10-20	11.09	13.86	75	1.9	1.21	4.72	4.39	0.0017	0.0211
	20-50	11.16	14.97	74	1.0	1.26	3.32	4.48	0.0010	0.0220
	50-100	17.62	10.68	72	0.3	1.60	3.51	4.36	0.0009	0.0186
Clay	0-10	27.85	27.85	44	4.2	1.08	9.52	3.91	0.0041	0.0105
	10-20	33.18	19.91	47	2.5	1.15	8.33	3.97	0.0038	0.0053
	20-50	47.54	13.72	39	1.2	1.28	7.95	3.99	0.0034	0.0052
	50-100	64.63	10.67	25	0.7	1.41	6.61	4.01	0.0012	0.0013

Climate data 1 (30 days of consecutive drought) used for model simulation, retrieved from database: PT. Agro Menara Rachmat year 2012 (South Sumatra) Annual precipitation, 2200 mm.

Days	Date	Rainfall (mm)	Soil temperature	Pot. Evap. Trans.
1	1-Jan-12	0	27.80	4.62
2	2-Jan-12	0	27.40	4.62
3	3-Jan-12	0	26.80	4.62
4	4-Jan-12	0	25.10	4.62
5	5-Jan-12	27	23.80	4.62
6	6-Jan-12	0	25.40	4.62
7	7-Jan-12	0	26.80	4.62
8	8-Jan-12	0	26.40	4.62
9	9-Jan-12	0	26.80	4.62
10	10-Jan-12	0	26.40	4.62
11	11-Jan-12	0	25.70	4.62
12	12-Jan-12	0	25.90	4.62
13	13-Jan-12	0	26.40	4.62
14	14-Jan-12	0	26.70	4.62
15	15-Jan-12	0	29.10	4.62
16	16-Jan-12	0	27.80	4.62
17	17-Jan-12	0	26.60	4.62
18	18-Jan-12	0	28.10	4.62
19	19-Jan-12	0	25.70	4.62
20	20-Jan-12	0	26.67	4.62
21	21-Jan-12	99	26.67	4.62
22	22-Jan-12	0	28.20	4.62
23	23-Jan-12	53	27.10	4.62
24	24-Jan-12	16	28.30	4.62

25	25-Jan-12	0	26.90	4.62
26	26-Jan-12	0	26.40	4.62
27	27-Jan-12	0	26.40	4.62
28	28-Jan-12	0	28.80	4.62
29	29-Jan-12	0	25.70	4.62
30	30-Jan-12	0	25.30	4.62
31	31-Jan-12	0	25.50	4.62
32	1-Feb-12	0	26.40	4.55
33	2-Feb-12	0	24.60	4.55
34	3-Feb-12	0	26.60	4.55
35	4-Feb-12	0	25.60	4.55
36	5-Feb-12	29	27.60	4.55
37	6-Feb-12	20	26.40	4.55
38	7-Feb-12	35	25.90	4.55
39	8-Feb-12	0	26.30	4.55
40	9-Feb-12	21	25.90	4.55
41	10-Feb-12	0	26.30	4.55
42	11-Feb-12	0	27.10	4.55
43	12-Feb-12	0	26.10	4.55
44	13-Feb-12	0	24.80	4.55
45	14-Feb-12	32	26.80	4.55
46	15-Feb-12	0	25.90	4.55
47	16-Feb-12	22	25.60	4.55
48	17-Feb-12	0	26.90	4.55
49	18-Feb-12	0	25.00	4.55
50	19-Feb-12	0	26.55	4.55
51	20-Feb-12	45	25.30	4.55
52	21-Feb-12	5	25.30	4.55
53	22-Feb-12	0	28.10	4.55
54	23-Feb-12	10	27.90	4.55
55	24-Feb-12	14	29.70	4.55
56	25-Feb-12	0	28.30	4.55
57	26-Feb-12	0	28.20	4.55
58	27-Feb-12	0	27.70	4.55
59	28-Feb-12	0	26.50	4.55
60	1-Mar-12	0	28.40	4.69
61	2-Mar-12	0	27.60	4.69
62	3-Mar-12	0	27.04	4.69
63	4-Mar-12	0	29.90	4.69
64	5-Mar-12	0	27.30	4.69
65	6-Mar-12	0	29.60	4.69
66	7-Mar-12	0	28.10	4.69
67	8-Mar-12	0	27.30	4.69
68	9-Mar-12	0	26.00	4.69
69	10-Mar-12	0	27.04	4.69
70	11-Mar-12	34	26.10	4.69

71	12-Mar-12	5	29.40	4.69
72	13-Mar-12	0	25.80	4.69
73	14-Mar-12	0	25.10	4.69
74	15-Mar-12	48	25.80	4.69
75	16-Mar-12	0	26.70	4.69
76	17-Mar-12	0	27.04	4.69
77	18-Mar-12	0	25.30	4.69
78	19-Mar-12	0	25.70	4.69
79	20-Mar-12	78	27.10	4.69
80	21-Mar-12	22	27.10	4.69
81	22-Mar-12	23	25.30	4.69
82	23-Mar-12	35	27.30	4.69
83	24-Mar-12	0	24.10	4.69
84	25-Mar-12	0	28.80	4.69
85	26-Mar-12	0	26.40	4.69
86	27-Mar-12	0	26.60	4.69
87	28-Mar-12	39	28.20	4.69
88	29-Mar-12	0	26.90	4.69
89	30-Mar-12	11	27.90	4.69
90	31-Mar-12	28	27.30	4.69
91	1-Apr-12	28	27.70	4.65
92	2-Apr-12	0	25.60	4.65
93	3-Apr-12	5	27.30	4.65
94	4-Apr-12	20	26.70	4.65
95	5-Apr-12	3	24.80	4.65
96	6-Apr-12	0	27.40	4.65
97	7-Apr-12	17	27.40	4.65
98	8-Apr-12	0	27.70	4.65
99	9-Apr-12	0	27.00	4.65
100	10-Apr-12	10	26.80	4.65
101	11-Apr-12	25	27.10	4.65
102	12-Apr-12	0	26.60	4.65
103	13-Apr-12	0	26.20	4.65
104	14-Apr-12	0	27.80	4.65
105	15-Apr-12	0	26.90	4.65
106	16-Apr-12	0	28.10	4.65
107	17-Apr-12	15	25.30	4.65
108	18-Apr-12	20	26.86	4.65
109	19-Apr-12	0	26.60	4.65
110	20-Apr-12	17	26.40	4.65
111	21-Apr-12	50	26.86	4.65
112	22-Apr-12	24	27.60	4.65
113	23-Apr-12	25	25.20	4.65
114	24-Apr-12	6	26.80	4.65
115	25-Apr-12	4	27.50	4.65
116	26-Apr-12	2	26.90	4.65

