Understanding potential yield in the context of the climate and resource constraint to sustainably intensify cropping systems in tropical and temperate regions

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Georgica, Liber Primus: 250-258
Publius Vergilius Maro (70-19 BC)

Contents

I. General introduction

1. Conceptual background of the study: Sustainable intensification of crop production

The United Nations forecasts a rise in world population from current 7 to 9 billion people in 2050 (Godfray et al., 2010). Furthermore, living standards and consumption increase in transition and developing countries. There is a general consensus that these process will lead to an even stronger demand for agricultural products – food, fodder, fiber and bio-fuels; although there is still a debate about the extent of the demand increase (Bindraban and Rabbinge, 2012; Foley et al., 2011; Godfray et al., 2010). Suggestions to avoid running into the Malthusian trap, i.e. increase of world population increases faster than food supply, can be categorized into three main approaches (Carberry et al., 2010);

The first one proposes a reduction in demand, which includes a modified biofuel policy based on no food crops and a reduction in food waste and human consumption of meat. The second strategy focuses on maintaining the current production capacity. That means a limited transformation of agricultural soils into infrastructure (housing, streets etc.), investing in breeding programs to guarantee pest and disease resistance, mitigation and adaptation to climate change, and avoiding soil and water degradation. The third approach deals with the increase of productivity. One solution could be the expansion of agricultural land, which would require a reduction of land used for other purposes, e.g. infrastructure, housing, nature conservation parks. As such expansion into the latter one would strongly threaten global biodiversity (Matson and Vitousek, 2006) and suitable land for agriculture is limited, the increase in production of existing land remains as feasible pathway. This can be done either by increased yield ceilings based on breeding progress (Fischer and Edmeades, 2010) or by closing the gap between attainable yield and actual yield based on improved agronomy (Carberry et al., 2013; Foley et al., 2011). However, input resources will become partly limiting for agricultural production, such as fertilizer (phosphor) and oil. Furthermore, environmental concerns are growing with regards to high input agriculture, linked to greenhouse gas emissions, nitrogen leaching to the groundwater, eutrophication of lakes and rivers due to too much phosphor application to agricultural land, and the effects of biocides on biodiversity and human health (Bindraban and Rabbinge, 2012; Foley et al., 2011; Burney et al., 2011; Tscharntke et al., 2012).

Therefore, producing more from existing agricultural land and simultaneously increasing resource use efficiency is the key challenge for farming in the coming decades (Garnett et al., 2013; Keating et al., 2010). Important tools for such eco-efficiency, or the often synonymously used sustainable intensification approach, is the setting of the attainable yield, which allows for a yield gap analysis that investigates the factors causing the gap between the attainable and the current yield level (Cassman, 1999; Lobell et al., 2009). Inputs such as fertilizers and pesticides can then be applied to match the attainable yield, and the threat of oversupply and undersupply can be reduced.

2. Conceptual background: Yield gap and setting of attainable yield

Commonly, three different production levels are distinguished; potential, attainable and actual yield (van Ittersum and Rabbinge, 1997) (Figure 1). Potential yield is defined as the optimum growth of a crop defined by solar radiation, current air CO_2 concentrations and temperature. Attainable yield is then further restricted by water and nutrients. Both are ideally managed by irrigation and fertilizer supply. However, under rain-fed conditions potential yield is further reduced by rainfall and soil hydrological properties to water-limited yield. Finally, actual yield is the average reached yield on farmer's fields (Lobell et al., 2009; van Ittersum et al., 2013). A yield gap analysis will then calculate the difference between the different production levels.

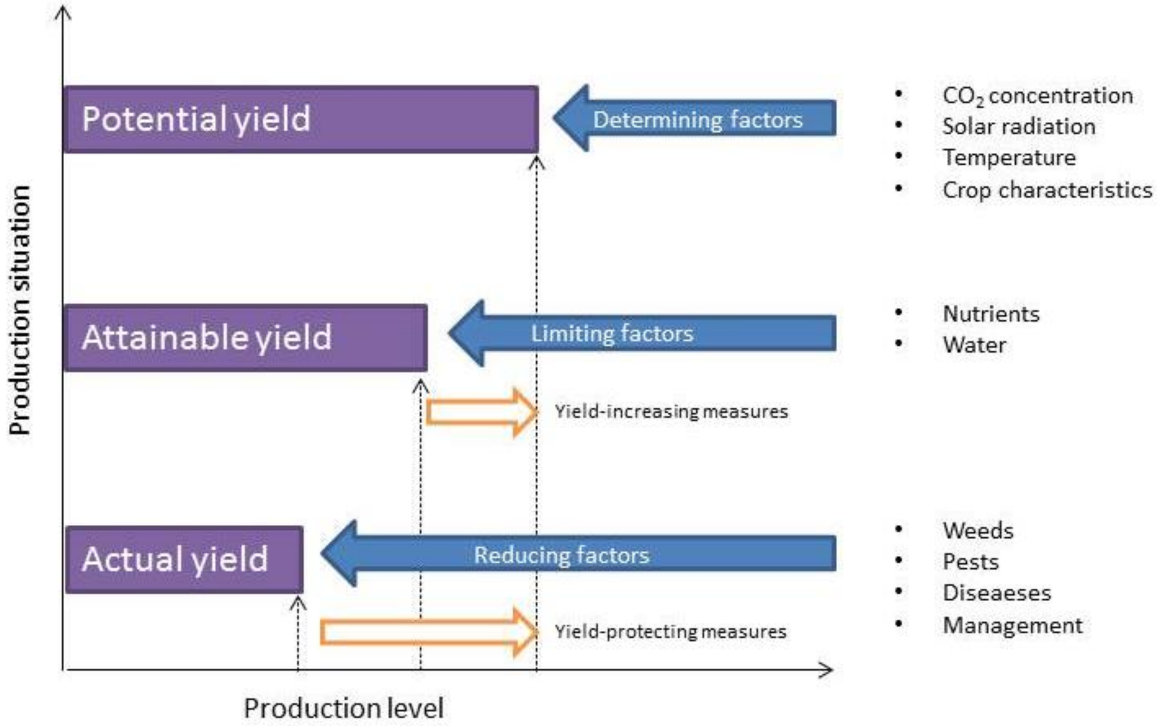

Figure 1: Yield gap concept after van Ittersum and Rabbinge (1997).

Recently there has been a lot of attention towards yield gaps among policy debates, but also within the scientific community. However, the published reports and papers differ strongly in regard to the scale of assessment. In a widely cited study Mueller et al. (2012), analyzed the yield gaps for major crops on a global scale. They found that global yield variability is strongly related to fertilizer use, irrigation and climate. Large production increases (45% to 70% for most crops) are possible from closing yield gaps to 100% of attainable yields. The changes to management practices that are needed to close yield gaps vary considerably by region and current intensity. Furthermore, they found that there are large opportunities to reduce the environmental impact of agriculture by eliminating nutrient overuse, while still allowing an approximately 30% increase in production of major cereals (maize, wheat and rice). In this instance, researchers worked with recently developed climate analog techniques, which map agro-ecological zones characterized by growing degree day (temperature) and precipitation (Johnston et al., 2011; Licker et al., 2010). Yields and the management of similar zones are compared to identify the yield gaps and factors causing it.

While the agro-ecological zoning approach has been popular among geographers, agronomy field trials have been traditionally conducted under optimal supply to define potential and attainable yield levels in a certain region (for instance Blumenthal et al., 2003; French and Schultz, 1984; Henke et al., 2007). Due to time, labor and financial constraints, field trial results are usually restricted to a few years and sites for a given region. Therefore, results are difficult to extrapolate for longer time periods, or other regions. Nevertheless, statistical models are usually derived from such field trials to provide fertilizer or irrigation recommendations (for instance Henke et al., 2008). Furthermore, highest yield records from farmers within a region are often used to benchmark attainable yield levels (for instance Affholder et al., 2013; Dang et al., 2010; Hall et al., 2013; Meng et al., 2013).

However, field experiments, yield contests and highest yields obtained by farmers are useful to determine maximum achievable yields in a specific location. It is difficult to know for certain if all biotic and abiotic stresses were avoided. In addition, as already stated it is difficult to extend this to other sites and years. Therefore, yields from these sources may not be adequate to derive robust estimates of potential or attainable yield representative of the dominant weather and soil conditions in a given cropping system or region (van Ittersum et al., 2013). The latter one is a key problem, as attainable yield can differ strongly from season to season. This is well known for dryland systems such as the southern Australia wheat cropping region or dry regions of eastern and southern Africa. For example attainable yield in southern Australia can vary from one year with good rain from 3-4 ton/ha grain wheat yield to a complete failure in the next year with rainfalls below 60-70 mm (Figure 2; Chapter 6). Even in temperate regions with high rainfall like in rainfall the attainable yield can differ from year to year at an amplitude of a ton grain yield for example in oilseed rape cultivation (Chapter

Five). Management decisions, in dryland systems in particular, have to be seen in the context climate risk and the varying character of the attainable yield. So far this risk element has often been neglected.

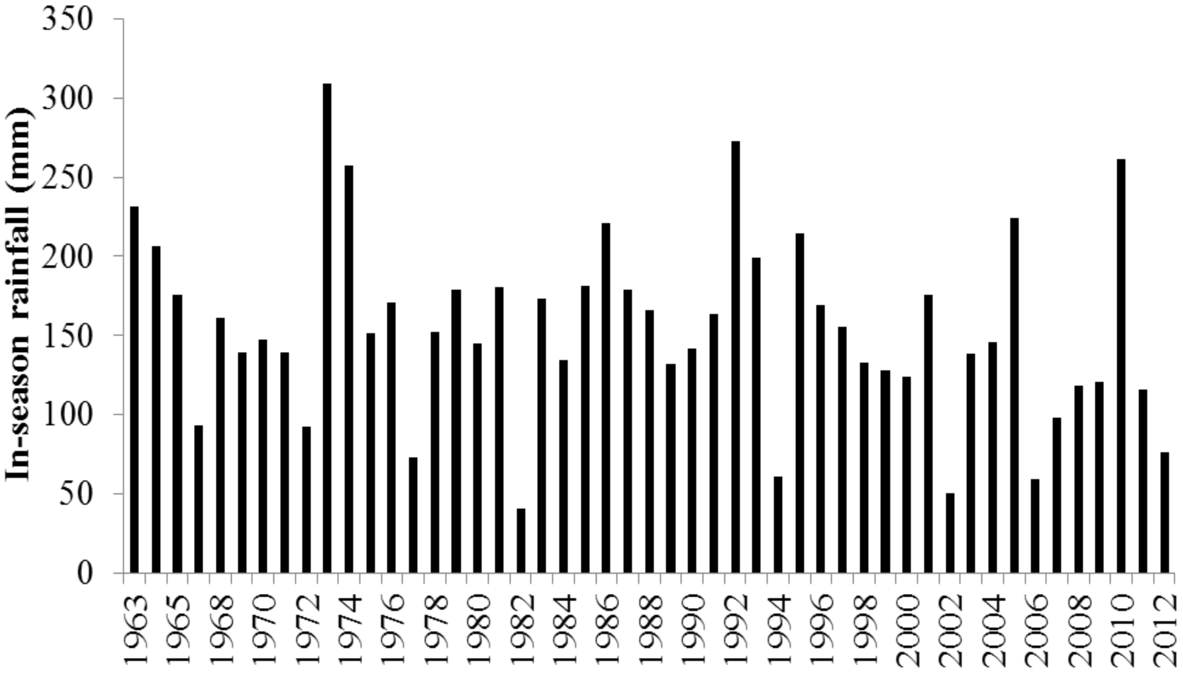

Figure 2: In-season rainfall for Loxton, located in southeastern Australia.

However, there is growing awareness of this in the scientific literature (Carberry et al., 2010, Hochman et al., 2009, Monjardino et al. 2013, Power and Chaco 2014, Rurinda et al. 2014, Rusinamhodzi et al. 2012, Sadras, 2002). Generally, to better manage risk it is necessary to know the long-term variation of attainable yield. As already mentioned field trials are expensive and consequently long-term data is often lacking, so that this information is difficult to generate. As an alternative process, crop modelling has been developed in the last two decades in order to assess attainable yield (for instance: http://www.yieldgap.org). Coupling such models with historical climate data, or improved weather forecasts, it is possible to generate fertilizer and general management recommendations (for instance: Asseng et al., 2012, Soler et al., 2007). In the following section the current crop modelling frameworks and their limitations are reviewed against the setting of attainable yields.

3. Methodology: Process based crop modelling

3.1 Annual crops

Currently, there are a range of process based crop models available (Table 1). While these differ in the description of certain processes, such as growth (for example: APSIM (Keating et al., 2003 and Holzworth et a., 2014) and DSSAT (Jones et al., 2003)) are driven by incoming solar radiation, AquaCrop (Steduto et al., 2009) calculates potential growth based on water availability) they share attributes in line with van Ittersum et al. (2013). These simulate the growth of the plant, which is divided by the organs such as stems, leaves, roots and generative parts on a daily time step. Plant development is divided into different growth stages (emerging, juvenile, flower initiation, flowering, grain filling and maturity). The calibration of site-specific cultivars is reduced to few parameters, so that the applicability for a range of agro ecosystems is guaranteed. The models contain a water balance, which enables them to assess the effect of water limitations on growth, and ideally also a nitrogen soil module to quantify nitrogen deficiency. The models have been tested against a range of field observed variables such as biomass growth, leaf area index, soil water and nitrogen. Finally, these models are well documented, i.e. the source code is accessible (see Table 1 for references).

In the following section, the main processes, which are addressed in the two most common crop models, APSIM and DSSAT, are shortly described. Both models are similar and have their roots in the CERES maize and wheat models.

Table 1: A collection of the most common process based crop models.

Abbreviation	Name	Reference	Homepage
APSIM	Agricultural Production Systems sIMulator	Holzworth et al., 2014	www.apsim.info
DSSAT	Decision Support System for Agrotechnology Transfer	Jones et al., 2003	dssat.net
STICS	Simulateur mulTIdisciplinaire pour les Cultures Standard	Brisson et al., 2003	www6.paca.inra.fr
CropSyt	CropSyst	Stöckle, Donatelli, & Nelson, 2003	www.sites.bsyse.wsu.edu/CS_Suite_4
MONICA	MOdel of Nitrogen and Carbon dynamics in Agro-ecosystems	Nendel, 2014	www.monica.agrosystem-models.com
LINTUL/WOFOST	“Wageningen school”	van Ittersum et al., 2003	www.models.pps.wur.nl
AquaCrop	AquaCrop	Steduto,et al. 2009	www.fao.org/nr/water/aquacrop.html
EPIC	The Environmental Policy Integrated Climate model	Kiniry & Williams, 1995	www.epicapex.tamu.edu
InfoCrop	InfoCrop	Aggarwal et al., 2006	

3.1.1 Temperature and photoperiod effects on crop development

The growth duration of the crops are affected by temperature and photoperiod. In crop models the development of a crop is divided into the main growth stages (often according to the Zadok or BBCH scale; see for instance (Soltani and Sinclair, 2012). How long a crop stays in one stage is determined by thermal time requirements, which are calculated using the temperature of that day minus the base temperature. A certain crop stage is finished when the accumulated thermal temperature meets the requirement for that stage. The duration in a certain stage can be further affected by the photoperiod. Such a simple approach is found in most crop models and has shown very accurate simulations when compared to observed crop development.

3.1.2 Light use

Monteith found that growth is linearly related to incoming light under optimum conditions (Monteith, 1972, 1977). From this observation, the following equation can be derived:

Growth rate (g/m^2) = PAR (MJ/m^2) * Fraction of Intercepted Light (%) * Radiation Use Efficiency (g/MJ) eqn. 1

PAR is the photosynthetic active radiation, which is usually considered as about half of the incoming total shortwave radiation (Monteith, 1972, 1977). The plant however, is not able to intercept all of the available light as this is limited by the properties of the canopy. The canopy properties are complex as plants differ widely in terms of the direction and characteristics of the leaves. As a simplification, the concept of the extinction coefficient and LAI has become a widely used approach to define the ability of the canopy to intercept light (Lambert-Beer law) (Goudriaan & Monteith, 1990). The extinction factor is a representation of the plant canopy to intercept light. LAI describes the ratio between the leaf size per m^2 against one m^2. Stationary and transportable devices have been developed to measure LAI (Bréda, 2003). For well-developed annual crops LAI typically starts from 0 at emergence to 3 and above at flowering. A good crop stand can intercept up to 90% of PAR. Furthermore, plants differ in terms of the property to convert the intercepted light into biomass growth. One reason for that is that a certain amount of the produced gross assimilates are used for respiration (maintenance and growth). In crop models such as LINTUL, these processes are explicitly modelled by calculating the respiration demand of the crop based on the biochemical compounds of the different organs (van Ittersum et al., 2003). This approach has been criticized due to the fact that the respiration processes are still not fully understood, and as the separation of growth and respiration is potentially just an artificial construct (Boote et al., 2013; Gifford, 2003). An alternative approach has been based on the concept of radiation use efficiency (RUE) which is widely employed by crop models such as APSIM and DSSAT (Sinclair & Muchow, 1999). RUE assumes respiration rates implicitly and can be defined as the conversion rate of intercepted light to biomass (Sinclair and Muchow, 1999). This approach ensures it can be measured under optimum growth conditions. Weakness of this approach is that it ignores temperature effects, crop aging and CO_2 limitations. This causes a wider range of values for the RUE than are found in the literature for the same crop. In APSIM and most crop models within DSSAT, RUE is modified based on cardinal temperatures (optimum, minimum and maximum temperature), CO_2 increase (climate change studies) and ageing (different RUE for different crop stages), an empirically derived approach.

3.1.3 Water balance

In terms of light and other resources, the availability of the resource, the uptake rate and the use efficiency (in the case of water this is known as the transpiration efficiency) determine potential growth (Soltani and Sinclair, 2012). First of all, the soil plant available water holding capacity has to be taken into account. Typically, this is simulated by the tipping bucket approach (More complex water balance models such as SWIM (Connolly et al., 2002) are rarely used); the difference between wilting point (or crop lower limit) and field capacity (or drained upper limit). This capacity determines the maximum plant available water in the soil and the storage capacity. Water supply beyond field capacity (when the soil is saturated) will lead to macro pore drainage through the soil profile. Before water can infiltrate the soil, runoff can occur. This process depends mainly on the soil type and is more pronounced on compacted and heavy soils. Runoff is typically modelled using the USDA runoff curve, which relates a runoff number with soil texture (Boughton, 1989). A second pathway of water losses is evaporation, which is more difficult to simulate. Several approaches have been developed over the years (Taylor-Priestley, Penman-Monteith, Shuttleworth etc.). A simple standard method in APSIM is Taylor-Priestley, which needs the following inputs: temperature, rain and solar radiation (Priestley and Taylor, 1972). However, this simple method ignores effects of wind and differences in relative humidity (in Priestley-Taylor it is calculated assuming that the dew point equals the minimum temperature). Contrary to this, the Penmen-Monteith approach takes wind effects into account, but consequently also needs wind speed (for wind speed no relationships with other climate variables are suggested) as an input, which is often difficult to acquire (Monteith, 1992). A third way of water loss is drainage, the flow of water in deeper soil layers, which is beyond maximum rooting depth.

Modelling the plant available water is complex and requires a careful parameterization of the relevant soil properties. Water uptake in the model is commonly described by water extraction rate and the conversion efficiency of water taken up to biomass is called transpiration efficiency. In many crop models, including the ones reviewed in this study, stress occurs when the demand of the standing and growing biomass is higher than the amount of transpired water.

3.1.4 Nitrogen cycle

Nitrogen is more complex to model, as it needs a working water balance to simulate events such as nitrate leaching or denitrification. Generally, organic nitrogen is distributed to three organic matter pools, which are called in APSIM: FBIOM, FINERT and FHUM. These pools are mainly defined by an C:N ratio, which determines the potential mineralization rate. FINERT is the fraction, which does not decompose in a relevant timeframe; FHUM is the slow decomposing material and FBIOM the fast decomposing fraction. The mineralization rate is affected by soil temperature and soil moisture. The organic nitrogen is then transformed to ammonium and finally nitrate. Losses can occur such as leaching or denitrification. The plant takes the mineral nitrogen up at potential rate. Every organ in APSIM needs a critical nitrogen concentration to maintain potential growth rate. If this level falls below that threshold nitrogen deficiency occurs and the growth is slowed down. However, the crop is able to maintain nitrogen levels above the critical nitrogen concentration to an upper limit (luxury uptake). After harvest, the harvested organ is removed from the system, while the residues with a certain C:N ratio typically remain on the field. These residues are mineralized depending on tillage, climate and residue quality, where immobilization can occur in the short run.

3.1.5 Summary modelling annual crops

Modelling frameworks such as discussed along the example APSIM retain increasing attention by the agronomical, but also the wider scientific and policy community (see for example increasing citation rate of APSIM: www.apsim.info). Most of the climate change assessments on effects on crops are based on crop models within a modular framework. The AGMIP initiative (Agricultural Model Intercomparison and Improvement Project; www.agmip.org) fosters this trend by bringing together these groups and produces a range of high impact publications (see the respective webpages). One of the advantages of the modelling frameworks are usually the user friendly interface user. Therefore agronomists with no software engineering background are able to use these models. APSIM (Holzworth et al., 2014), but also other examples like CropSyst (Stöckle et al., 2003) or STICS (Brisson et al., 2003) are more and more developing into a complete agro-ecosystem model (Stöckle et al., 2014, Bergez et al., 2014). Stand-alone models or also ad-hoc modelling (Affholder et al. 2012) developed in the 1990ies have stand behind these more popular modelling framework approaches. Ad-hoc modelling bases on the idea that there cannot be one modelling framework to address all research questions an agronomist face. Rather, the research question should finally determine the development of a crop model - so the model suits only the specific research question. However, due to the complexity of model building for most agronomists, there is a growing user community of available, widely tested annual crop models, which are easy to use, but cover a complex array of biophysical processes in an agro-ecosystem.

3.2 Perennial crops

In the last 40 years of crop modelling development from its beginnings of the pioneering work of de Witt, Monteith and many others, over the first complete crop model by van Keulen and van Laar (1982) and the CERES-maize model the focus of research was annual crops; mainly the staple ones – maize, wheat and rice. Consequently, for such crops now a wide range of models are available, built into modelling frameworks and are well tested. Recently, there is a strong focus on improving these models to better capture climate change effects on crop growth. Rötter et al. (2011) asked for an overhaul of crop models in particular modelling crops under heat stress. Projects like MACSUR and AGMIP ((Modelling European Agriculture with Climate Change for Food Security; www.macsur.eu and Agricultural Model Intercomparison and Improvement Project; www.agmip.org) deal mainly with model intercomparisons to identify shortcomings in the description of the crop physiology. However, all these activities are related to annual crops. The modelling of perennial crops is still in its infancy (van Oijen et al., 2010a). There are three different reasons for that:

1) Missing field trial data to find appropriate ways to calibrate and test the models
2) Knowledge gap in describing the complex physiology of the perennials
3) Missing input data, especially climate data to run complex daily process based models in tropical environments

Field trial data are difficult to generate for perennials as it is necessary to run such trials for many years. Labor and money are usually scarce, in particular in developing countries. In opposite, mechanistic crop modelling needs very detailed information on crop physiology. This is very hard to acquire, especially for root growth. Understanding of complex physiology like the four year fruiting cycle of oil palm is not fully understood, and consequently difficult to implement in models.

The third mentioned challenge is probably the most important one; climate and also soil data are often missing. Due to these constraints perennial crop models are rarely found in the literature - despite its potential usefulness as decision making tool for plantation manager in terms of climate change, fertilizer management etc.

In the following section, I will review prominent, available models for tropical perennials, and their applicability:

1) WaNulCAS
2) Coffee
3) SURCOS-Cocoa
4) APSIM oil palm
5) InfoCrop

3.2.1 WaNulCAS

While the above mentioned description plant processes in the crop models worked well and have been tested widely for annuals (see Table 1), they are difficult to apply to perennial crops, in particularly tropical plantation crops. One of the first tree model used in agronomy was WaNulCAS. It is an agroforestry model, with main emphasis on modelling competition between different plant species.

The climate data is often not available to run this model (Huth et al., 2014, van Oijen et al., 2010a). on the other hand, the agroforestry model WaNulCAS does not need solar radiation and temperature as inputs (Noordwijk and Lusiana, 1999). It uses a potential crop/tree growth rate instead. The authors suggest that the potential growth rate can be derived from more mechanistic models. The growth rate is defined under optimum conditions (no nutrient and no water stress, and no pest and diseases) for a specific environment. However, that means that the potential growth rate has to be defined for a specific environment based on assessment over multiple years as solar radiation and temperature can differ significantly from year to year. Technically speaking, the potential growth is the average solar radiation times the RUE of several seasons. Despite this simplification, WaNulCAS takes light competition into account (in terms of light interception). The resource light is treated similarly as water and nitrogen stress in models as APSIM. Fully potential growth rate is only reached when the plant canopy is directly exposed to the sun, and the LAI has reached canopy closure. Therefore three different kinds of canopy strata are assumed: an upper canopy (with only one type of leaves), a mixed one (with both types of leaves present) and a lower one (with one only). Total LAI for each plant in each zone is fractionated according to the relative heights of tree and crop, thus ensuring symmetry in the relations and the possibility of crops shading trees depending on relative heights. Light capture is calculated from the LAI in each canopy layer and a plant-specific light extinction coefficient (Noordwijk, Lusiana, & Khasanah, 2004).

Competition for water in the WaNulCAS model is described by sharing the potential uptake rate calculated on the basis of the combined root length densities for all plants in a given soil compartment. This is multiplied by relative demand. The actual uptake rate will be a fraction (between 0 and 1) of this potential, depending on the sum of potential uptake by a given plant and its current demand, so similar simulated as in APSIM or DSSAT. The key idea of WaNulCAS is that it allows soil compartments where roots from different crops interfere, where root competition is evaluated by root length density, while there are soil compartments where only roots of one crop occur. This offers the opportunity to simulate competition for water under intercropping conditions more mechanistically; the model user has more options to modify crops/varieties according to their suitability for intercropping systems. For example, it might be of interest to modify root growth of two different crops in the model; so that they use the water in a most efficient way by vertical (crop A) and horizontal (crop B) root growth.

3.2.2 Coffee

For coffee production, van Oijen et al. (2010 a,b) developed a simple physiological model. An important feature of coffee production is that often shade trees are included in the plantation. Therefore, they accounted for competition effects between the shade tree and coffee in terms of light, water and nitrogen. In terms of light the shade tree is assumed to be be higher than the coffee. Intercepted light by the tree is calculated by the Beer’s Law based on leaf area index. The transmitted light is then available to the coffee plant. The water balance assumes only one large bucket, and does not differentiate into layers. However, this model has not been tested against field trial data. The authors conclude that the available data in terms of crop data but also climate data are not sufficient.

3.2.3 SUCROS-Cacao

Zuidema et al. (2005) present a process-based production model. It is based on the Wageningen crop modelling framework SUCROS (van Keulen and van Laar, 1982). It simulates growth intercepted light and produced assimilates are then distributed to the different organs. As well as coffee, cacao is partly cultivated with shade trees. The authors here used a simple shade fraction, which reduces light availability for the crop. Water limitations are simulated with the typical water-bucket approach defining three soil layers. The higher amount of roots in the top layers allows the cacao plant to take up more water than from layers below. This is represented in the model by a higher water extraction rate.

The model was tested using a sensitivity analysis to explore the most important parameters and against reported data from the main growing regions (Ghana, Brazil, Malaysia, Costa Rica). However, site-specific knowledge of soil, weather and management was not available. A detailed testing as for annual crops was therefore not possible.

3.2.4 APSIM oil palm

Just recently, a new oil palm model was developed by Huth et al. (2014) using the APSIM framework. Based on data from three sites in Papua New Guinea they implemented an oil palm model based on the APSIM modular system. Therefore it is theoretically able to simulate the growth based on solar radiation, water availability, temperature and nitrogen availability. One key challenge was the modelling of the bunch developments. They assumed cohorts of bunches with similar age, which run through the cycle of sex determination, inflorescence abortion, bunch failure and bunch growth. Although it argues that it is general possible to develop a perennial crop model in such a modern simulation framework (with process based description of water cycle, nitrogen limitation), several critical points arise from this study: The testing is restricted to only one region. To prevent calibration errors in terms of model fitting it would be necessary to run the model also for other sites (where data is as above mentioned scarce). The second critical point is the missing knowledge about rooting depths and the ability of the crop to take up water under stress conditions (Carr, 2011). The third point, which is also addressed by the authors, is the missing input data; partly soil information, but more important climate information. In this study they used data from NASA (http://power.larc.nasa.gov/), and disaggregate monthly observed rainfall data (when available). Despite these shortcomings APSIM oil palm is huge step forward to develop a perennial crop model in the same complex way as for annuals.

3.2.5 Infocrop coconut

One of the most promising presentation is the coconut model by Kumar et al. (2008). Here, they used, as Huth et al. (2014) an existing complex model framework - Infocrop (Aggarwal et al., 2006) - where they built in the coconut model. Infocrop simulates crop growth based on solar radiation, temperature rainfall and nitrogen availability. Based on intensive field trial data, they were able to calibrate the model independently from the evaluation data set. The accurate information of the field trials allows also a statistical evaluation of the model in a similar way than for annual crops. However, due to the model complexity, it has a demand for input, especially for climate variables: Daily weather data needed for the model are minimum and maximum air temperatures (°C), solar radiation (kJm^{-2} day^{-1}), vapor pressure (kPa), wind speed ($m\ s^{-1}$) and rainfall (mm), which limits the applicability of the model.

4. Research needs

There has been wide evaluation and application of such process based crop models for a range of typical agronomical questions such as: optimizing fertilizer strategies, optimal planting times x variety, intercropping and relay planting, weed-crop interactions, risk assessment and in-season decisions, new crop potential, plant breeding (G x E interactions), irrigation and drainage and climate change issues (Asseng et al., 2013; Boote et al., 2010; Hammer et al., 2010; Hochman et al., 2009; Whitbread et al., 2010). However, this research has been mostly limited to annual crops.

Most crop models were developed for the major staples, such as maize, wheat and rice and to a lesser extent sorghum, millet, sugar cane, cotton and a few legumes. Ongoing projects on model improvement and uncertainty assessment such as MACSUR or AGMIP, deal with these crops so far. While this fundamental research improving model mechanism is essential, it is also necessary to extend the availability of further crops in modelling frameworks (which will also benefit from knowledge derived from the above mentioned projects). This will allow the representation of the many options farmers have to adjust management (cultivars, planting dates, fertilizer applications, rotations) to the challenges they face in the model. For example, there are hardly, respectively no models in simulation frameworks for oilseed rape or sugar beet, which are important crops in central Europe. For African conditions, a well working Cassava model is still under development. Beside crops, certain soil properties that affect water-limited yield, such as high salt concentration (which reduces the water uptake capacity of a crop) represent a neglected challenge for crop modelling. Modelling perennial crop production systems, in particular, tropical plantation crops, is still in its infancy, despite their potential usefulness. This is due to missing climate data and to lacking detailed field trials to parameterize models for the complex physiology of perennial crops and the evaluation of the models.

To sum up, crop modelling is proven to be very useful for decision support: however there is a strong need to improve the modelling infrastructure in terms of data availability (soil parameters and climate, cultivar), new crops parameterization, in particular for perennial crops, and the assessment of uncertainty by comparing crop models. For situations in which data availability is limited, simpler models/ tools have to be developed to be applicable for yield gap studies. In the long run the improvement of the modelling infrastructure will allow more detailed crop models.

5. Overall research objectives

Within this context of research needs, the PhD thesis has following objectives:

(i) in 3 widely differing agro-ecosystems, apply crop model approaches to determining yield potential as influenced by the environment and production system characteristics.

(ii) evaluate the accuracy of the model outputs against measured field data and develop scenarios to investigate issues relevant to management (scale varying from field to region).

(iii) utilizing these contrasting model applications, discuss the application of modelling to the debates around sustainable intensification strategies to close yield gaps in the context of each agro-ecosystem, considering climate, soils, resource constraint and production system.