117	27-Apr-12	0	26.86	4.65
118	28-Apr-12	0	27.70	4.65
119	29-Apr-12	14	26.80	4.65
120	30-Apr-12	0	27.30	4.65
121	1-May-12	0	25.40	4.75
122	2-May-12	0	28.10	4.75
123	3-May-12	0	29.70	4.75
124	4-May-12	0	26.80	4.75
125	5-May-12	0	26.90	4.75
126	6-May-12	0	28.10	4.75
127	7-May-12	0	26.30	4.75
128	8-May-12	2	25.70	4.75
129	9-May-12	3	26.20	4.75
130	10-May-12	20	27.60	4.75
131	11-May-12	0	27.00	4.75
132	12-May-12	0	27.10	4.75
133	13-May-12	33	26.40	4.75
134	14-May-12	0	27.20	4.75
135	15-May-12	17	26.70	4.75
136	16-May-12	0	27.23	4.75
137	17-May-12	0	27.80	4.75
138	18-May-12	0	27.70	4.75
139	19-May-12	0	26.30	4.75
140	20-May-12	0	25.90	4.75
141	21-May-12	34	28.30	4.75
142	22-May-12	0	27.60	4.75
143	23-May-12	7	28.20	4.75
144	24-May-12	0	28.50	4.75
145	25-May-12	0	25.40	4.75
146	26-May-12	0	27.30	4.75
147	27-May-12	0	29.20	4.75
148	28-May-12	0	26.40	4.75
149	29-May-12	11	26.90	4.75
150	30-May-12	35	25.90	4.75
151	31-May-12	0	30.20	4.75
152	1-Jun-12	0	28.30	4.73
153	2-Jun-12	0	27.60	4.73
154	3-Jun-12	21	28.40	4.73
155	4-Jun-12	0	26.70	4.73
156	5-Jun-12	0	27.90	4.73
157	6-Jun-12	21	28.60	4.73
158	7-Jun-12	32	28.80	4.73
159	8-Jun-12	9	28.00	4.73
160	9-Jun-12	8	26.80	4.73
161	10-Jun-12	10	27.70	4.73
162	11-Jun-12	0	29.20	4.73

163	12-Jun-12	0	26.80	4.73
164	13-Jun-12	73	25.40	4.73
165	14-Jun-12	1	26.40	4.73
166	15-Jun-12	11	28.70	4.73
167	16-Jun-12	18	27.80	4.73
168	17-Jun-12	0	28.20	4.73
169	18-Jun-12	0	27.10	4.73
170	19-Jun-12	0	27.13	4.73
171	20-Jun-12	0	25.80	4.73
172	21-Jun-12	0	26.20	4.73
173	22-Jun-12	0	26.50	4.73
174	23-Jun-12	0	28.40	4.73
175	24-Jun-12	0	24.20	4.73
176	25-Jun-12	0	25.20	4.73
177	26-Jun-12	0	26.80	4.73
178	27-Jun-12	0	26.00	4.73
179	28-Jun-12	14	25.10	4.73
180	29-Jun-12	0	27.30	4.73
181	30-Jun-12	0	26.90	4.73
182	1-Jul-12	0	26.90	4.55
183	2-Jul-12	0	27.10	4.55
184	3-Jul-12	0	24.90	4.55
185	4-Jul-12	0	26.40	4.55
186	5-Jul-12	0	26.10	4.55
187	6-Jul-12	0	26.70	4.55
188	7-Jul-12	0	25.50	4.55
189	8-Jul-12	0	29.20	4.55
190	9-Jul-12	0	28.10	4.55
191	10-Jul-12	0	23.80	4.55
192	11-Jul-12	0	25.60	4.55
193	12-Jul-12	0	27.10	4.55
194	13-Jul-12	0	26.80	4.55
195	14-Jul-12	0	26.80	4.55
196	15-Jul-12	57	26.20	4.55
197	16-Jul-12	0	27.10	4.55
198	17-Jul-12	0	26.20	4.55
199	18-Jul-12	24	26.20	4.55
200	19-Jul-12	28	25.80	4.55
201	20-Jul-12	0	25.60	4.55
202	21-Jul-12	11	25.30	4.55
203	22-Jul-12	36	26.30	4.55
204	23-Jul-12	55	27.10	4.55
205	24-Jul-12	3	27.10	4.55
206	25-Jul-12	0	26.80	4.55
207	26-Jul-12	0	27.40	4.55
208	27-Jul-12	0	27.80	4.55

209	28-Jul-12	0	28.70	4.55
210	29-Jul-12	19	27.20	4.55
211	30-Jul-12	0	26.80	4.55
212	31-Jul-12	0	25.20	4.55
213	1-Aug-12	0	26.90	4.71
214	2-Aug-12	0	27.10	4.71
215	3-Aug-12	0	25.80	4.71
216	4-Aug-12	0	26.90	4.71
217	5-Aug-12	0	25.70	4.71
218	6-Aug-12	0	26.80	4.71
219	7-Aug-12	0	28.70	4.71
220	8-Aug-12	0	28.10	4.71
221	9-Aug-12	0	27.60	4.71
222	10-Aug-12	0	27.10	4.71
223	11-Aug-12	0	27.30	4.71
224	12-Aug-12	0	27.10	4.71
225	13-Aug-12	34	26.90	4.71
226	14-Aug-12	0	25.30	4.71
227	15-Aug-12	0	25.20	4.71
228	16-Aug-12	0	27.20	4.71
229	17-Aug-12	0	28.10	4.71
230	18-Aug-12	0	25.90	4.71
231	19-Aug-12	0	27.00	4.71
232	20-Aug-12	0	28.10	4.71
233	21-Aug-12	34	26.10	4.71
234	22-Aug-12	4	27.40	4.71
235	23-Aug-12	0	28.00	4.71
236	24-Aug-12	0	24.80	4.71
237	25-Aug-12	0	28.30	4.71
238	26-Aug-12	0	27.90	4.71
239	27-Aug-12	0	27.80	4.71
240	28-Aug-12	0	27.30	4.71
241	29-Aug-12	0	27.70	4.71
242	30-Aug-12	0	27.70	4.71
243	31-Aug-12	0	27.90	4.71
244	1-Sep-12	0	26.40	4.77
245	2-Sep-12	17	27.10	4.77
246	3-Sep-12	8	27.60	4.77
247	4-Sep-12	0	27.90	4.77
248	5-Sep-12	0	28.10	4.77
249	6-Sep-12	0	27.70	4.77
250	7-Sep-12	0	27.80	4.77
251	8-Sep-12	0	26.70	4.77
252	9-Sep-12	0	27.50	4.77
253	10-Sep-12	0	27.50	4.77
254	11-Sep-12	26	26.70	4.77

255	12-Sep-12	0	27.24	4.77
256	13-Sep-12	0	27.40	4.77
257	14-Sep-12	0	29.10	4.77
258	15-Sep-12	0	25.70	4.77
259	16-Sep-12	0	26.20	4.77
260	17-Sep-12	0	26.80	4.77
261	18-Sep-12	0	28.80	4.77
262	19-Sep-12	0	24.00	4.77
263	20-Sep-12	0	28.90	4.77
264	21-Sep-12	0	25.90	4.77
265	22-Sep-12	0	25.70	4.77
266	23-Sep-12	0	27.24	4.77
267	24-Sep-12	0	27.00	4.77
268	25-Sep-12	0	27.70	4.77
269	26-Sep-12	18	26.70	4.77
270	27-Sep-12	0	28.30	4.77
271	28-Sep-12	0	26.50	4.77
272	29-Sep-12	0	27.30	4.77
273	30-Sep-12	0	29.80	4.77
274	1-Oct-12	0	27.50	4.68
275	2-Oct-12	0	27.60	4.68
276	3-Oct-12	0	24.90	4.68
277	4-Oct-12	0	27.80	4.68
278	5-Oct-12	0	27.80	4.68
279	6-Oct-12	0	27.30	4.68
280	7-Oct-12	0	26.40	4.68
281	8-Oct-12	0	27.70	4.68
282	9-Oct-12	0	25.50	4.68
283	10-Oct-12	0	26.20	4.68
284	11-Oct-12	0	25.80	4.68
285	12-Oct-12	44	28.50	4.68
286	13-Oct-12	0	27.90	4.68
287	14-Oct-12	27	26.20	4.68
288	15-Oct-12	11	28.00	4.68
289	16-Oct-12	0	25.50	4.68
290	17-Oct-12	0	25.80	4.68
291	18-Oct-12	0	29.10	4.68
292	19-Oct-12	10	28.80	4.68
293	20-Oct-12	5	29.40	4.68
294	21-Oct-12	0	27.01	4.68
295	22-Oct-12	7	27.01	4.68
296	23-Oct-12	7	30.20	4.68
297	24-Oct-12	0	28.70	4.68
298	25-Oct-12	0	26.40	4.68
299	26-Oct-12	0	25.30	4.68
300	27-Oct-12	0	27.40	4.68

301	28-Oct-12	0	26.30	4.68
302	29-Oct-12	0	24.70	4.68
303	30-Oct-12	19	24.30	4.68
304	31-Oct-12	0	26.20	4.68
305	1-Nov-12	0	26.49	4.59
306	2-Nov-12	0	30.20	4.59
307	3-Nov-12	0	25.90	4.59
308	4-Nov-12	0	24.60	4.59
309	5-Nov-12	0	26.40	4.59
310	6-Nov-12	0	25.90	4.59
311	7-Nov-12	0	28.10	4.59
312	8-Nov-12	0	25.40	4.59
313	9-Nov-12	0	26.49	4.59
314	10-Nov-12	0	27.30	4.59
315	11-Nov-12	12	27.50	4.59
316	12-Nov-12	0	27.70	4.59
317	13-Nov-12	13	28.30	4.59
318	14-Nov-12	13	24.80	4.59
319	15-Nov-12	15	27.70	4.59
320	16-Nov-12	0	27.20	4.59
321	17-Nov-12	0	25.10	4.59
322	18-Nov-12	0	24.50	4.59
323	19-Nov-12	0	25.10	4.59
324	20-Nov-12	0	25.60	4.59
325	21-Nov-12	0	26.70	4.59
326	22-Nov-12	0	24.40	4.59
327	23-Nov-12	0	26.49	4.59
328	24-Nov-12	0	28.20	4.59
329	25-Nov-12	0	26.49	4.59
330	26-Nov-12	0	26.49	4.59
331	27-Nov-12	0	24.60	4.59
332	28-Nov-12	0	26.20	4.59
333	29-Nov-12	0	28.40	4.59
334	30-Nov-12	0	26.49	4.59
335	1-Dec-12	0	25.20	4.50
336	2-Dec-12	0	26.90	4.50
337	3-Dec-12	3	25.70	4.50
338	4-Dec-12	0	26.10	4.50
339	5-Dec-12	29	24.90	4.50
340	6-Dec-12	0	26.60	4.50
341	7-Dec-12	98	24.80	4.50
342	8-Dec-12	0	26.60	4.50
343	9-Dec-12	0	25.20	4.50
344	10-Dec-12	0	25.60	4.50
345	11-Dec-12	36	26.80	4.50
346	12-Dec-12	17	26.00	4.50

347	13-Dec-12	0	25.20	4.50
348	14-Dec-12	36	25.10	4.50
349	15-Dec-12	0	26.60	4.50
350	16-Dec-12	5	25.90	4.50
351	17-Dec-12	4	25.20	4.50
352	18-Dec-12	0	26.29	4.50
353	19-Dec-12	29	26.60	4.50
354	20-Dec-12	0	25.40	4.50
355	21-Dec-12	7	25.50	4.50
356	22-Dec-12	0	26.30	4.50
357	23-Dec-12	0	26.80	4.50
358	24-Dec-12	0	28.30	4.50
359	25-Dec-12	0	27.50	4.50
360	26-Dec-12	0	28.40	4.50
361	27-Dec-12	0	28.60	4.50
362	28-Dec-12	0	27.70	4.50
363	29-Dec-12	0	27.00	4.50
364	30-Dec-12	0	26.10	4.50
365	31-Dec-12	0	26.20	4.50

Adjusted climate data (60 days of consecutive drought) used for model simulation, retrieved from database: PT. Agro Menara Rachmat year 2012 (South Sumatra) Annual precipitation, 2200 mm.

Days	Date	Rainfall (mm)	Soil temperature	Pot. Evap. Trans.
1	1-Jan-12	0	27.80	4.62
2	2-Jan-12	0	27.40	4.62
3	3-Jan-12	0	26.80	4.62
4	4-Jan-12	0	25.10	4.62
5	5-Jan-12	27	23.80	4.62
6	6-Jan-12	0	25.40	4.62
7	7-Jan-12	0	26.80	4.62
8	8-Jan-12	0	26.40	4.62
9	9-Jan-12	0	26.80	4.62
10	10-Jan-12	0	26.40	4.62
11	11-Jan-12	0	25.70	4.62
12	12-Jan-12	0	25.90	4.62
13	13-Jan-12	0	26.40	4.62
14	14-Jan-12	0	26.70	4.62
15	15-Jan-12	0	29.10	4.62
16	16-Jan-12	0	27.80	4.62
17	17-Jan-12	0	26.60	4.62
18	18-Jan-12	0	28.10	4.62
19	19-Jan-12	0	25.70	4.62
20	20-Jan-12	0	26.67	4.62
21	21-Jan-12	99	26.67	4.62
22	22-Jan-12	0	28.20	4.62
23	23-Jan-12	53	27.10	4.62