To verify them three very distinctive systems were selected: (i) commercial oil palm production in Indonesia and Malaysia, (ii) wheat cropping in southern Australia (iii) and oilseed rape production in rotation with wheat in central Europe. All three systems are of relevance for global food security (Mueller et al., 2012b; Spink et al., 2009; FAOSTAT, 2013). However, in all production systems challenges arose in using crop modelling, which are often neglected in yield gap assessments. To improve the capability for such conditions the model approach was kept as simple as possible (in particular for data input, the major constraint for applying crop models) and at the same time incorporates sufficient plant physiological knowledge to be generally applicable across sites with different growing conditions. As the scale of management in the three production systems differs; in oil palm the smallest management unit is a block (often larger than 25 ha), in oilseed rape a field (1-5 ha) usually still managed homogenously, in wheat production in Southeast Australia, because of the large variability within a field (<100 ha), the management scale is zone specific. However, the data availability (Climate) differs; while in Australia and Europe data for soil and daily weather is available, this is not the case for oil palm plantations in remote tropical areas. Therefore these production systems depict a challenge for crop modelling and will further foster approaches to apply crop models in decision making process at plantation/farmer level.

6. Structure of the PhD thesis

The thesis is divided into six chapters. The first chapter presents the scientific background and the overall research objectives of the thesis. Chapter two, three, four and five collect the research results written in the form of journal articles. Chapter two, four and five are published respectively and submitted to international refereed journals. Chapter three is seen as collection of ideas about how the PALMSIM model can be used further. In chapter six the research results are shortly compared and the conclusions from this exercise are discussed against the overall research objectives of the thesis.

Chapter II:

The second chapter is published as Hoffmann, M.P., Castaneda Vera, A., 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. This describes the physiological oil palm growth model PALMSIM. The key idea of this model is that it is both simple and at the same time incorporates sufficient plant physiological knowledge to be generally applicable across sites with different growing conditions. The presented version in this chapter simulates the potential growth of oil palm based on solar radiation; all other climatic factors are ignored. In a second step, the model is evaluated against a range of data from several sites and a sensitivity analysis is conducted. After successful evaluation, the model is preliminary applied by generating a potential yield map for oil palm production in Southeast Asia.

Chapter III:

The third chapter Hoffmann, M.P, Donough, C., Oberthür, T., Castaneda Vera, A., van Wijk, M.T., Lim, C.H., Asmono, D., Samosir, Y., Lubis, A.P., Moses, D.S., Whitbread, A.M. (2014) "**Benchmarking yield for sustainable intensification of oil palm production in Indonesia using PALMSIM**" (accepted by *The Planter*; 01.04.2015) presents the further development of the PALMSM oil palm model by implementing a simple water balance. Thereby the model is able to roughly assess water limited yield. The model is then used in two case studies supporting sustainable intensification in oil palm: (i) establishment of new oil palm plantations on degraded or pre-existing cropland sites only (ii) the intensification of production in existing plantations to reduce the gap between actual and water-limited potential yield. The first case study makes use of a recent published map of degraded land for Kalimantan, which is overlayed with a map of simulated water limited potential yield. In the second case study the potential and water-limited yield is simulated with PALMSIM for six plantation sites in Indonesia. The simulated yields are then compared to observed yields from best-managed blocks and standard managed blocks of the plantation.

Chapter IV:
In the fourth chapter, which is published as Hoffmann, M.P., Jacobs, A., Whitbread, A.M., (2015) **Crop modelling based analysis of site-specific production limitations of winter oilseed rape (*Brassica Napus* L.) in northern Germany for improved nitrogen management** *Field Crops Research*; 178, 49-62, an adaption of the APSIM canola model for winter oilseed rape is presented. After calibration and evaluation the model is used to assess water limited potential yields and nitrogen balance for different rooting depths of a loamy soil and six sites across northern Germany. Limited rooted depth and the climate of some sites in that region cause water stress at flowering and reduced nitrogen uptake in the grains. Site-specific fertiliser strategies therefore appear promising according to the model.

Chapter V:
Chapter five, which is submitted as Hoffmann, M.P., Llewellyn, R., Davoren, B. Whitbread, A.M. (2014) **Assessing the potential for zone-specific management of cereals in low rainfall South-eastern Australia: Combining on-farm results and simulation analysis** (submitted to *Journal of Agronomy and Crop Science*; 21.10.2014) presents the parameterisation of the APSIM soil water balance for heavily constrained soils in low rainfall south-eastern Australia. After the validation against observed on-farm yield data, the APSIM model is used to investigate the attainable yield in relation to nitrogen application at different soil types; from course to fine textured soils.

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II. Simulating potential growth and yield of oil palm (*Elaeis guineensis*) with PALMSIM: Model description, evaluation and application[1]

1. Introduction

Oil palm is one of the most important oil crops in the world. Palm oil production is five times greater per unit land than other oil crops such as soybean or rapeseed, which together with the growing global demand for vegetable oil and biofuels drives its profitability (Sheil et al., 2009). Malaysia and Indonesia account for 81% of the total global production. In Indonesia six million ha are covered by oil palm with an annual production of 102 million Mg fresh fruit bunches (FFB). Malaysia produces 88 million Mg from four million ha. FFB yield in Indonesia averages 17 Mg ha^{-1}, and in Malaysia it averages 22 Mg ha^{-1} (FAO, 2013). The rapid expansion of oil palm cultivation is seen as a severe threat for the conservation of rain forest and swamp areas and their associated ecosystem services (Koh et al., 2011; Koh and Wilcove, 2007). For example, the area in Indonesia dedicated to oil palm production doubled from 2003 to 2011 (FAO, 2013).

Considering both the growing demand for palm oil and the environmental consequences of oil palm cultivation, two strategies have been proposed for more sustainable oil palm systems: (i) the establishment of new oil palm plantations on degraded or pre-existing cropland sites only (ii) the intensification of production in existing plantations to reduce the gap between actual and water-limited potential yield (Gingold et al., 2012; Sayer et al., 2012). Within the context of the first strategy, Gingold et al. (2012) provide an assessment of extension and suitability of marginal areas for oil palm cultivation in Kalimantan (http://www.wri.org/project/potico). Based on social, economic, legal and environmental criteria marginal areas were classified qualitatively into groups with poor to good suitability for oil palm. Gingold et al. (2012) concluded that there is substantial scope for the expansion of plantations into marginal areas in agreement with Indonesia’s national REDD+ (Reducing Emissions from Deforestation and Degradation) scheme, but that the definition of ‘degraded land’ or ‘marginal land’ is still under debate. The exact extent of degraded land is unclear, therefore, estimates of yield that could be achieved in such sites are often lacking. Within the context of the second strategy, comparisons of actual yields with records of the largest yields indicate the scope for yield intensification for existing plantations. In 2006, the IOI Group, one of the leading plantation

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[1] This chapter is published as Hoffmann, M.P., Castaneda Vera, A., 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.

groups in Malaysia, reported an average annual FFB yield of 38 Mg ha^{-1}, with an estimated oil yield over 8 Mg ha^{-1}, for their best performing estate. At company level (ca. 150,000 ha), average oil yields of 6 Mg ha^{-1} and FFB yields exceeding 27 Mg ha^{-1} have been reported. FFB yields higher than 40 Mg ha^{-1} have been recorded for single blocks in many estates in Indonesia and Malaysia (Donough et al., 2009).

As such data is site and year specific, and not available for sites without oil palm production history, the use of simulation models offers a viable way to assess potential and attainable growth and yield (van Ittersum et al, 2013). The available models that simulate oil palm production are demanding in terms of the data needed for parameterization and running of the model (Combres et al., 2013; Dufrene et al., 1990; Henson, 2009, van Kraalingen et al., 1989). This makes them less useful for a scoping analysis of potential and attainable oil palm yield across a wide range of locations. The first mechanistic oil palm model, OPSIM, was developed by van Kraalingen (1985). This simulates potential growth and yield based on radiation and assumes no other production limitations. To run the model, measurements on vegetative development are necessary. OPSIM’s demand for crop data is similar to that of another oil palm model, SIMPALM (Dufrene et al., 1990), which was parameterized for oil palm production in Africa. A recent oil palm growth model OPRODSIMv1 is able to simulate the growth of oil palm from the day of planting (Henson, 2009). This is a detailed daily time step model, which simulates growth based on solar radiation, and growth is limited by temperature stress, vapor pressure deficit and water availability. Essentially, OPRODSIMv1 is demanding in terms of daily weather input (solar radiation, net radiation, humidity or vapor pressure deficit, air temperature, actual to potential evapotranspiration ratio, rainfall and wind). Combres et al. (2013) developed a site-specific model to investigate flowering dynamics, intended to serve as a management decision tool. However, due to the need for high accuracy to assess flowering dynamics a large database is necessary to estimate cultivar and plantation characteristics (Combres et al., 2013).

A mechanistic oil palm growth model that is limited in its demands for input variables and physiological parameters, and, which can be easily applied across a wide range of sites is lacking. The objectives of this study were therefore to develop a model (PALMSIM) that simulates, on a monthly time step, the potential growth of oil palm as determined by solar radiation and to evaluate model performance against measured oil palm yields under optimal water and nutrient management for a range of sites across Indonesia and Malaysia.

While we acknowledge that, depending on the soils and climatic environment, yields may be often water limited, we suggest a relatively simple physiological approach to simulate potential yield, which can be usefully applied to high rainfall environments and is considered as a first step in developing an oil palm model that also simulates water-limited potential yield. We assessed the usefulness of the current version of the model as an exploratory tool for decision makers in the planning of land use for oil palm by creating a potential yield map for Malaysia and Indonesia.

2. Material and Methods

2.1 General structure of PALMSIM

The simulation model PALMSIM consists of a plant growth module, which simulates the potential growth and yield of an individual oil palm stand on a per hectare basis, and a radiation module (Figure 1). Potential production is defined in this case by radiation under otherwise optimal environmentally determined growing conditions: no growth limitation in terms of water or nutrient availability, and no incidence of pests or diseases (van Ittersum et al., 2013). The model also assumes uniform planting material and recommended canopy management in terms of pruning. Planting density is set to 143 palms ha^{-1} following standard practices in the oil palm industry (Corley and Tinker, 2003). However, planting density and also the pruning regime can be altered in the model.

The growth and radiation modules are linked through a run module, which contains all the general settings of the model run. The oil palm growth module can also be used as a standalone tool for applications to individual sites when measured or estimated radiation values are available. Using the combined plant growth and radiation modules the model can be run for any given site. PALMSIM simulates the growth and the yield of a palm stand using a monthly time step over a period of 30 years, which covers the maximum commercial life span of an oil palm plantation of 23-25 years. A detailed description of the model together with the mathematical equations is given in the supplementary material; here we provide a general description of the model. Incoming radiation is calculated based on latitude, slope, azimuth and monthly cloudiness index. PALMSIM is based on the assumption that under optimum conditions monthly growth of the plant is linearly related to the quantity of intercepted light (Monteith, 1977). Intercepted light is determined by the amount of incoming photosynthetic active radiation (PAR) and the capacity of the plant to intercept this light, using the leaf area index (LAI) and a light extinction factor (k) (i.e. Beer-Lambert law). LAI is calculated based on the specific leaf area (SLA) and the total biomass contained in fronds per hectare. Intercepted light is then converted into gross assimilates by applying a constant light use efficiency factor (LUE) (c.f. Combres et al., 2013). Frond biomass is produced by plant growth and removed by pruning.

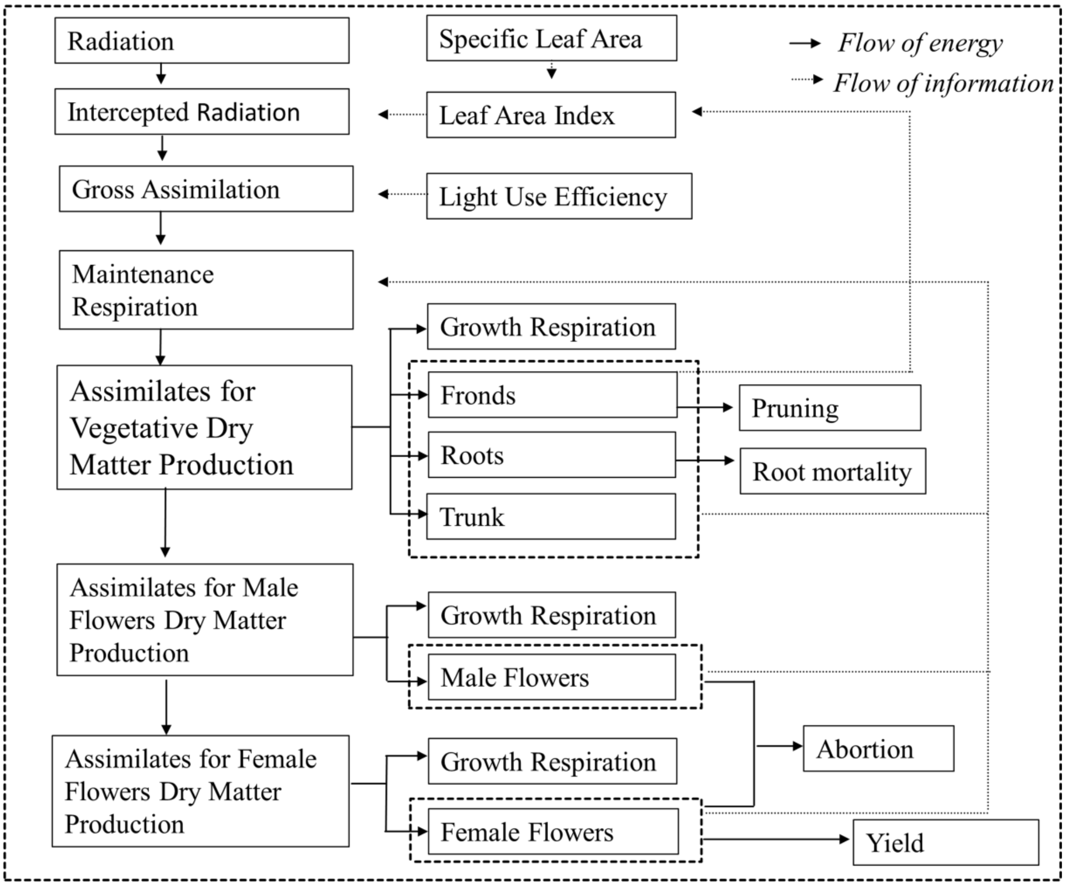

Figure 1: Schematic overview of PALMSIM. Dashed boxes represent standing biomass.

Produced assimilates are first used to satisfy maintenance respiration (c.f. van Kraalingen et al., 1989). The remaining assimilates are first allocated to the growth of the vegetative plant parts (roots, trunk, fronds). If minimal requirements for vegetative growth and growth respiration are satisfied, assimilates are used for generative biomass production (i.e. female and male flower production). The amount of assimilates used for male flowers are related to the vegetative standing biomass. Any remaining assimilates are used for female flower production. A growth respiration coefficient is applied for generative growth. Bunch production is therefore considered to be source limited, except for with young palms, where maximum bunch weight is dependent on the age of the palm stand. The model therefore predicts maximum total biomass production and yield, as well as the yield components and the weight of bunches produced at a certain moment in time.

2.2 Parameterization of PALMSIM

The input variables (Table 1a, b, c) are based on values suggested in the literature or derived from the process-based models SIMPALM (Dufrene et al., 1990), OPSIM (van Kraalingen et al., 1989) and OPRODSIMv1 (Henson, 2009) (Table 1 a, b, c).

2.2.1 Radiation, light interception and photosynthesis

Solar radiation is calculated from the cloudiness index, azimuth and slope following the method presented and tested in Augustine and Nnabuch (2009) and Ruth and Chant (1976). Following Monteith (1972), PAR is assumed to be half of the total solar shortwave radiation. The standard value for specific leaf area in oil palm is 0.31 ha Mg^{-1} (Breure, 2003). Various values have been found for k in oil palm (Noor and Harun, 2004). The value of k is related to the morphology of the palm, since more erect fronds mean that less light is intercepted than if they are more horizontal (Breure, 2003). In PALMSIM, k is determined by a relationship in regard to LAI adapted from van Kraalingen (1985; Appendix).