24	24-Jan-12	16	28.30	4.62
25	25-Jan-12	0	26.90	4.62
26	26-Jan-12	0	26.40	4.62
27	27-Jan-12	0	26.40	4.62
28	28-Jan-12	0	28.80	4.62
29	29-Jan-12	0	25.70	4.62
30	30-Jan-12	0	25.30	4.62
31	31-Jan-12	0	25.50	4.62
32	1-Feb-12	0	26.40	4.55
33	2-Feb-12	0	24.60	4.55
34	3-Feb-12	0	26.60	4.55
35	4-Feb-12	0	25.60	4.55
36	5-Feb-12	29	27.60	4.55
37	6-Feb-12	20	26.40	4.55
38	7-Feb-12	35	25.90	4.55
39	8-Feb-12	0	26.30	4.55
40	9-Feb-12	21	25.90	4.55
41	10-Feb-12	0	26.30	4.55
42	11-Feb-12	0	27.10	4.55
43	12-Feb-12	0	26.10	4.55
44	13-Feb-12	0	24.80	4.55
45	14-Feb-12	32	26.80	4.55
46	15-Feb-12	0	25.90	4.55
47	16-Feb-12	22	25.60	4.55
48	17-Feb-12	0	26.90	4.55
49	18-Feb-12	0	25.00	4.55
50	19-Feb-12	0	26.55	4.55
51	20-Feb-12	45	25.30	4.55
52	21-Feb-12	5	25.30	4.55
53	22-Feb-12	0	28.10	4.55
54	23-Feb-12	10	27.90	4.55
55	24-Feb-12	14	29.70	4.55
56	25-Feb-12	0	28.30	4.55
57	26-Feb-12	0	28.20	4.55
58	27-Feb-12	0	27.70	4.55
59	28-Feb-12	0	26.50	4.55
60	1-Mar-12	0	28.40	4.69
61	2-Mar-12	0	27.60	4.69
62	3-Mar-12	0	27.04	4.69
63	4-Mar-12	0	29.90	4.69
64	5-Mar-12	0	27.30	4.69
65	6-Mar-12	0	29.60	4.69
66	7-Mar-12	0	28.10	4.69
67	8-Mar-12	0	27.30	4.69
68	9-Mar-12	0	26.00	4.69
69	10-Mar-12	0	27.04	4.69

70	11-Mar-12	34	26.10	4.69
71	12-Mar-12	5	29.40	4.69
72	13-Mar-12	0	25.80	4.69
73	14-Mar-12	0	25.10	4.69
74	15-Mar-12	48	25.80	4.69
75	16-Mar-12	0	26.70	4.69
76	17-Mar-12	0	27.04	4.69
77	18-Mar-12	0	25.30	4.69
78	19-Mar-12	0	25.70	4.69
79	20-Mar-12	78	27.10	4.69
80	21-Mar-12	22	27.10	4.69
81	22-Mar-12	23	25.30	4.69
82	23-Mar-12	35	27.30	4.69
83	24-Mar-12	0	24.10	4.69
84	25-Mar-12	0	28.80	4.69
85	26-Mar-12	0	26.40	4.69
86	27-Mar-12	0	26.60	4.69
87	28-Mar-12	39	28.20	4.69
88	29-Mar-12	0	26.90	4.69
89	30-Mar-12	11	27.90	4.69
90	31-Mar-12	28	27.30	4.69
91	1-Apr-12	28	27.70	4.65
92	2-Apr-12	0	25.60	4.65
93	3-Apr-12	5	27.30	4.65
94	4-Apr-12	20	26.70	4.65
95	5-Apr-12	3	24.80	4.65
96	6-Apr-12	0	27.40	4.65
97	7-Apr-12	17	27.40	4.65
98	8-Apr-12	0	27.70	4.65
99	9-Apr-12	0	27.00	4.65
100	10-Apr-12	10	26.80	4.65
101	11-Apr-12	25	27.10	4.65
102	12-Apr-12	0	26.60	4.65
103	13-Apr-12	0	26.20	4.65
104	14-Apr-12	0	27.80	4.65
105	15-Apr-12	0	26.90	4.65
106	16-Apr-12	0	28.10	4.65
107	17-Apr-12	15	25.30	4.65
108	18-Apr-12	20	26.86	4.65
109	19-Apr-12	0	26.60	4.65
110	20-Apr-12	17	26.40	4.65
111	21-Apr-12	50	26.86	4.65
112	22-Apr-12	24	27.60	4.65
113	23-Apr-12	25	25.20	4.65
114	24-Apr-12	6	26.80	4.65
115	25-Apr-12	4	27.50	4.65

116	26-Apr-12	2	26.90	4.65
117	27-Apr-12	0	26.86	4.65
118	28-Apr-12	0	27.70	4.65
119	29-Apr-12	14	26.80	4.65
120	30-Apr-12	0	27.30	4.65
121	1-May-12	0	25.40	4.75
122	2-May-12	0	28.10	4.75
123	3-May-12	0	29.70	4.75
124	4-May-12	0	26.80	4.75
125	5-May-12	0	26.90	4.75
126	6-May-12	0	28.10	4.75
127	7-May-12	0	26.30	4.75
128	8-May-12	2	25.70	4.75
129	9-May-12	3	26.20	4.75
130	10-May-12	20	27.60	4.75
131	11-May-12	0	27.00	4.75
132	12-May-12	0	27.10	4.75
133	13-May-12	33	26.40	4.75
134	14-May-12	0	27.20	4.75
135	15-May-12	17	26.70	4.75
136	16-May-12	0	27.23	4.75
137	17-May-12	0	27.80	4.75
138	18-May-12	0	27.70	4.75
139	19-May-12	0	26.30	4.75
140	20-May-12	0	25.90	4.75
141	21-May-12	34	28.30	4.75
142	22-May-12	0	27.60	4.75
143	23-May-12	7	28.20	4.75
144	24-May-12	0	28.50	4.75
145	25-May-12	0	25.40	4.75
146	26-May-12	0	27.30	4.75
147	27-May-12	0	29.20	4.75
148	28-May-12	0	26.40	4.75
149	29-May-12	11	26.90	4.75
150	30-May-12	35	25.90	4.75
151	31-May-12	0	30.20	4.75
152	1-Jun-12	0	28.30	4.73
153	2-Jun-12	0	27.60	4.73
154	3-Jun-12	21	28.40	4.73
155	4-Jun-12	0	26.70	4.73
156	5-Jun-12	0	27.90	4.73
157	6-Jun-12	21	28.60	4.73
158	7-Jun-12	32	28.80	4.73
159	8-Jun-12	9	28.00	4.73
160	9-Jun-12	8	26.80	4.73
161	10-Jun-12	10	27.70	4.73