A monthly value of 4.5 g CH_2O MJ^{-1} is used for LUE based on an optimization procedure against field data sets carried out by Combres et al., (2013). This value of LUE is used to calculate gross primary production and is therefore substantially higher than radiation use efficiency of 1.4 g CH_2O MJ^{-1} in oil palm reported by Noor and Harun (2004), which includes the costs of respiration (estimated at between 60 - 80 % of gross assimilation) and assimilates for roots.

Table 2a: List of parameters used in PALMSIM related to light interception and photosynthesis.

Parameter function	Parameter term	Value	Unit	Source
Conversion rate from incoming global radiation to photosynthetic active Radiation	P_{AR}	0.5	-	Monteith, 1972
Specific Leaf Area	S_{LA}	0.31	ha Mg^{-1}	Breure, 2003
Light Extinction Factor (k)	k_1	0.1	ha ha^{-1}	Adapted from van Kraalingen, 1985
	k_2	0.45	-	Adapted from van Kraalingen, 1985
	k_3	2	-	Adapted from van Kraalingen, 1985
Light Use Efficiency	L_{UE}	4.5	g CH2O MJ^{-1}	Combres et al. 2013

2.2.2 Maintenance respiration and vegetative biomass production

Dufrene et al. (1990) present detailed values for the biochemical composition of the different organs. Based on this information - the nitrogen content, the mineral content, the coefficient for the conversion of nitrogen into protein, a coefficient for the costs to maintain ionic gradients and a coefficient for the renewal of free protein and membrane - they calculated maintenance respiration coefficients for roots (0.0022 g CH_2O g^{-1} day^{-1}), for the trunk (0.0005 g CH_2O g^{-1} day^{-1}), for the leaflet (0.0083 g CH_2O g^{-1} day^{-1}) and for the rachis/petiole (0.0020 g CH_2O g^{-1} day^{-1}), which are implemented in PALMSIM. Following Ng and Thamboo (1967) and Ng et al. (1968), fronds are divided into leaflets (75% of fronds) and rachis/petioles (25% of fronds). The respiration coefficient for the generative part is 0.0022 g CH_2O g^{-1} day^{-1} (van Kraalingen, 1985). The maintenance respiration coefficients are defined for a temperature of 25°C.

The parameter for the maximum amount of assimilates allocated to vegetative production is taken from Breure (2003). 70 % of these assimilates are partitioned to the fronds, and the remainder to roots (18%) and trunk (12%) growth (Henson, 2009). Growth respiration coefficients follow the calculations of tissue composition presented in Dufrene et al. (1990). Root biomass increase is impeded over time through root mortality, which is estimated from the relationship between root mortality and root biomass in OPRODSIMv1 (Henson, 2009). Trunk growth is not considered to be limited. Standing frond biomass is controlled by pruning, which is calculated using the approach of OPRODSIMv1 (Henson, 2009). A limit of standing frond biomass is defined by the age of the palm stand and is called fronds goal. Fronds pruned is the difference between the frond standing biomass at a certain moment in time and the corresponding value of fronds goal.

Table 1b: List of parameters used in PALMSIM related to maintenance respiration and vegetative biomass production.

Parameter function	Parameter term	Value	Unit	Source
Maintenance respiration coefficients:				
a) Roots	a_{roots}	0.066	Mg CH$_2$O Mg DM^{-1} mo^{-1}	Dufrene et al., 1990
b) Trunk	a_{Trunk}	0.015	Mg CH$_2$O Mg DM^{-1} mo^{-1}	Dufrene et al., 1990
c) Rachis	a_{Rachis}	0.060	Mg CH$_2$O Mg DM^{-1} mo^{-1}	Dufrene et al., 1990
d) Leaflet	$a_{Leaflet}$	0.249	Mg CH$_2$O Mg DM^{-1} mo^{-1}	Dufrene et al., 1990
e) Generative Part	$a_{Generative}$	0.066	Mg CH$_2$O Mg DM^{-1} mo^{-1}	van Kraalingen et al. 1989
Rachis weight in dependence on frond weight		0.75	Mg Mg^{-1}	Ng et al., 1967 and 1968
Leaflet weight in dependence on frond weight		0.25	Mg Mg^{-1}	Ng et al., 1967 and 1968
Maximum assimilates for vegetative biomass production	b_1	0.51	-	Breure, 2003
	b_2	0.0024	-	Henson, 2009
	b_3	0.23	-	Henson, 2009
Assimilates partitioning factor:				
a) Fronds	c_{Fronds}	0.70	-	Henson, 2009
b) Roots	c_{Roots}	0.18	-	Henson, 2009
c) Trunk	c_{Trunk}	0.12	-	Henson, 2009
Growth respiration coefficients:				
a) Roots	d_{Roots}	0.69	Mg CH$_2$O Mg DM^{-1} mo^{-1}	Dufrene et al., 1990
b) Trunk	d_{Trunk}	0.69	Mg CH$_2$O Mg DM^{-1} mo^{-1}	Dufrene et al., 1990
c) Fronds	d_{Fronds}	0.72	Mg CH$_2$O Mg DM^{-1} mo^{-1}	Dufrene et al., 1990
d) Male Flower	d_{Male}	0.57	Mg CH$_2$O Mg DM^{-1} mo^{-1}	Dufrene et al., 1990
e) Female Flower	d_{Female}	0.5	Mg CH$_2$O Mg DM^{-1} mo^{-1}	Dufrene et al., 1990
Root death	e_1	0.13	-	Henson, 2009
	e_2	0.06	Mg ha^{-1} mo^{-1}	Henson, 2009
Fronds Pruning	f_1	0.001	Mg DM mo^{-1} palm^{-1}	Henson, 2009
	f_2	0.0083	Mg DM palm^{-1}	Henson, 2009
	f_3	0.0006	Mg DM mo^{-1} palm^{-1}	Henson, 2009
	f_4	0.0636	Mg DM palm^{-1}	Henson, 2009
	f_5	0.16	Mg DM palm^{-1}	Henson, 2009

2.2.3 New fronds and flowering

The values proposed by von Uexküll et al. (2003) are used to determine the number of fronds expected for every development stage of the crop (i.e. the time after planting or the age of the plantation). A new flower is initialized at the inception of each new frond. A time period of 39 months from flower initiation to bunch harvest is assumed. Under field conditions this period might vary according to environmental conditions. For the first 15 months, flowers are asexual and thereafter become differentiated as either male or female (Corley and Tinker, 2003).

Table 1c: List of parameters used in PALMSIM related to flowering.

Parameter function	Parameter term	Value	Unit	Source
Development of new fronds	g_1	-0.039	# mo^{-1}	von Uexkull, 2003
	g_2	5.3	#	von Uexkull, 2003
	g_3	-0.006	# mo^{-1}	von Uexkull, 2003
	g_4	3.05	#	von Uexkull, 2003
	g_5	1.83	#	von Uexkull, 2003
Maximum of fronds opened per palm in one time step		2.55	#	von Uexkull, 2003
Fraction of flowers, which become female	h_1	-0.0045	Palm Mg DM^{-1}	Corley and Gray, 1976, Corley and Tinker, 2003
	h_2	0.9484	-	Corley and Gray, 1976, Corley and Tinker, 2003
Assimilates for male flower biomass production	i_1	0.00002	ha Mg CH_2O mo^{-1} Mg DM^{-1}	Henson, 2009
	i_2	0.0006	Mg CH_2O mo^{-1} Mg DM^{-1}	Henson, 2009

The fraction of indeterminate flowers that differentiate to female flowers decreases from 90% in the fourth year after planting to about 60% from year 15 onwards. This assumption is based on observations of Corley and Gray (1976) for coastal sites across Malaysia, who found a relationship between biomass and flower differentiation. To convert this into a time or age-driven relationship we assume an overall relationship between years after planting and biomass (based on values simulated by OPRODSIMv1) thereby obtaining a relationship between years after planting and flower differentiation. Once sex differentiation has occurred the flowers develop over 18 months until maturity and pollination. Once female flowers are pollinated, male flowers die off, and bunches develop for the next 6 months until harvest (Breure, 2003).

Quantitative knowledge on flower abortion in oil palm is lacking with little consensus about the factors that determine flower abortion, neither with regard to intensity nor timing. To capture the effects of flower abortion, an average of observations made by Corley and Gray (1976), Liau and Ahmad Alwi (1995), and Sparnaaij (1959) was taken with the resulting assumption that losses of 1% per month for indeterminate, male and female inflorescences occurred. Abortion of the inflorescence after anthesis, commonly known as bunch failure, is assumed in PALMSIM to account for 10% of total bunch loss per month (Corley and Tinker, 2003). Assimilates used for male inflorescence production are based on analyses performed with OPRODSIMv1; assimilates used for male inflorescence were plotted against total vegetative biomass for different planting densities (52, 100, 148, 196, 292 and 340 palms ha^{-1}). The resulting relationship between assimilates for total vegetative biomass and for male inflorescence is used in PALMSIM.

In PALMSIM, the assimilates that remain for biomass production of female flowers are calculated as the available gross assimilates after subtracting those used for maintenance respiration, vegetative biomass production and male biomass production, taking a growth respiration factor into account. It has been found that there is a strong relationship between gross assimilation and bunch production. This suggests that yield in oil palm is source limited (Squire and Corley, 1987; Breure, 2003), except in the case of young palms where the size of bunches may limit yield (Henson, 1990). In PALMSIM, bunch production is determined by the amount of available female flowers for the first four years of plant growth, afterwards bunch production is determined only by the available assimilates.

2.2 Model evaluation

2.2.1 Comparison of simulated versus observed data

Evaluation of model performance against observed results is a challenge as comprehensive climate and yield data sets for oil palm are scarce, as for other tree crops (van Oijen 2010a, Zuidema et al., 2005). For example, Zuidema et al. (2005) limit the validation of a cocoa model to comparison between model output with regularly reported plantation output as yield or standing biomass. Site-specific data of climate and soil were often not available. Here we use oil palm yield and frond weight data from 13 sites covering 15 trials in Malaysia and Indonesia, where optimal fertilization practices were used (Table 2). We assumed that optimum fertilized plots in environments where water is in sufficient supply are close to potential yield (van Ittersum et al., 2013). However, fertilizer rates used in the plantations included in the data set can differ from site to site, or even trial to trial. For the optimum fertilizer regimes, nitrogen rates ranged from 0.92 to 1.75 kg palm^{-1} year^{-1}, phosphorus from 0.3 to 0.8 kg palm^{-1} year^{-1} and potassium from 1 to 2.4 kg palm^{-1} year^{-1}. As controls, data from plots where no fertilizer was applied were available. Of the 13 sites, it was possible to calculate total frond production on a per hectare basis at 7 sites (9 trials, 46 observations). This was based on measurements of the average frond weight, the number of fronds per palm and the planting density. Frond dry weight was either directly available or was calculated according to Corley and Tinker (2003). The annual number of fronds produced per palm was not available for most of the sites, so an average of 22 was used (von Uexkull et al., 2003). For all sites (15 trials, 89 observations) yield as bunch production data was available. They were expressed in kg of fresh matter and converted into dry matter by assuming a commonly used dry matter content of 53% in the bunches (Breure, 2003). PALMSIM was run for every trial by taking the planting density of the palm stand into account (Table 2). Average monthly cloudiness data for the period between 2001 and 2010 for these sites were downloaded from the NASA Earth Observation website (NASA, 2012). This means an average year was used for the simulation of the whole life span of the plantation. This approach has been proposed for data scarce environments if potential growth is to be assessed for a given site (c.f. Henson, 2009). Observed frond weight and bunch production were compared with the predicted results taking the age of the palm stand into account.

For statistical analysis, the maximum observed yield and the corresponding predicted value were compared for each of the 13 sites. To assess the goodness of fit of these simulated - measured yield comparisons the root mean square error (RMSE) between predicted and observed data was calculated as follows:

$$\mathrm{RMSE} = [(\sum (\mathrm{O} - \mathrm{P})^2/n)]^{0.5}$$

where O and P are the paired observed and predicted data and n is the total number of observations.

Table 3: Overview of the available data set to evaluate PALMSIM.

Site Number	Region	Planting Density (ha)	Frond data available	Trial name[a]
1	Sabah	132	+	Sabah
2	Malaysia Peninsular	136	-	Jenderata
3	Lampung	143	-	Lonsum
4	North Sumatra	143	-	North Sumatra
5	Sumatra Riau	143	-	Riau Sumatra
6	South Kalimantan	136	-	South Kalimantan
7	North Sumatra	128	+	231
8	North Sumatra	128	-	232
9	North Sumatra	128	+	275
10	North Sumatra	128	+	277
11	South Eastern Sumatra	143	+	1411
12	South Eastern Sumatra	143	+	1403, 1412
13	South Eastern Sumatra	143	+	1413, 1414

[a] Trial names refer to soil type, location or planting material.

2.2.2 Sensitivity analysis

A sensitivity analysis was carried out for the site in Sabah (Malaysia) from the available data set. 19 physiological, two management and one climate input parameters were changed by adding or subtracting 10% to the default values and the effect on annual dry bunch yield was calculated. Such an analysis will identify parameters that have a strong influence on oil palm production and therefore need to be estimated accurately (Zuidema et al., 2005).

2.3 Potential yield map for Indonesia and Malaysia

To illustrate the applicability of the PALMSIM model, it was run for all points (along a 0.1° grid) from 7° North to 6° South (latitude) and from 96° to 129° East (longitude), covering the oil palm growing regions of Malaysia and Indonesia (i.e. Borneo, Sumatra and the Malaysian Peninsular). A digital elevation model and maps of monthly average cloudiness from 2005 to 2010 were obtained from the NASA Earth Observation website (NASA, 2012). Slope and azimuth (orientation of the field with respect to the horizon) were calculated from the digital elevation model. Growth and dry bunch yield for every month for a 30 year period for each point in the grid were calculated using PALMSIM. The planting density of 143 palms ha^{-1} was used in the simulation run following the recommended practice in the oil palm industry. Maximum simulated annual dry bunch yield were transformed into FFB yield by assuming a dry weight of 53% (Breure, 2003). These FFB yields were mapped with ArcGIS 10.1.

3. Results

3.1 Model evaluation

3.1.1 Single model run

For a better understanding of the simulation output generated by PALMSIM we present model output for Site 1 in Sabah (Malaysia). Simulated monthly PAR for that site ranged from 239 to 260 MJ m^{-2}, with an annual total of 2992 MJ m^{-2} (Table 3). Yearly gross assimilation was 130 Mg ha^{-1} 10 years after planting (Figure 2a).

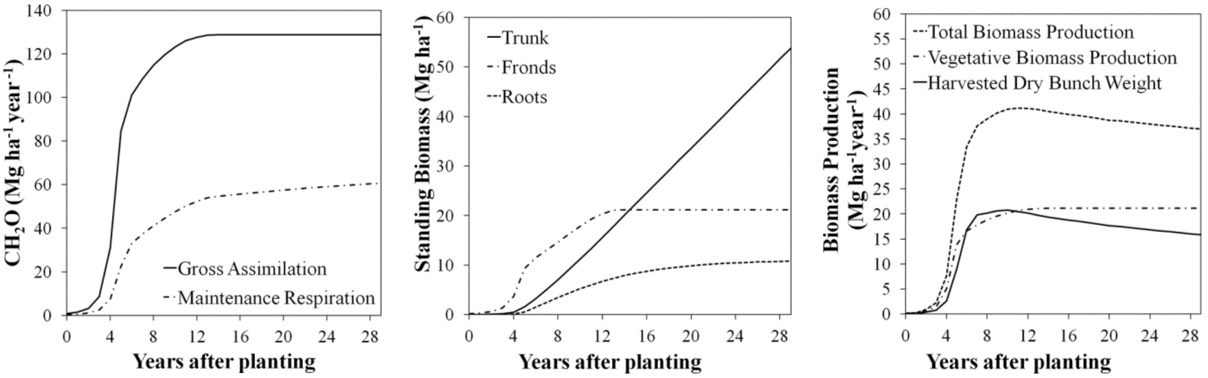

Figure 2: *Example of the main output of the PALMSIM model for Site 1 (Sabah, Malaysia); (a) Annual gross assimilation and maintenance respiration. (b) Vegetative growth. (c) Annual total, vegetative and bunch biomass production.*

Maintenance respiration accounted for a loss of up to 50 percent in the final years and for about 40 percent of the total gross assimilates over the entire lifespan of the palm (Figure 2a). While frond biomass dominated in the juvenile phase of the palm, the trunk accounted for the greatest share of the biomass in the later periods (Figure 2b). Total vegetative biomass production remained constant after year eleven with 20 Mg ha^{-1} year^{-1} for the simulated growth period, while bunch production decreased with age (Figure 2c).

3.1.2 Comparison with observed data

Simulated PAR for the ten-year average cloudiness data was highest in North Sumatra (3122 MJ m^{-2}) and least in Peninsular Malaysia (2866 MJ m^{-2}) (Table 3). Model predictions coincided with the largest observed frond production (Figure 3 and 5) and yields (Figure 4 and 6). The maximum frond weight reached in control plots was 18.1 Mg ha^{-1}, the maximum weight in the fertilizer plot 19.2 Mg ha^{-1} and largest simulated frond weight 21.1 Mg ha^{-1}. The overall gap between predicted and observed frond weight was smaller for the fertilizer plots (4.2 Mg ha^{-1}) than for the control plots (7.6 Mg ha^{-1}). Simulated frond production over time showed a similar trend as observed fronds weight for the different ages of the palm stands (Figure 5).

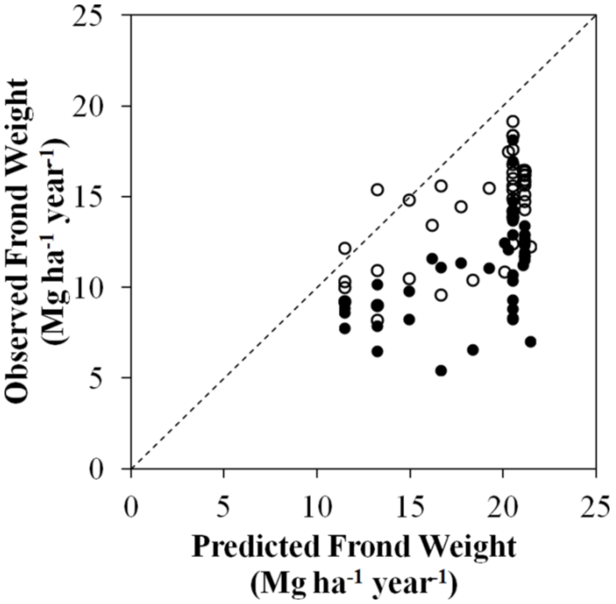

Figure 3: Observed versus predicted frond weight. Observed data from 9 trials in Indonesia and Malaysia is distinguished between optimum fertilised plots (open symbols) and control plots (closed symbols). The dotted line represents the 1:1 relationship.

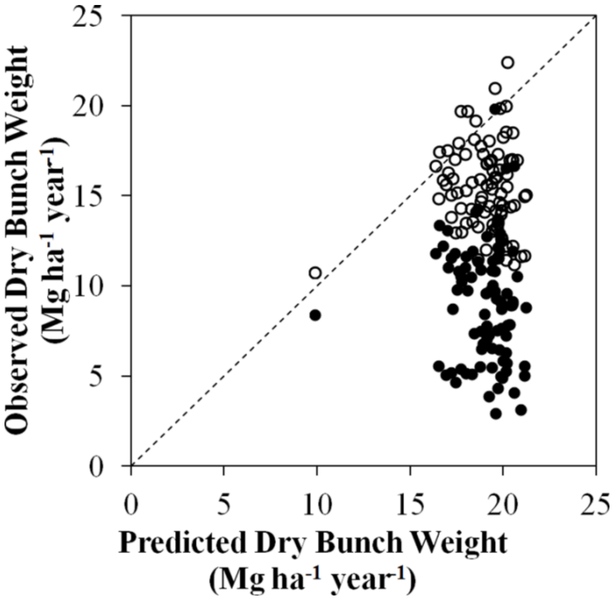

Figure 4: Observed versus predicted dry bunch yield. Observed data from 15 trials in Indonesia and Malaysia is distinguished between optimum fertilised plots (open symbols) and control plots (closed symbols). The dotted line represents the 1:1 relationship.

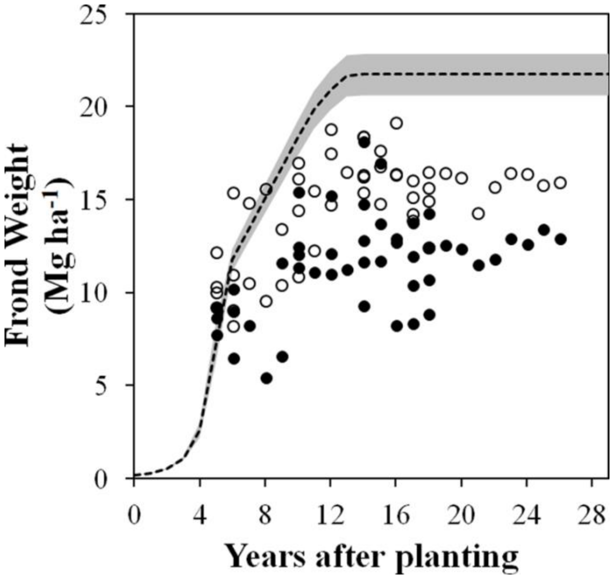

Figure 5: Simulated potential frond weight averaged across all sites (curve) with standard deviation (grey spread) and observed frond weight across sites from fertilizer plots (open symbols) and control plots (closed symbols).

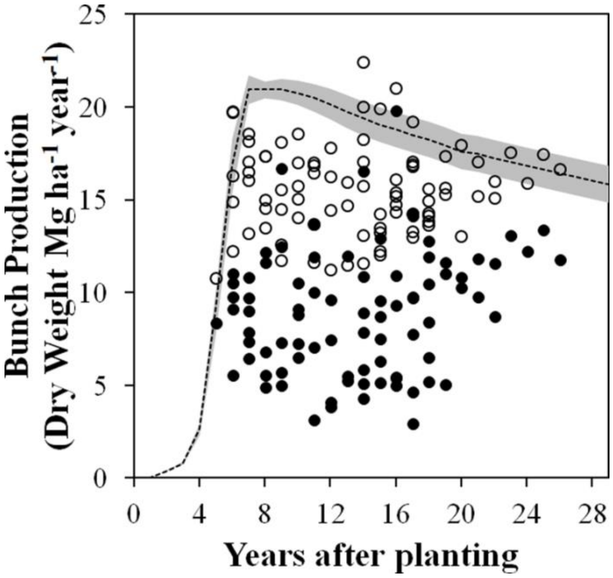

Figure 6: Simulated potential dry bunch weight averaged across all sites (curve) with standard deviation (grey spread) and observed dry bunch weight across sites from fertilizer plots (open symbols) and control plots (closed symbols).

The mean gap for dry bunch weight between fertilizer and predicted plots was 3.5 Mg ha^{-1}, and for the control plots 10.0 Mg ha^{-1} (Figure 4). The simulated mean of potential yield across all sites and ages was 19.0 Mg ha^{-1}. Overall the fertilizer plots reached 81 % of this predicted yield, and the control plots 47 %. Maximum observed yields for the sites ranged from 14.4 Mg ha^{-1} in Lampung (South Sumatra) to 22.4 Mg ha^{-1} in North Sumatra (Table 3). The mean for maximum observed yields and their corresponding predicted yields was 18.5 Mg ha^{-1}, and

19.3 Mg ha^{-1} respectively. The age of the palm stand varied from seven years after planting to 20 years. The RMSE for the maximum observed yields and their corresponding predicted values - 12 sites, excluding the site in Lampung - was 1.7 Mg ha^{-1} (8.75%). Overall, the simulations showed decreasing yields with age, which matched the maximum observed yields (Figure 6)

Table 4: Maximum observed yield for each site, years after planting of the site and the simulated dry bunch yield.

Site Nr.	Region	Years after planting	Simulated PAR (MJ m^{-2} year^{-1})	Maximum observed dry bunch weight (Mg ha^{-1} year^{-1})	Predicted bunch dry weight (Mg ha^{-1} year^{-1})
1	Sabah	18	2992	19.2	18.5
2	Malaysia Peninsular	8	2866	18.2	18.4
3	Lampung	12	3025	14.4	20.4
4	North Sumatra	11	3122	18.6	20.1
5	Sumatra Riau	20	2949	17.4	17.9
6	South Kalimantan	7	3078	19.8	20.3
7	North Sumatra	15	3110	22.4	20.2
8	North Sumatra	15	3137	17.1	20.5
9	North Sumatra	15	3080	18.3	20.0
10	North Sumatra	17	3098	21.0	20.1
11	South Eastern Sumatra	7	3048	19.7	18.1
12	South Eastern Sumatra	7	2980	16.3	17.1
13	South Eastern Sumatra	9	2917	17.4	19.7

3.1.3 Sensitivity analysis

Changes in LUE had the strongest effect on dry bunch yield (12%), followed by the cloudiness index (9%), which was included in the analysis as an external driver (Figure 7). Maintenance and growth respiration modifications lead to yield changes of slightly more than 5 percent. Parameters affecting the light interception (specific leaf area and the extinction factor) accounted both for about a 3 percent change in predicted yield. Modification of flower development only had a minor impact on predicted yield. Finally, changes of 10% in pruning and planting density, both management factors, had almost no effect on predicted yield.

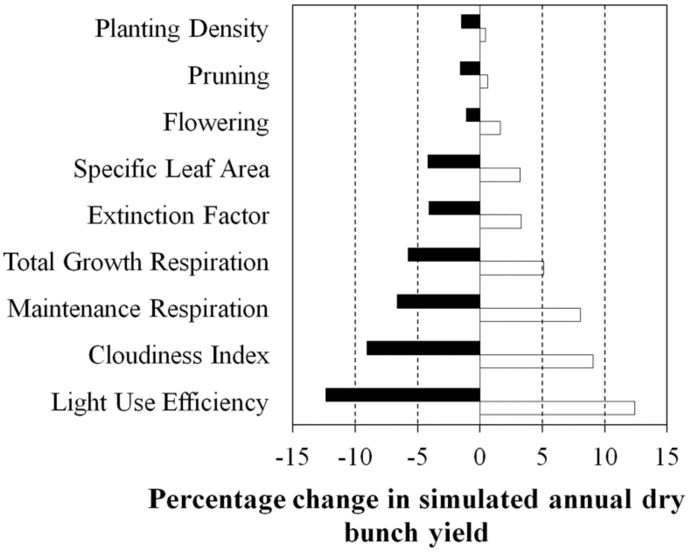

Figure 7: Results of the sensitivity analysis for simulated potential annual dry bunch yield in Sabah. The percentage change in potential yield after increasing or decreasing the value of the parameter along the y-axis with 10% is shown.

3.2 Potential yield map

The largest potential yield was simulated generally for the costal sites with FFB yields of 36 Mg ha^{-1} to an absolute maximum of 48 Mg ha^{-1} (Figure 8). Large areas of coastal plains can be found in Eastern and Southeastern Sumatra and South Kalimantan. Poor potential yields of less than 15 Mg ha^{-1}, or as little as 9 Mg ha^{-1} were predicted for the mountainous areas of Northeastern Borneo, Northern Sumatra and Central Peninsular Malaysia.

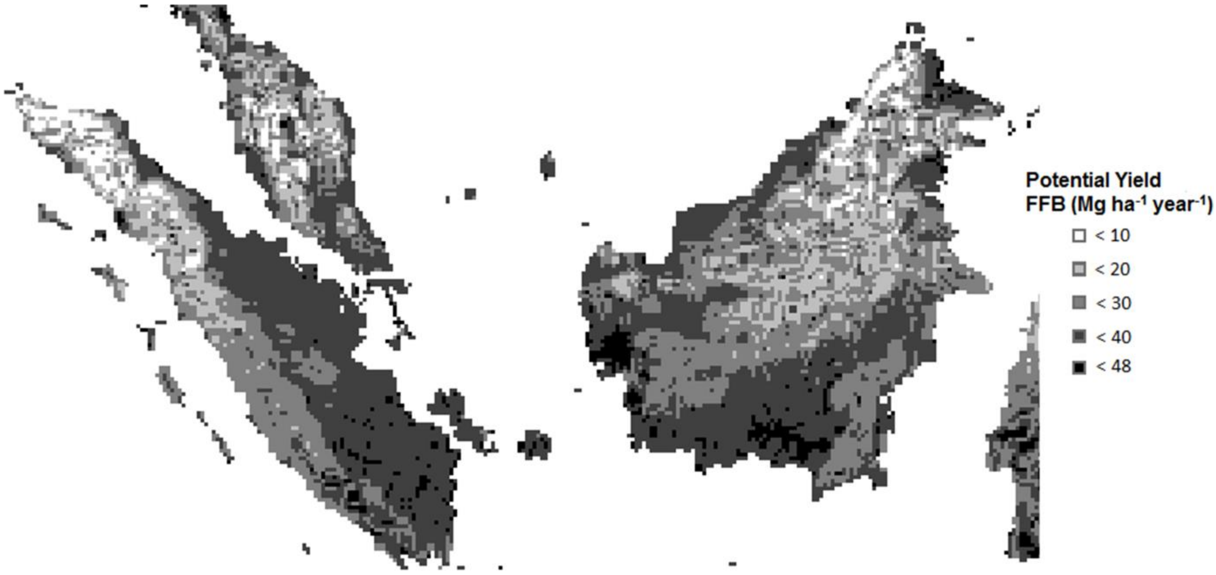

Figure 8: Potential yield (Mg FFB ha^{-1} year^{-1}) map of the main oil palm regions in Indonesia and Malaysia based on simulation runs of the PALMSIM model. Simulation runs take into account incoming solar radiation, but ignore other limitations.

4. Discussion

4.1 Model performance

Generally, the model predicted the upper ranges of the observed yield and frond production values for a range of sites (Figure 3, 4, 5 and 6; and a RMSE of 1.7 Mg ha^{-1} for the maximum observed yields, table 3). Therefore the model performed well in describing potential production in the context of tree crop modeling (Zuidema et al., 2005). Other available oil palm models need detailed daily climate information (rainfall, temperature, radiation, potential evapotranspiration) (Dufrene et al., 1990; Henson, 2009). Furthermore, existing crop data is required to run the models, such as annual vegetative dry matter production, leaf area index or standing vegetative biomass (Dufrene et al., 1990; van Kraalingen, 1985) or to parameterize the model (Combres et al., 2013). In depth comparisons between the performance of PALMSIM and other oil palm models cannot be made as statistical analyses of the models' performances are not available (Dufrene et al., 1990; Henson, 2009; van Kraalingen et al., 1989).

Detailed validation data sets, which allow the testing and parameterization of oil palm models in a comparable way to the validation of annual crops, are scarce (Kumar et al., 2008; van Oijen et al., 2010a). A review of the literature on tropical tree crop models showed that attempts at model testing differ from only sensitivity analysis to common statistical testing against field data for few sites. Generally, the accuracy of annual crop models is rarely reached, even though the tree models were often specifically parameterized for a given site (Combres et al., 2013; Kumar et al., 2008; van Oijen et al., 2010b; Zuidema et al., 2005;). Given the primary aim of developing PALMSIM as a model to determine potential yield across a wide range of sites, the minimal parameterization requirement is an important consideration. We follow approaches used in dynamic summary crop models for data scarce environments as for example presented by Chikowo et al. (2008). We show that PALMSIM can be tested with less detailed data sets and missing climate information, and that the model still reproduces the upper ranges of production.

Production in PALMSIM is driven by radiation alone, which can be calculated from existing cloudiness index data-base of the NASA, or directly provided. This makes it easy to apply, but leads consequently to the fact that the model is strongly sensitive to the radiation regime. Changes of 10% in cloudiness lead to similar changes in the bunch yield of mature oil palm stand (Figure 7). Similarly, the model is sensitive to the efficiency with which the intercepted radiation is used, as modification of LUE by 10% affects yield by 12 %.