162	11-Jun-12	0	29.20	4.73
163	12-Jun-12	0	26.80	4.73
164	13-Jun-12	73	25.40	4.73
165	14-Jun-12	1	26.40	4.73
166	15-Jun-12	11	28.70	4.73
167	16-Jun-12	18	27.80	4.73
168	17-Jun-12	0	28.20	4.73
169	18-Jun-12	0	27.10	4.73
170	19-Jun-12	0	27.13	4.73
171	20-Jun-12	0	25.80	4.73
172	21-Jun-12	0	26.20	4.73
173	22-Jun-12	0	26.50	4.73
174	23-Jun-12	0	28.40	4.73
175	24-Jun-12	0	24.20	4.73
176	25-Jun-12	0	25.20	4.73
177	26-Jun-12	0	26.80	4.73
178	27-Jun-12	0	26.00	4.73
179	28-Jun-12	14	25.10	4.73
180	29-Jun-12	0	27.30	4.73
181	30-Jun-12	0	26.90	4.73
182	1-Jul-12	0	26.90	4.55
183	2-Jul-12	0	27.10	4.55
184	3-Jul-12	0	24.90	4.55
185	4-Jul-12	0	26.40	4.55
186	5-Jul-12	0	26.10	4.55
187	6-Jul-12	0	26.70	4.55
188	7-Jul-12	0	25.50	4.55
189	8-Jul-12	0	29.20	4.55
190	9-Jul-12	0	28.10	4.55
191	10-Jul-12	0	23.80	4.55
192	11-Jul-12	0	25.60	4.55
193	12-Jul-12	0	27.10	4.55
194	13-Jul-12	0	26.80	4.55
195	14-Jul-12	0	26.80	4.55
196	15-Jul-12	57	26.20	4.55
197	16-Jul-12	0	27.10	4.55
198	17-Jul-12	0	26.20	4.55
199	18-Jul-12	24	26.20	4.55
200	19-Jul-12	28	25.80	4.55
201	20-Jul-12	0	25.60	4.55
202	21-Jul-12	11	25.30	4.55
203	22-Jul-12	36	26.30	4.55
204	23-Jul-12	55	27.10	4.55
205	24-Jul-12	3	27.10	4.55
206	25-Jul-12	0	26.80	4.55
207	26-Jul-12	0	27.40	4.55

208	27-Jul-12	0	27.80	4.55
209	28-Jul-12	0	28.70	4.55
210	29-Jul-12	19	27.20	4.55
211	30-Jul-12	0	26.80	4.55
212	31-Jul-12	0	25.20	4.55
213	1-Aug-12	0	26.90	4.71
214	2-Aug-12	0	27.10	4.71
215	3-Aug-12	17	25.80	4.71
216	4-Aug-12	0	26.90	4.71
217	5-Aug-12	0	25.70	4.71
218	6-Aug-12	0	26.80	4.71
219	7-Aug-12	18	28.70	4.71
220	8-Aug-12	0	28.10	4.71
221	9-Aug-12	0	27.60	4.71
222	10-Aug-12	0	27.10	4.71
223	11-Aug-12	34	27.30	4.71
224	12-Aug-12	0	27.10	4.71
225	13-Aug-12	0	26.90	4.71
226	14-Aug-12	0	25.30	4.71
227	15-Aug-12	0	25.20	4.71
228	16-Aug-12	0	27.20	4.71
229	17-Aug-12	0	28.10	4.71
230	18-Aug-12	0	25.90	4.71
231	19-Aug-12	0	27.00	4.71
232	20-Aug-12	0	28.10	4.71
233	21-Aug-12	0	26.10	4.71
234	22-Aug-12	0	27.40	4.71
235	23-Aug-12	0	28.00	4.71
236	24-Aug-12	0	24.80	4.71
237	25-Aug-12	0	28.30	4.71
238	26-Aug-12	0	27.90	4.71
239	27-Aug-12	0	27.80	4.71
240	28-Aug-12	0	27.30	4.71
241	29-Aug-12	0	27.70	4.71
242	30-Aug-12	0	27.70	4.71
243	31-Aug-12	0	27.90	4.71
244	1-Sep-12	0	26.40	4.77
245	2-Sep-12	0	27.10	4.77
246	3-Sep-12	0	27.60	4.77
247	4-Sep-12	0	27.90	4.77
248	5-Sep-12	0	28.10	4.77
249	6-Sep-12	0	27.70	4.77
250	7-Sep-12	0	27.80	4.77
251	8-Sep-12	0	26.70	4.77
252	9-Sep-12	0	27.50	4.77
253	10-Sep-12	0	27.50	4.77

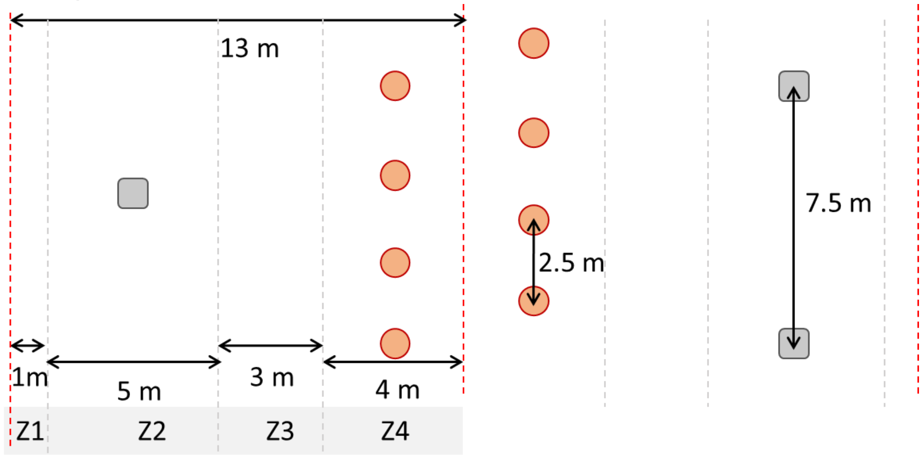
254	11-Sep-12	0	26.70	4.77
255	12-Sep-12	0	27.24	4.77
256	13-Sep-12	0	27.40	4.77
257	14-Sep-12	0	29.10	4.77
258	15-Sep-12	0	25.70	4.77
259	16-Sep-12	0	26.20	4.77
260	17-Sep-12	0	26.80	4.77
261	18-Sep-12	0	28.80	4.77
262	19-Sep-12	0	24.00	4.77
263	20-Sep-12	0	28.90	4.77
264	21-Sep-12	0	25.90	4.77
265	22-Sep-12	0	25.70	4.77
266	23-Sep-12	0	27.24	4.77
267	24-Sep-12	0	27.00	4.77
268	25-Sep-12	0	27.70	4.77
269	26-Sep-12	0	26.70	4.77
270	27-Sep-12	0	28.30	4.77
271	28-Sep-12	0	26.50	4.77
272	29-Sep-12	0	27.30	4.77
273	30-Sep-12	0	29.80	4.77
274	1-Oct-12	0	27.50	4.68
275	2-Oct-12	0	27.60	4.68
276	3-Oct-12	0	24.90	4.68
277	4-Oct-12	0	27.80	4.68
278	5-Oct-12	0	27.80	4.68
279	6-Oct-12	0	27.30	4.68
280	7-Oct-12	0	26.40	4.68
281	8-Oct-12	0	27.70	4.68
282	9-Oct-12	0	25.50	4.68
283	10-Oct-12	0	26.20	4.68
284	11-Oct-12	38	25.80	4.68
285	12-Oct-12	44	28.50	4.68
286	13-Oct-12	0	27.90	4.68
287	14-Oct-12	27	26.20	4.68
288	15-Oct-12	11	28.00	4.68
289	16-Oct-12	0	25.50	4.68
290	17-Oct-12	0	25.80	4.68
291	18-Oct-12	0	29.10	4.68
292	19-Oct-12	10	28.80	4.68
293	20-Oct-12	5	29.40	4.68
294	21-Oct-12	0	27.01	4.68
295	22-Oct-12	7	27.01	4.68
296	23-Oct-12	7	30.20	4.68
297	24-Oct-12	0	28.70	4.68
298	25-Oct-12	0	26.40	4.68
299	26-Oct-12	0	25.30	4.68