The simulated assimilates in the demonstration run (Figure 2a) showed a similar pattern as observed in the field by Breure (1988) and Henson (2004) and in simulations by Dufrene et al. (1990) for Southeast Asia. It is known that maintenance respiration accounts for large losses of gross assimilates in oil palm (Corley and Tinker, 2003; Henson, 2004). Therefore the model is sensitive to changes of the maintenance coefficients. Sensitivity to the respiration coefficients is further enlarged if growth respiration is also taken into account. The demonstration run simulated roughly 40% losses due to maintenance respiration, within the range reported by Henson (2004) and Dufrene et al. (1990). While total maintenance respiration increases with standing biomass, it declines per unit biomass as observed by Henson (2004). Frond production is the dominant vegetative growth demand, but standing frond dry matter is restricted by pruning. Strict pruning management in the simulation runs causes the overlapping points for the predicted frond weight in Figure 3. Observed values are in general below the predicted frond weights (Figure 3 and 5), supporting the assumption that the 1:1 line indeed describes potential frond growth. Possible reasons why the frond weights from the fertilizer plots do not more closely match the predicted values might be the use of average cloudiness data and the indirect calculation of frond weight. The model simulates low frond weights around the 4th year and largest weights after the 12th year, which agrees with the observed frond data (Figure 5). However, simulated frond weight for young plantations (<4 years) are too low when compared with reported data (Henson and Dolmat, 2003). Simulated root weight is the smallest of the three vegetative simulated organs. Only limited knowledge of root growth in oil palm exists (Jourdan and Rey, 1997). The trunk has a low demand for assimilates, but it is free of growth reductions; while the total amount of frond dry matter is reduced by pruning and roots are affected by mortality. Consequently, the trunk is dominant in terms of biomass weight in mature oil palm stands (Breure, 1988). However, when compared with published data it seems that PALMSIM underestimates trunk growth. Henson (2004) reported for a sixteen-year-old plantation a trunk weight of 32.5 Mg ha^{-1}. In the simulation run it was only 23 Mg ha^{-1}, although total simulated standing biomass is very close with predicted 52 to measured 55 Mg ha^{-1}. Therefore frond weight is higher in the model results than the one reported (Henson, 2004). The ratio between total vegetative biomass and bunch production (bunch index) of roughly one to one in the model reflects the suggestion of Breure (2003). Similar relationships were reported by van Kraalingen et al. (1989) and Henson (2004).

After a plateau period starting from seven years onwards, bunch production starts to decline after the 10th year due to increasing losses of gross assimilates to respiration (Figure 2c and 6).

This pattern is well documented in oil palm and is supported by the comparison with observed yields (Figure 6; Corley and Tinker, 2003). The maximum observed yield for every site closely matches the corresponding predicted yields with a RMSE of 1.7 Mg ha^{-1} year^{-1} against an observed yield of 18.8 Mg ha^{-1}, with the exception of the trial in Lampung in southern Sumatra (Table 3). The larger yield gap in Lampung in comparison with the other sites suggests that factors other than radiation limit yield in this trial. Oil palm production in Lampung seems to be strongly limited in several years by a lack of sufficient water. Generally, the direct impacts of water shortages on yield in oil palm are not easy to define due to the long time-lag between initiation of the flowers and fruit bunch production (Carr, 2011).

Observed yields from the optimum fertilizer plots across all sites reach 81.4% of the average simulated potential yield; the unfertilized control plots only 47.5%. Possible explanations of why some of the observed yields of the fertilized plots are not closer to the potential yields could be that the growth and yield of the palm stand, even in these favourable production regions, is affected in some years and sites by water shortage (a limiting factor) and heat stress (a defining factor), which are both not taken into account by the model. Carry over effects of production stress in previous years could be present in the observed yields, but no information was available to study this. Given these shortcomings, the current version of the PALMSIM model cannot be used as a site-specific decision making support tool to address questions, such as when the harvest peak for the bunches in a specific year can be expected. However, given that radiation is the major yield determining factor on a regional scale across Borneo, Sumatra and the coastal areas of the Malaysian Peninsular, PALMSIM can be a valuable tool to explore potential yield on a wider scale (Corley and Tinker, 2003).

The evaluation against field data shows that the model predicts reasonable potential yields. The sensitivity analysis demonstrates that PALMSIM is robust, although specific attention has to be paid to the LUE, which needs careful parameterization. Changes in terms of yield by modifying the parameters by 10% are comparable to other tree crop model evaluations (Dufrene et al., 1990; Zuidema et al., 2005).

4.2 Mapping potential yield of oil palm for Indonesia and Malaysia

The capability of PALMSIM to estimate potential yield for large areas is shown in Figure 8. Sites situated in mountainous areas receive on average less PAR due to increased cloud cover in the mountains in comparison with the lowland. This difference is particularly pronounced during the dry months. This is important for the mountainous areas of Borneo in the northeast, the highlands in the center of the Malaysian Peninsular and the hilly sites of north-western

Sumatra. Western Sumatra is dominated by a chain of mountains, which results in a relatively small potential yield. The favourable sites in terms of radiation are mainly coastal areas. The simulation results reproduce the known trend that actual yields are larger in coastal plains, where FFB yields above 40 Mg ha^{-1} have been reached (Corley and Tinker, 2003; Donough et al., 2009).

However, the map suggests that there are large areas in Southeast Asia with potential yields above 30 Mg FFB ha^{-1} year^{-1}. The gap between potential yields and average reported yields from the plantations directly leads to the question of the most important growth limiting and reducing factors. In regions with high rainfall (more than 2500 mm) and good soils, yields of more than 30 Mg ha^{-1} are possible as discussed by Corley and Tinker (2003). The fertilizer trial results show that it is possible to reach simulated potential yields, at least at plot level. Exploring the gaps caused by nutrient limitations and biotic stresses could improve yields significantly as shown by Donough et al. (2009). Overall, our results suggest a need to investigate this gap further and to identify attainable yield levels.

The presented regional map based on PALMSIM simulations (Figure 8) can contribute to the second proposed strategy for sustainable oil palm production; the cultivation of marginal sites in Indonesia and Malaysia. Identifying appropriate degraded sites with high potential yields is a challenge (Corley and Tinker, 2003). The map can be used to select preferable regions for surveys and land use planning for oil palm. However, the simulated potential yields assume optimum conditions, which are rarely achievable. Oil palm production is affected in certain years by water shortages even in Indonesia and Malaysia (Carr, 2011). Water availability from year to year and soil constraints affecting water storage and supply in relation to the impacts of water stress on growth and production of oil palm would have to be included to simulate water-limited yields. Despite these considerations the yield gap between potential yield and water-limited yield in Indonesia and Malaysia is likely to be small in comparison to other regions such as West Africa or Thailand, where oil palm expansion currently takes place (Carr, 2011; Corley and Tinker, 2003).

To identify suitable sites for the expansion of oil palm production it is necessary to combine this potential yield map with existing maps within the marginal areas for factors such as soil type, rainfall, infrastructure and land rights as recently published by the World Resource Institute for Kalimantan (Gingold et al., 2012).

4.3 Limits and future necessary improvements of PALMSIM

Models can play an important role in identifying the growth limiting and reducing factors and quantifying their effects across large regions. Such a yield gap analysis could contribute to the identification of appropriate intensification strategies for existing plantations. Available oil palm production models are not yet capable of such a wide range analysis. Despite their potential usefulness in decision support and yield gap assessments, as discussed above, the development of physiological growth models for tree crops is still in its infancy, not only in terms of validation but also in the description and parameterization of the physiological processes (van Oijen et al., 2010a; 2010b). The lack of detailed data sets is a major constraint in this context. Therefore, the challenge is to develop PALMSIM further by taking water, nutrient and other limitations into account and keeping the data input low so that it can be tested with available data sets and applied across a wide range of scales. Improvements in monitoring daily weather at oil palm plantation sites would be of great benefit to provide the high quality climate data needed by the model and could replace the current approach in PALMSIM that calculates radiation data indirectly using satellite derived cloudiness images.

5. Conclusion

We present a relatively simple model, PALMSIM, to simulate the potential growth and yield of oil palm. The model performed well against field data from several sites across Malaysia and Indonesia and a sensitivity analysis showed that the model is robust. PALMSIM can simulate potential yield of oil palm for a wide range of sites. When combined with information on soil and other maps of marginal sites, such simulation results may be used to support the selection of potential new sites for oil palm plantations. A priority for future work with the PALMSIM model should be the incorporation of the effects of water stress on biomass production and yield.

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Appendix: Detailed model description

1. Radiation

The radiation reaching the earth's surface differs from the terrestrial radiation due to the effect of the atmosphere. The final total radiation received (H_T) is composed by the beam radiation (H_B) and diffuse radiation (H_R).

$H_T = H_B + H_R$ (eqn 1)

where

$H_B = (H - H_d)\ R_b$ (eqn 1.1)

$H_R = H_D\ (\ H - H_d / P_{AR}\ x\ R_b + (1 + \cos\beta / 2)\ (1 - H - P_{AR} / P_{AR})\ )$ (eqn 1.2)

Where H is the radiation received in the horizontal surface, H_d is the diffuse radiation received in the horizontal surface, Rb is the ratio of the radiation received on a tilted surface to that of a horizontal surface, β is the slope of the field and P_{AR} is the photoactive radiation. The diffuse solar radiation is the fraction of solar radiation scattered downwards by the molecules in the atmosphere, mainly related to cloudiness. This can be measured based on the clearness index that is based on monthly cloudiness.

2. Light interception and gross assimilation

Gross Assimilation (G_{Assim}) depends on the ability of the crop to intercept light and on the efficiency with which the intercepted light is used (L_{UE}).

$G_{Assim} = P_{AR}\ x\ (1 - e^{-k\ x\ LAI})\ x\ L_{UE}$ (eqn 2)

Leaf area index (LAI) is calculated based on the specific leaf area (SLA) and the fronds standing biomass per hectare ($Fronds_{SB}$).

$LAI = SLA * Fronds_{SB}$ (eqn 3)

The extinction coefficient (k) is determined by following relationship:

$k = k_1 + k_2\ x\ LAI / (k_3 + LAI)$

where k_1, k_2 and k_3 are parameters. (eqn 4)

3. Maintenance respiration and vegetative biomass production

Respiration is subdivided into maintenance and growth respiration. The maintenance respiration is calculated for the different plant parts (roots, trunk, fronds, and generative part) based on their dry weight, protein and mineral content of the tissue (a_{Organ}). The total maintenance respiration (M_{aint}) is the sum of the individual rates.

$M_{aint} = MR_{Trunk} + MR_{Fronds} + MR_{Generative}$ (eqn 5)

$MR_{Organ} = a_{Organ}\ x\ DryWeight_{Organ}$ (eqn 5.1)

The assimilates that are available for vegetative biomass production ($V_{egAssim}$) are calculated as a proportion of the total available assimilates after accounting for maintenance losses and limited by a maximum that is a function of the total biomass of fronds in the stand ($Fronds_{SB}$), where b_1, b_2 and b_3 are parameters.

$V_{egAssim} = b_1\ x\ (G_{Assim}-M_{aint})$ (eqn 6)

$MaxV_{egAssim} = (Fronds_{SB} / b_2 + Fronds_{SB})\ x\ G_{Assim}\ x\ b_3$ (eqn 7)

These assimilates are then distributed for the growth of the different organs - fronds, trunk and roots - according to a partitioning factor (c_{Organ}). Growth respiration is included as an efficiency coefficient (d_{Organ}) for the available assimilates of different organs.

$Growth_{Organ} = c_{Organ}\ x\ d_{Organ}\ x\ V_{egAssim}$ (eqn 8)

Vegetative biomass is reduced by root mortality and pruning. Trunk mortality is assumed to be zero. Root mortality ($DRoots$) is a function of the total root biomass ($Roots_{SB}$).

$DRoots = e_1\ x\ Roots_{SB} + e_2$ (eqn 9)

Pruning management maintains fronds standing biomass below a certain value ($Fronds_{Goal}$).

$Fronds_{Goal} = min\ (f_1\ x\ t + f_2, f_3\ x\ t + f_4, f_5\ x\ P_{Density})$ (eqn 10)

$DFronds = Fronds_{SB} - Fronds_{Goal}$ (eqn 11)

Where f_1, f_2, f_3, f_4 and f_5 are parameters and $P_{Density}$ is the planting density of the plantation.

4. New fronds and flowering

The number of fronds is kept track of to control flowering, as a new flower is initialized with the growth of each new frond. Taking into account the number of fronds opened per time step, together with the number of fronds expected at different plantation ages, the following piecewise function defines the pattern of frond opening depending on the time after planting:

$Fronds_{Op} = max\ (g_1\ x\ t + g_2, g_3\ x\ t + g_4, g_5)$ (eqn 12)

where g_1, g_2, g_3, g_4 and g_5 are parameters.

The fraction of flowers that become females (F_{racFem}) is related to the total standing biomass per palm, where h_1 and h_2 are parameters.

$F_{racFem} = h_1\ x\ Veg_{SB} / P_{Density} + h_2$ (eqn 13)

Abortion rates are applied to the undifferentiated flowers, to the sex differentiated flowers before pollination and to developing bunches. In terms of biomass production, no increase in weight was considered during the first period of undifferentiated flowers, but only from the time flowers are defined as male or females.

In the case of male inflorescences, the calculation of available assimilates ($M_{aleAssim}$) is as follows, where i_1 and i_2 are parameters.

$$M_{aleAssim} = min\ (G_{Assim} - Maint,\ i_1\ x\ Veg_{SB}^2 + i_2\ x\ Veg_{SB}) \qquad \text{(eqn 14)}$$

A growth respiration factor (d_{Male}) is applied to available assimilates for the male flower dry weight growth. In PALMSIM, assimilates that remain for female biomass production are calculated as the available gross assimilates after extracting those used for maintenance respiration, vegetative biomass production, male biomass production and taking a growth respiration factor into account (d_{female}).

III. Benchmarking yield for sustainable intensification of oil palm production in Indonesia using PALMSIM[2]

1. Introduction

Driven by high productivity of up to 6 tons oil ha-1, oil palm production expanded rapidly in Indonesia, in particular in Sumatra and Kalimantan, over the last two decades. Land dedicated to oil palm doubled in the last ten years. Accordingly, Indonesia became the largest global producer of palm oil, reaching 31 million tons in 2013 (FAOSTAT, 2013).

Environmental concerns are mainly related to drainage of peatlands for conversion to plantations as a source of greenhouse gas emissions and clearance of biodiversity-rich forests for establishment of oil palm estates (Koh et. al., 2011). Non-governmental organizations accuse oil palm producers of land right crimes in relation to indigenous groups (Sayer et. al., 2012). However, studies also show that oil palm can be a driver of rural development (Feintrenie et. al., 2010; Rist et. al., 2010). Furthermore, global population growth will make a further increase in demand highly likely (Corley, 2009).

To minimize further rainforests conversion, the keys for future oil palm production are therefore to focus expansion to degraded sites and to close the yield gap between current and attainable yield by simultaneously increasing the resource use efficiency (Sayer et. al., 2012). Current oil palm statistics in Indonesia show scope for such sustainable intensification: Indonesian average national yield of 17 tons ha-1 fresh fruit bunches (FFB) is below the Malaysian average of 21 tons ha-1. Field trial results for several sites in Sumatra and Kalimantan have shown that yields of over 30 tons FFB ha-1 can be reached when optimally managed (Hoffmann et. al., 2014). Climatic conditions of these islands are classified mostly as favourable for oil palm with an average annual rainfall of 2,000 mm and solar radiation of 6,000-6,300 MJ m-2.

In a recent report, Gingold et. al. (2012) aimed to identify degraded sites in Kalimantan. They used information on soil type, rainfall, nature parks, infrastructure and possible land rights to estimate the size of degraded sites. Although they had to admit that there is still some discussion over the definition of degraded land, they concluded that there is, even when very vaguely defined, a reasonable scope for oil palm expansion into degraded sites. However, no

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[2] This capter has been accepted as Hoffmann, M.P, Donough, C., Oberthür, T., Castaneda Vera, A., van Wijk, M.T., Lim, C.H., Asmono, D., Samosir, Y., Lubis, A.P., Moses, D.S., Whitbread, A.M. (2014) "Benchmarking yield for sustainable intensification of oil palm production in Indonesia using PALMSIM" (accepted by The Planter; 01.04.2015)

assessment of potential productivity of these sites was possible, which would further help to reduce the time spent to identify suitable land for oil palm.