300	27-Oct-12	0	27.40	4.68
301	28-Oct-12	0	26.30	4.68
302	29-Oct-12	0	24.70	4.68
303	30-Oct-12	19	24.30	4.68
304	31-Oct-12	0	26.20	4.68
305	1-Nov-12	0	26.49	4.59
306	2-Nov-12	0	30.20	4.59
307	3-Nov-12	0	25.90	4.59
308	4-Nov-12	0	24.60	4.59
309	5-Nov-12	0	26.40	4.59
310	6-Nov-12	0	25.90	4.59
311	7-Nov-12	0	28.10	4.59
312	8-Nov-12	0	25.40	4.59
313	9-Nov-12	0	26.49	4.59
314	10-Nov-12	0	27.30	4.59
315	11-Nov-12	12	27.50	4.59
316	12-Nov-12	0	27.70	4.59
317	13-Nov-12	13	28.30	4.59
318	14-Nov-12	13	24.80	4.59
319	15-Nov-12	15	27.70	4.59
320	16-Nov-12	0	27.20	4.59
321	17-Nov-12	0	25.10	4.59
322	18-Nov-12	0	24.50	4.59
323	19-Nov-12	0	25.10	4.59
324	20-Nov-12	0	25.60	4.59
325	21-Nov-12	0	26.70	4.59
326	22-Nov-12	0	24.40	4.59
327	23-Nov-12	0	26.49	4.59
328	24-Nov-12	0	28.20	4.59
329	25-Nov-12	0	26.49	4.59
330	26-Nov-12	0	26.49	4.59
331	27-Nov-12	0	24.60	4.59
332	28-Nov-12	0	26.20	4.59
333	29-Nov-12	0	28.40	4.59
334	30-Nov-12	0	26.49	4.59
335	1-Dec-12	0	25.20	4.50
336	2-Dec-12	0	26.90	4.50
337	3-Dec-12	3	25.70	4.50
338	4-Dec-12	0	26.10	4.50
339	5-Dec-12	29	24.90	4.50
340	6-Dec-12	0	26.60	4.50
341	7-Dec-12	98	24.80	4.50
342	8-Dec-12	0	26.60	4.50
343	9-Dec-12	0	25.20	4.50
344	10-Dec-12	0	25.60	4.50
345	11-Dec-12	36	26.80	4.50

346	12-Dec-12	17	26.00	4.50
347	13-Dec-12	0	25.20	4.50
348	14-Dec-12	36	25.10	4.50
349	15-Dec-12	0	26.60	4.50
350	16-Dec-12	5	25.90	4.50
351	17-Dec-12	4	25.20	4.50
352	18-Dec-12	0	26.29	4.50
353	19-Dec-12	29	26.60	4.50
354	20-Dec-12	0	25.40	4.50
355	21-Dec-12	7	25.50	4.50
356	22-Dec-12	0	26.30	4.50
357	23-Dec-12	0	26.80	4.50
358	24-Dec-12	0	28.30	4.50
359	25-Dec-12	0	27.50	4.50
360	26-Dec-12	0	28.40	4.50
361	27-Dec-12	0	28.60	4.50
362	28-Dec-12	0	27.70	4.50
363	29-Dec-12	0	27.00	4.50
364	30-Dec-12	0	26.10	4.50
365	31-Dec-12	0	26.20	4.50

APPENDIX 7 – Density and Spacing: Cacao & Rubber

Oil palm - Cacao

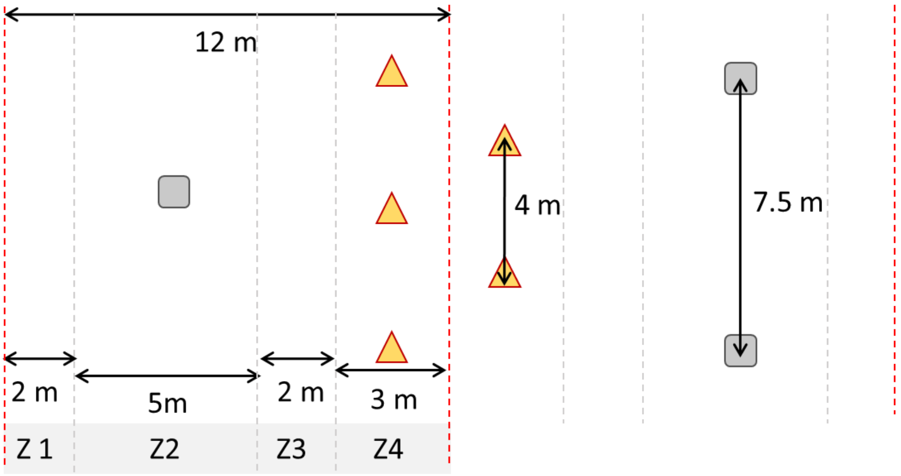


Zone (#)	Width (m)	Species	Density (trees/ha)	Spacing (m)
1	1	-	-	
2	5	Oil palm	100	7 x 7.5
3	3	-	-	
4	4	Cacao	308	4 x 2.5
Total	13			

▢ Oil palm

● Cacao tree

Oil palm - Rubber



Zone (#)	Width (m)	Species	Density (trees/ha)	Spacing (m)
1	2	-	-	
2	5	Oil palm	111	9 x 7.5
3	2	-	-	
4	3	Rubber	200	3 x 4
Total	12			

▢ Oil palm

△ Rubber tree

(Unit: trees/ha)	Oil palm	Cocoa	Rubber	Relative density
Mono culture density	138	1000	700	-
Scenario: Oil palm cocoa	100	308		1.03
Scenario: Oil palm rubber	111		200	1.09

APPENDIX 8 – P-Fertilizer yield response

Table: Oil palm yield response to phosphate rock from two studies in Indonesia and Malaysia.