Assessing the water-limited yield of a specific site would support both identifying degraded sites with potential high productivity and intensification measures in existing plantations. Field trials and highest yield records from plantations are valuable sources of data to set such yield targets. However, field trials are financially demanding, in time and labour, and are restricted to existing plantation sites. Furthermore, both highest yield records as well as field trial results are difficult to extrapolate to other sites and years, due to variations in weather conditions during the observed period or the management practices employed. Therefore, mechanistic crop growth modeling has become a standard method in annual crops to set yield targets and explore yield gaps (van Ittersum et. al., 2013).

For perennial crops, especially tropical plantation crops, the development of such process-based models is still in its infancy. This might be due to lack of information to parameterize (physiological data) and run (mainly climate and soil data) such data-demanding models (van Oijen et. al., 2010; Huth et. al., 2014). Furthermore, the complex development of perennials (for example, fruit development in oil palm needs four years) makes this challenging to describe in a model.

However, the growing interest in oil palm has led to the release of a few oil palm models. A very detailed model in terms of flowering, ECOPALM, was developed by Combres et. al. (2013). A production model was implemented in APSIM (Huth et. al., 2104). A slightly older model is OPRODSIM by Henson (2009). All these models need very detailed information in terms of weather, and partly soil and crop physiology to be applicable.

Another model recently developed by Hoffmann et. al. (2014) called PALMSIM was built with the objective to make it simple enough to be applicable at a range of sites, but still capturing the main process determining yield. PALMSIM simulates the potential growth of an oil palm stand on a monthly step based on incoming solar radiation for the period of 30 years. Frond and yield data from field trials from a range of sites in Malaysia and Indonesia were successfully used to evaluate the model. Since then, a simple widely used water balance for oil palm has been added to the model to provide an assessment of water-limited yield taking solar radiation, rainfall, days of rain per month and an estimation of plant available water holding capacity into account. An application of the improved PALMSIM model can be found in Rhebergen et. al. (2014).

Against this background, the aims of this study are to assess yield benchmarks for (i) the potentially degraded sites in Kalimantan, identified by Gingold et. al. (2012) and (ii) for six oil palm plantations in Sumatra and Kalimantan where best management practices (BMP) for yield intensification were implemented (Donough et. al., 2009). Thereby, the scope for sustainable intensification at regional and at plantation level is explored in a quantitative manner – a novel approach to oil palm production.

2. Material and methods

2.1 PALMSIM

The simulation model PALMSIM consists of a plant growth module, which simulates the potential growth and yield of an individual oil palm stand on a per hectare basis, and a radiation module. Potential production is defined by radiation under otherwise optimal environmentally determined growing conditions, no growth limitation in terms of water or nutrient availability, and no incidence of pests or diseases (van Ittersum et. al., 2013). The model also assumes uniform planting material and recommended canopy management in terms of pruning. Planting density is set to 143 palms ha-1, which falls within the range (138 or 148 palms ha-1) most commonly used in the oil palm industry (Corley and Tinker, 2003). However, planting density and also the pruning regime can be altered in the model. The growth and the radiation modules are linked through a manager module, which serves as the user interface. The oil palm growth module can also be used as a standalone tool for applications to individual sites when measured or estimated radiation values are available.

PALMSIM was successfully tested against a range of optimal field trial results across Malaysia and Indonesia in terms of frond and bunch production. For a detailed description and an evaluation including sensitivity and plausibility assessment of the model we refer to Hoffmann et. al. (2014).

The effect of limiting water availability is now included in PALMSIM for this study. Due to the extended period of time bunches take to become mature, water deficits are thought to have an economical effect not only in the short but also in the medium and long term. PALMSIM uses a widely applied and simple method developed by CIRAD (Surre, 1968), in which a water balance is calculated for each month (Figure 1).

In the water balance, evapotranspiration is assumed as 150 mm when less than 10 days of rain per month and 120mm otherwise. Soil water not used to fulfill evapotranspiration demand per month is stored until the upper limit of the available soil water capacity for the next month. Water supply above that upper limit leads to losses from the system representing drainage and runoff. Yield i.e. assimilates available for flowers and bunches is reduced by a factor (0.0288) derived from oil palm irrigation trials when evapotranspiration demand is not fulfilled (Carr, 2011).

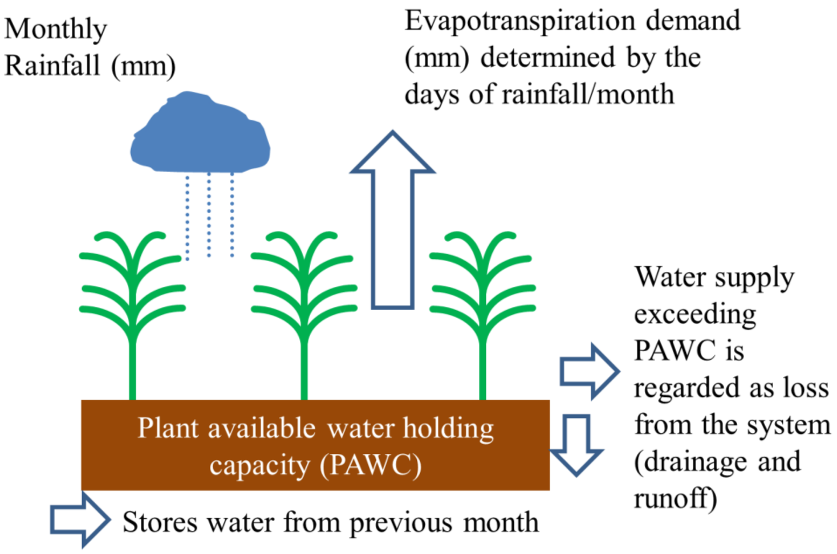

Figure 1: Illustration of the water balance implemented in the PALMSIM model.

2.2 Assessment of suitable degraded sites in Kalimantan for oil palm production

Gingold et. al. (2012) did a desktop study to assess the scope of the degraded sites suitable for oil palm production in Kalimantan. Currently, Kalimantan is of major interest for oil palm production. It is regarded as a region of major oil palm expansion with high deforestation rates (Carlson et. al., 2012). Land was classified by Gingold et. al. (2012) – based on available information on land cover, peatland, conservation areas with buffer zones, erosion risk, groundwater recharge potential, water resource buffers, topography, rainfall, soil properties (depth, type, drainage, acidity, color), size and accessibility of the land, and finally land owner rights – into three categories: high potential, potential and not suitable for oil palm cultivation.

In a second step, a field survey was done to control again size and accessibility of the land, and to investigate land classification and concessions. In the final stage, the data from field survey and desktop study were combined to create a map indicating suitable areas for oil palm cultivation. Land not suitable for oil palm production was defined as: peatlands, conservation areas, forests and settlement areas. Potential land suitable for oil palm production was defined as land which is currently used for mining, farming or timber production. High potential land was characterized by open land dominated by shrubs/bush and savannah. For detailed descriptions of the assessment we refer to Gingold et. al. (2012). The created maps are freely available from the web platform: http://www.wri.org/publication/how-identify-degraded-land-sustainable-palm-oil-indonesia.

PALMSIM was set up for Kalimantan on a 0.1° grid. Monthly cloudiness data to calculate solar radiation was available from NASA (http://earthobservatory.nasa.gov/). Average monthly rainfall data was used from the WORLDCLIM database (Figure 2). Soil type and plant available soil water capacity was extracted from the ISRIC-WISE soil database (Batjes, 2009) (Table 1 and Figure 3). Suitable areas for oil palm from the Gingold et. al. (2012) assessment were then related to the simulated yield of that region.

Table 1: Found soil types in Kalimantan according to the FAO soil map and their associated plant available water holding capacity used in this study.

Soil Type	**Plant available water holding capacity**
Acrisol	150 mm
Arenosols	100 mm
Ferralsols	50 mm
Fluvisols	150 mm
Gleysols	150 mm
Histosols	150 mm
Nitisol	150 mm
Luvisol	150 mm
Lixisols	20 mm
Podzols	100 mm

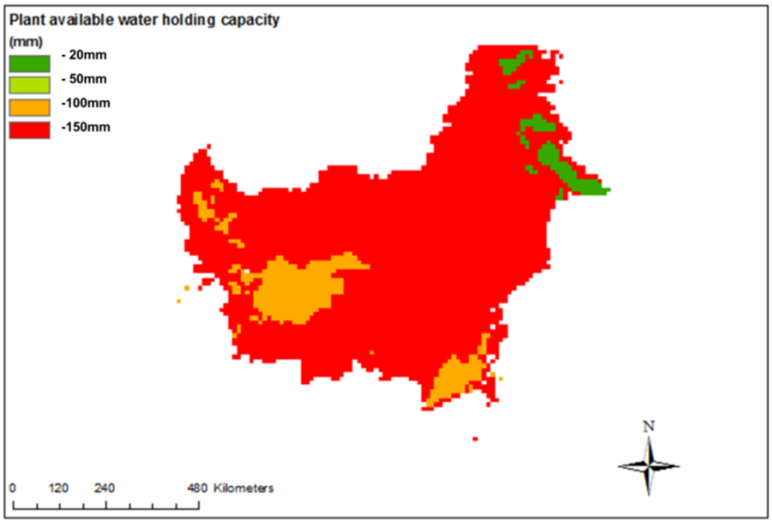

Figure 2: Plant available water holding capacity on a 0.1° grid for Kalimantan used for the study. Data were derived from soil type (FAO soil map).

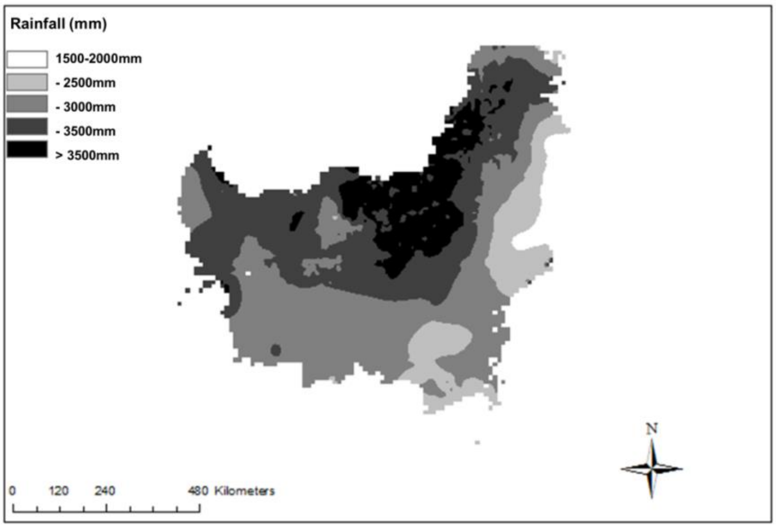

Figure 3: Average annual rainfall (mm) for Kalimantan. Data were derived from WorldClim.

2.3 Implementation of best management practices in Indonesia

From mid-2006 to mid-2011, the Southeast Asia Program (SEAP) of the International Plant Nutrition Institute (IPNI) implemented best management practices (BMP) at six oil palm plantation sites in Sumatra and Kalimantan with the aim of improving productivity and preserving soil quality (Table 2) (Donough et. al., 2010, 2011). The BMP implemented were classified into three functional categories viz. crop recovery, canopy management and nutrient management, details of which are given in Table 3 (Donough et. al., 2010).

In the experimental design, a parallel set of comparable blocks representative of a plantation are selected. Within the higher yielding block, standard commercial practices are maintained (REF blocks), while a set of BMP are identified and introduced in the lower yielding block of each pair for comparison (Table 3). For both fields, an inventory of limiting factors is prepared, but corrective action is only taken for the BMP block.

Table 2: Sites selected for the implementation of BMP by the International Plant Nutrition Institute (IPNI) Southeast Asia Program (SEAP) (after Donough et. al., 2010).

Site	**Location**	**Palm age range**	**Previous Yield level[3]**
1	North Sumatra	5-12 years	26-29 Mg/ha
2	North Sumatra	8-13 years	24-25 Mg/ha
3	South Sumatra	15-18 years	16-24 Mg/ha
4	West Kalimantan	8-9 years	16-17 Mg/ha
5	Central Kalimantan	8-9 years	12-13 Mg/ha
6	East Kalimantan	3-12 years	23-26 Mg/ha

Table 3: Characterisation of Best Management Practices (BMP) in oil palm developed by the International Plant Nutrition Institute (IPNI) (after Donough et al., 2010).

Crop recovery	**Canopy management**	**Nutrient management**
Harvest interval of 7 days	Maintenance of sufficient fronds to support high palm productivity	Spreading pruned fronds widely in inter-row area and between palms within rows
Minimum ripeness standard = 1 loose fruit before harvest	Removing abnormal, unproductive palms	Eradication of perennial woody weeds
Same day transport of harvested crop to palm oil mill	In-filling unplanted areas	Mulching with empty fruit bunches
Harvest audits to monitor completeness of crop recovery and quality (i.e. ripeness) of harvested crop	Selective thinning in dense areas	Management of applied fertilizer
Good in-field accessibility		Monitoring of plant nutrient status and growth
Clean weeded circles	Monitoring and management of pests and disease	
Palm platforms constructed and maintained whenever needed		
Minimum under-pruning in tall palms to ensure crop visibility		

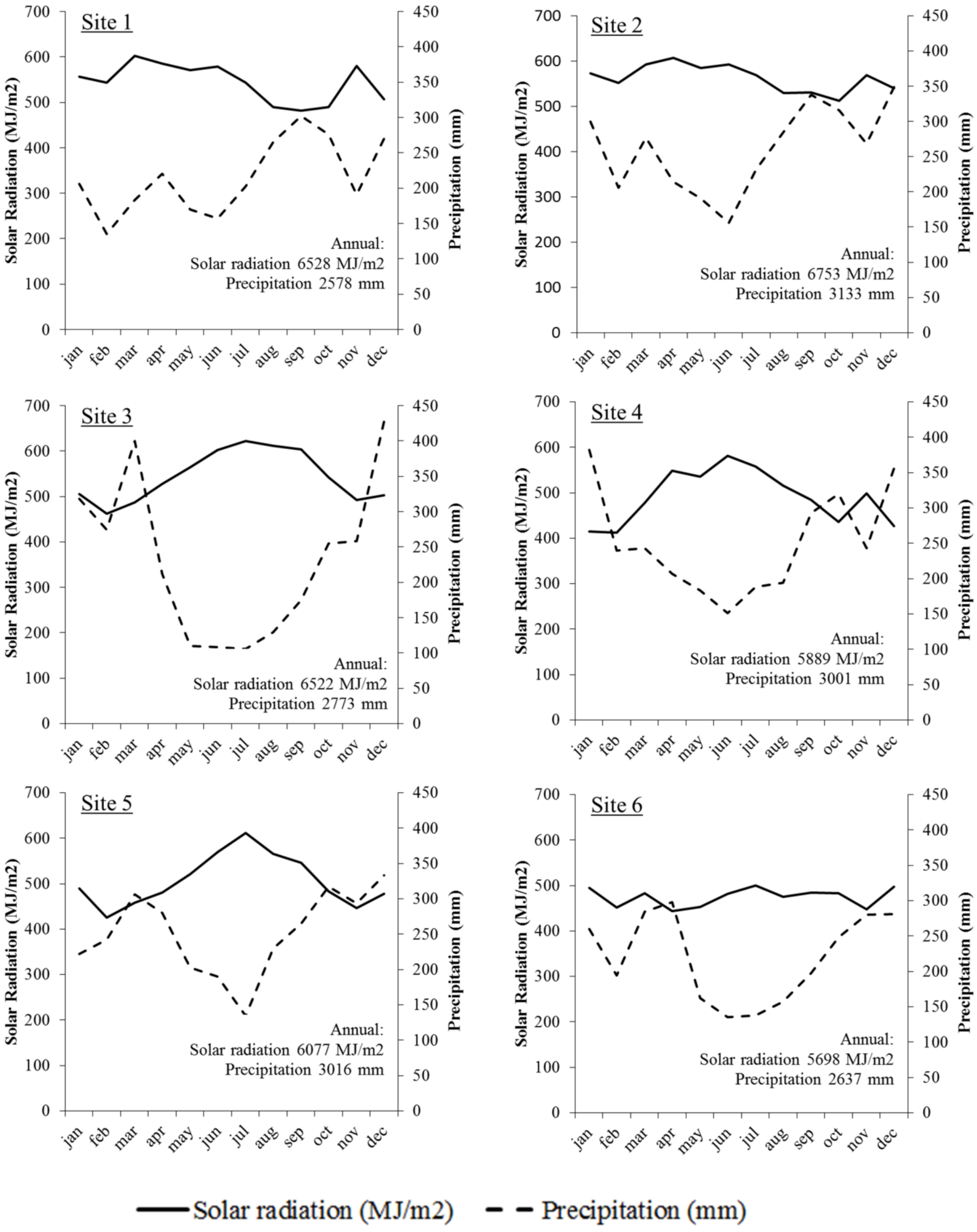

*Figure **4**: Average monthly solar radiation and rainfall for the six sites used in the study: site one (North Sumatra), site two (North Sumatra), site three (South Sumatra), site four (West Kalimantan), site five (Central Kalimantan), and site six (East Kalimantan) based on WorldClim data set and its use in the stochastic weather generator MarkSim.*

Since July 2006, 60 paired blocks (total area 2,184 ha) have been selected, with BMP applied on 30 blocks (total area 1,080 ha). Five plantation groups collaborated on the BMP project at six different locations throughout Indonesia, covering a wide range of environments in which oil palm is grown in North and South Sumatra, and West, Central and East Kalimantan (Table 2). More information about the field trial design may be found in Donough *et. al*. (2009, 2010) and Rhebergen (2012).