Soil	P rate (kg/palm)	FFB yield (t/ha) by given year after planting							
Indonesia:		4	5	6	7	8	12-14	15-18	
Podzolic utisol	0	-	12.1	13.2	11.3	16.1	-	-	13
	0.6	-	19.5	24	24.2	27.8	-	-	24
Yield increase									81%
Malay									
Red yellow podzolic utisol	0	15.5	26.7	19.9	22.6	-	14	14.3	18.8
	0.6	16.1	30.6	27.3	29.9	-	29.2	30.6	27.3
Yield increase							109%	114%	45%

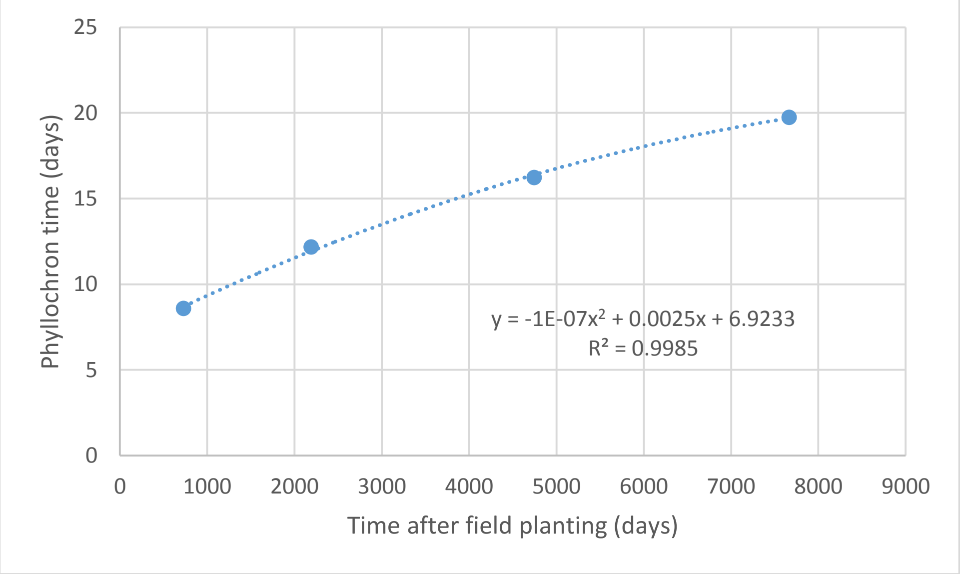
*) data retrieved from: Pushparajah, E., Cnah, F., & Magat, S. S. (1990). Phosphorus requirements and management of oil palm, coconut and rubber. *Phosphorus requirements for sustainable agriculture in Asia and Oceania*, 399-425.

APPENDIX 9 - Graph of phyllochron time dynamics

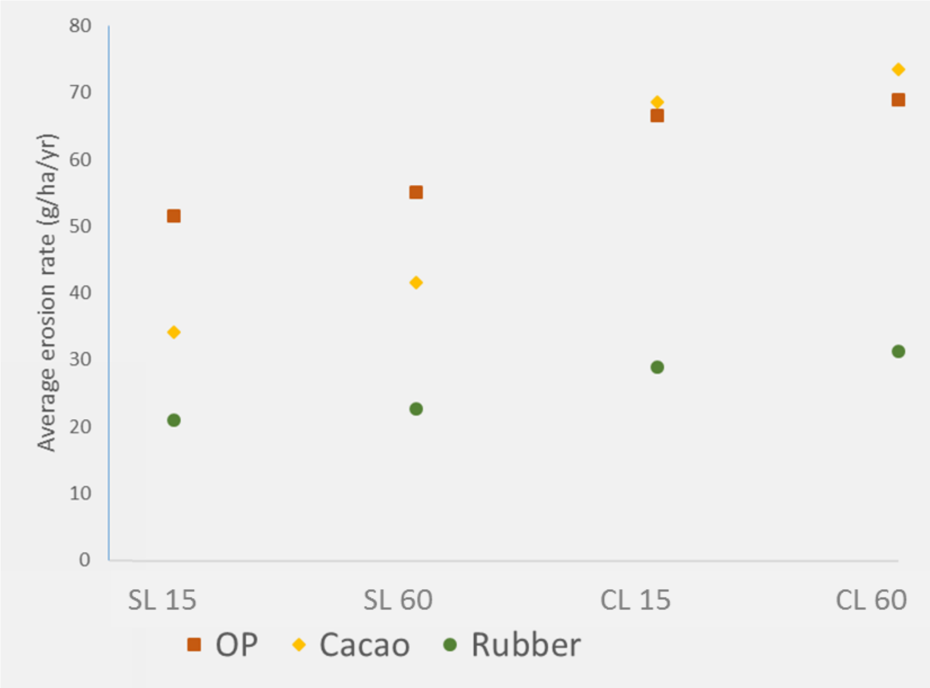
Updated model equation for phyllochron time as a function of days after planting (Khasanah, N., personal communication, 2016)

$y = -1e\text{-}07x^2 + 0.0025x + 6.9233$

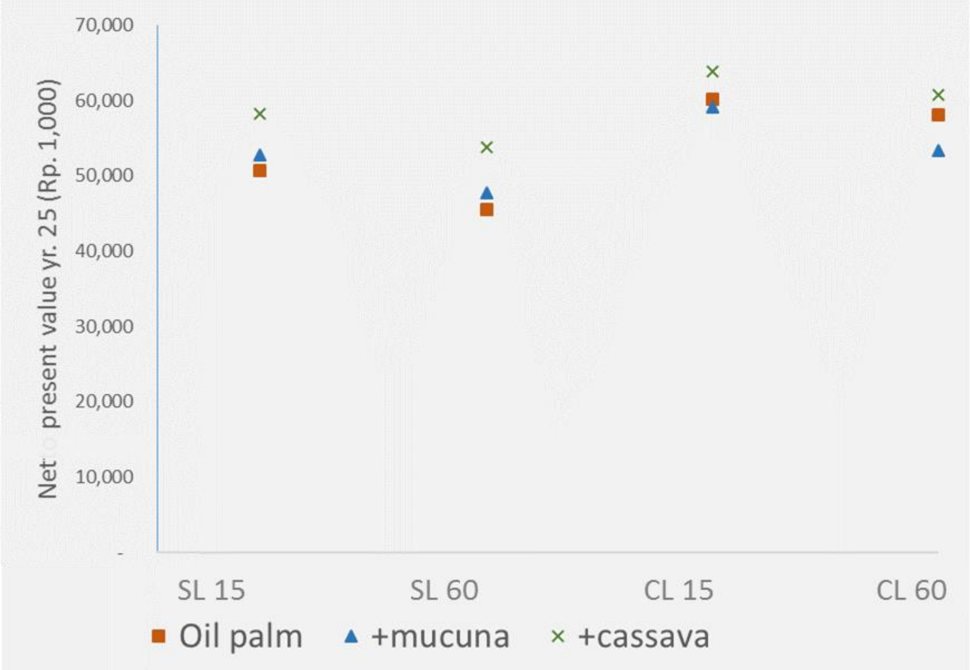
*) Adjusted from: Broekmans, 1957; Gerritsma and Soebagyo, 1999; Rafii *et al.*, 2013.



APPENDIX 10 – Two examples of performance variability over drought and soil



Average erosion rate (g/ha/yr) for the 25-year cycle, for the monoculture and cacao and rubber intercrop systems. On the Y-axis the 4 combinations of drought (15 or 60 days consecutive per year) and soil (sandy loam = SL, or clay loam = CL). The graph shows that cacao has reduced erosion levels for the sandy loam soil, but increased levels for the clay loam soils.



Net present value at year 25. On the Y-axis the 4 combinations of drought (15 or 60 days consecutive per year) and soil (sandy loam = SL, or clay loam = CL). The graph shows that the performance of the mucuna ground cover scenario is very similar to the performance of the oil palm monoculture. For SL the mucuna obtained a larger NPV whereas for the clay loam oil palm obtained a larger NPV.

APPENDIX 11 – Profitability module input

Perennial module: labour requirements, seed costs and tree product prices in Indonesian Rupiah (1 Rp. = $6.83*10^{-5}$ EURO, exchange rate 01/10/2016, XE currency 2016)			
	Oil palm[1]	Cacao	Rubber
Labour for planting (person days per tree)	0.126	0.126	0.178
Labour for pruning (person days per kg)	0.000405	0.02	-
Labour for fruit harvest (person days per kg)	0.00113	0.07	-
Labour for latex harvest (person days per kg)	-	-	0.115
Labour for fertilizer application (person days per ha)	4.5	2	1.5
Seed cost (Rp. per tree)	8000	1000	3000
Fruit price (Rp. per kg)[2]	1400	26000	-
Latex price (Rp. per kg) [3]	-	-	4485

Annual module: labour requirements (per cropping season), seed costs and crop yield prices in Indonesian Rupiah (1 Rp. = $6.83*10^{-5}$ EURO, exchange rate 01/10/2016, XE currency 2016).			
	Mucuna	Cassava	Groundnut
Labour for planting (person days per ha)	2	10	14.5
Labour for weeding (person days per ha)	2	20	12
Labour for harvesting (person days per Mg)	-	10	20
Labour for fertilizer application (person days per ha)	-	1.5	1.5
Seed cost (Rp. per kg)	2000	3000	20000
Yield price (Rp. per kg) [4]	-	900	3500

---

[1] Labour inputs based on: Corley & Tinker (2015), Table 11.6 p. 300

[2] FaoStat 10 year average Indonesia

[3] FaoStat 10 year average Indonesia

[4] FaoStat 10 year average Indonesia

APPENDIX 12- Spatial levels of importance and linked stakeholders

As explained oil palm cultivation is part of a complex system of interests from multiple stakeholders, which are acting at different spatial levels.

At a first level is the smallholder, addressed in the previous sections. At a second level are the local communities in which these smallholders and agribusinesses act. For this stakeholder the largest concern are: increased risk of flooding, water quality deterioration, reduced food security and food sovereignty (Colchester, 2011; Obidzinski *et al.,* 2012). The local and regional authorities are concerned with these issues, but also with the economic implications of oil palm and economic vulnerability of the region. Then there is a stakeholder, for this study simplified to 'External': including NGOs and food manufacturers, which focus on increasing *the image of* oil palm sustainability (McCarthy, 2010; Silva-Castañeda, 2012).

APPENDIX 13- Annual cumulative yield per cropping scenario over the 25-year simulation

The annual and cumulative simulated yields for the monoculture and intercropping scenarios in dry weight per hectare. The values are the average of the four productivity level for the soil and drought conditions.
OPF = Oil palm fruit.

	OPF (kg dm/ha)	OPF (kg dm/ha)	Cocoa pod (kg dm/ha)	OPF (kg dm/ha)	Latex (kg dm/ha)	OPF (kg dm/ha)	OPF (kg dm/ha)	Groundnut (kg dm/ha)	OPF (kg dm/ha)	Cassava kg dm/ha
year	Oil palm mono	Oil palm +Cacao		Oil palm +Rubber		Oil palm +Mucuna	Oil palm +Groundnut		Oil palm +Cassava	
1	0	0	0	0	0	0	0	4.1	0	6.6
2	0.1	0.2	0	0	0	0.1	0	4.1	0	6.3
3	0.2	0.4	0	0.2	0	0.2	0.2	1.7	0.2	0
4	0.6	0.7	0	0.3	0	0.6	0.6	0	0.4	0
5	0.8	0.8	0	0.4	0	0.8	0.9	0	0.7	0
6	0.9	0.9	0.1	0.3	0.1	1.1	1	0	1	0
7	1.1	1	0	0.3	0	1.1	1.3	0	1.1	0
8	1.3	1	0.1	0.4	0.1	1.4	1.3	0	1.4	0
9	1.5	1.2	0	0.5	0.1	1.4	1.5	0	1.4	0
10	1.5	1.2	0	0.5	0	1.5	1.5	0	1.5	0
11	1.5	1.2	0.1	0.6	0.1	1.5	1.5	0	1.6	0
12	1.6	1.2	0	0.7	0.1	1.7	1.7	0	1.6	0
13	1.7	1.3	0.1	0.7	0.1	1.6	1.5	0	1.6	0
14	1.6	1.4	0	0.6	0.1	1.6	1.6	0	1.7	0
15	1.6	1.4	0.1	0.7	0.2	1.7	1.7	0	1.7	0
16	1.7	1.3	0	0.7	0.1	1.6	1.7	0	1.6	0
17	1.5	1.2	0.1	0.8	0.1	1.6	1.5	0	1.5	0
18	1.5	1.3	0	0.6	0.1	1.5	1.5	0	1.6	0
19	1.5	1.3	0.1	0.7	0.2	1.5	1.5	0	1.5	0
20	1.5	1.1	0	0.7	0.1	1.5	1.5	0	1.5	0
21	1.4	1.2	0.1	0.7	0.2	1.4	1.4	0	1.5	0
22	1.5	1.1	0	0.6	0.1	1.4	1.4	0	1.4	0
23	1.3	1.1	0.1	0.7	0.2	1.4	1.4	0	1.4	0
24	1.3	1.1	0	0.6	0.1	1.3	1.3	0	1.3	0
25	1.3	1	0	0.7	0.2	1.3	1.2	0	1.3	0
CUM	**30.5**	**25.6**	**0.9**	**13**	**2.3**	**30.8**	**30.7**	**9.9**	**30.5**	**12.9**