PALMSIM was setup for every plantation site as follows: Monthly solar radiation, rainfall and days of rain were created using the MARKSIM weather generator.

MARKSIM uses observed data from the WORLDCLIM data base and stochastically generates a range of possible annual weather scenarios (Jones and Thornton, 2013). As no long-term weather record was available for these sites, we used 99 years of generated possible weather conditions and run PALMSIM with each one.

Average weather data for each site is presented in Figure 4: Radiation is highest in northern Sumatra (sites one and two) and lowest in East Kalimantan (site six). Lowest average rainfall per year is suggested for site one in North Sumatra with 2,578mm followed by site six in East Kalimantan (2,637mm) and site three in South Sumatra (2,773mm). The highest mean annual rainfall is generated for site two with 3,133mm. PAWC was derived from the major soil texture class at the plantation site (Table 4).

Table 4: Characterization of the plantations for PALMSIM simulations.

Location	**Main soil texture**	**PAWC**
Site 1	sandy clay loam/sandy loam	157
Site 2	sandy clay loam/sandy clay	142
Site 3	sandy clay loam/sandy clay	140
Site 4	loamy sand/loamy sand	107
Site 5	loamy sand	40
Site 6	clay loam	157

3. Results

3.1 A potential oil palm yield map of degraded sites in Kalimantan

PALMSIM simulated yields (limited by radiation and water only) for Kalimantan show a wide range from below 10 tons ha^{-1} in the center and the Northeast to very high levels of above 40 tons ha-1 at the coastal sites (Figure 5). The low simulated yields for the center and the Northeast present areas with higher altitude and intact rain forest - these are therefore not suitable. The very high simulated yields of above 40 tons ha^{-1} for the south are for regions with peatlands, which are not regarded as suitable for oil palm cultivation due to their environmental importance (Figure 5).

Overlaying the suitable regions identified by Gingold et. al. (2012) with the PALMSIM simulated potential yields (Figure 6) showed that 8.1% of the suitable land has a potential productivity of more than 40 tons ha^{-1} of FFB. The largest proportion (35.6% of the suitable land or 115,300 km^{2}) falls into the category between 35 and 40 tons FFB ha-1. Similar proportion of around 20% (or 63,000 km2) are simulated for the categories 25-30 and 30-35 tons FFB ha^{-1}. Of minor importance is the category of 15-25 tons FFB ha^{-1}, which covers an area of 56,500 km^{2} (17.4%). Only 1,300 km^{2} have very low yields below 15 tons FFB ha^{-1}.

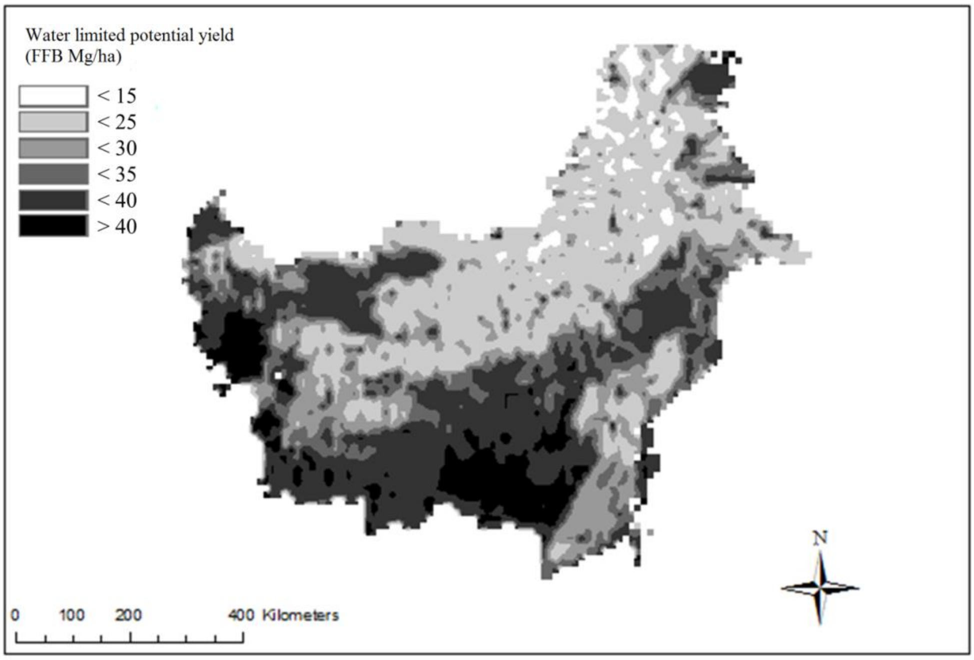

Figure 5: Simulated water-limited potential yield for Kalimantan on a 0.1° grid based on PALMSIM runs.

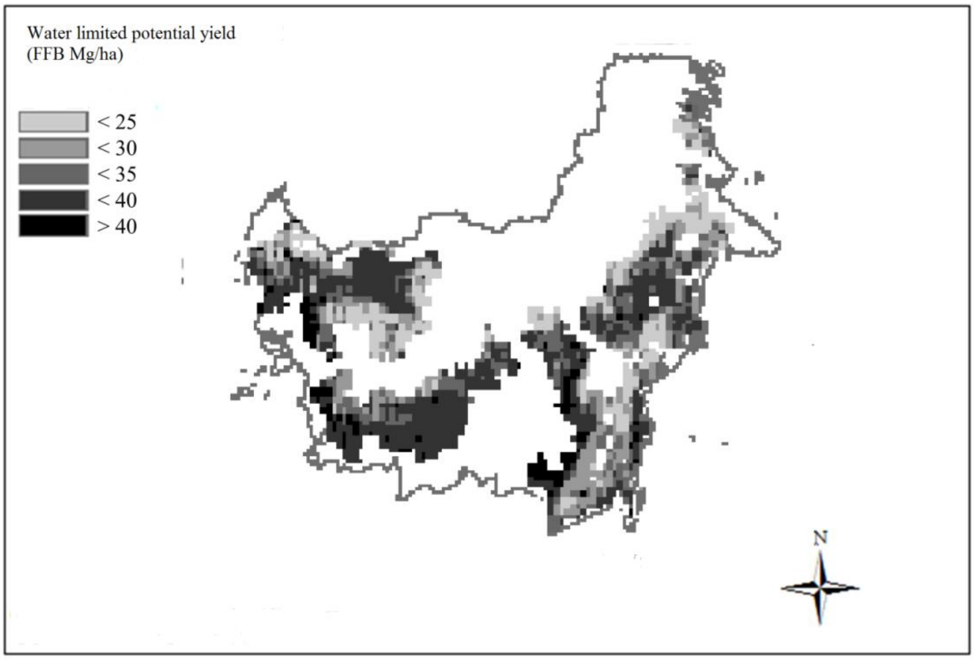

Figure 6: Simulated water limited potential yield for Kalimantan on a 0.1° grid based on PALMSIM runs. Sites, which are not suitable for oil palm according to Ginghold et al. (2012), are excluded.

3.2 Assessed yield gaps for the BMP project

Observed FFB yields from the BMP blocks are generally higher than the yields from REF blocks at sites two, three, four and five (Figure 7). At sites one and six, the BMP-REF yield gap is less pronounced. BMP FFB yield ranges from 25 to 38 tons ha^{-1} at site one, from 21 to 33 tons ha^{-1} at site two, 18 to 28 tons ha-1 at site three, from 16 to 27 tons ha^{-1} at site four, from 13 to 29 tons ha-1 at site five and from 27 to 32 tons ha^{-1} at site six.

PALMSIM simulated potential FFB yields differ from site to site (Figure 7): Potential yields at plateau phase are highest at sites one and two, reaching 45 tons ha^{-1}, and lowest at site six with 35 tons ha^{-1}. At sites one, two, four and six, there is only a very weak simulated gap between potential yield (limited by solar radiation only) and water-limited yield. For sites three and five, there is a gap of 5 tons ha^{-1}. In addition, the variability in possible yields indicated by the amplitude of the potential production zones (grey zone in Figure 7) is strongest in comparison with other sites.

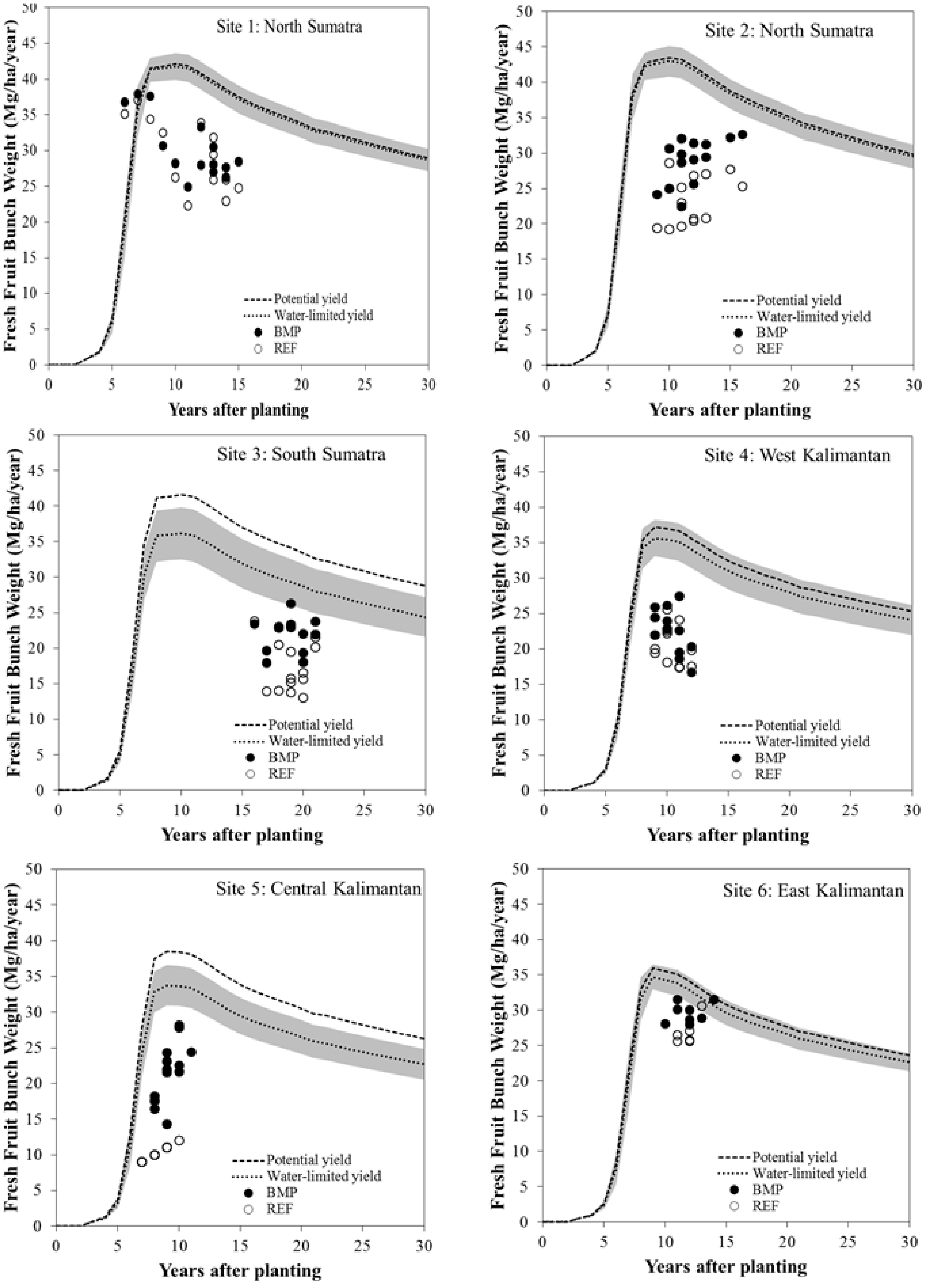

Figure 7: Simulated mean potential and water-limited yield for six plantation sites in Indonia based on 99 year runs with PALMSIM (data derived from MarkSim). The grey zone presents the standart deviation of the mean yield. Observed yields from blocks under best management practice and under reference practices are presented as points.

4. Discussion

4.1 Assessing potential productivity of degraded sites in Kalimantan for oil palm

The simulated water-limited yield map presents zones of high potential productivity (Figure 5). They are located in coastal and flat areas with higher solar radiation and less rainfall. With increasing altitude, higher cloud cover can be found (Corley and Tinker, 2003), which leads to low potential productivity. Lower temperatures (<20°C) associated with higher altitudes limit growth and bunch development (Corley and Tinker, 2003); areas with mean annual temperature less than 16oC are considered unsuitable for oil palm.

The high simulated potential yields (>40 tons ha^{-1}) for South Kalimantan have to be interpreted carefully as constraints of the dominant peatlands in that region are not captured by the model (cost of drainage, low nutrient status of the soil). Generally, these peatlands are of major environmental importance (sink of CO2), and were consequently classified as unsuitable for oil palm production.

However in West Kalimantan, high solar radiation and sufficient rainfall lead, according to the model, to high water-limited yields, and according to Gingold et. al. (2012) this region contains suitable land for oil palm. Surveys for oil palm land-use planning should take place in this region and in certain parts of East Kalimantan, where land classified as suitable matches high simulated yields. However, 43.7% of the land classified as suitable and very suitable by Gingold et al. (2012) has simulated water-limited yields above 35 tons ha^{-1} of FFB. This is mostly due to the high annual average rainfall of areas above 2,500 mm (Figure 2). Water deficiency will usually occur in dryer than average years or when soil conditions have a very low PAWC. Consequently, the solar radiation is often the limiting factor for growth in the simulation analysis.

In the literature, there is limited discussion about climate-related yield differences within Kalimantan. Usually, the climate of Kalimantan and Sumatra is seen as favourable for oil palm cultivation in comparison with other regions. However, more site-specific assessments beyond these large-scale agro-ecological zones are rarely found (Corley and Tinker, 2003).

4.2 Exploring management and climate related yield gaps in oil palm

Understanding climate-related production limitation is key when interpreting and comparing field trial results from several sites, as is the case of the BMP project of IPNI SEAP. Generally, solar radiation is higher in Sumatra than in Kalimantan, consequently the model results suggest potential yields (limited by solar radiation only) of more than 40 tons ha-1 of

FFB at the plateau phase for the sites in Sumatra. The simulation output for the sites in Kalimantan indicates potential yields below 40 tons ha-1. This might be due to higher cloud cover in Kalimantan.

The gap between attainable water-limited yield and potential yield differs from site to site: While for the two sites in North Sumatra no major water stress occurred throughout the simulation runs, minor stress events occurred for sites four and six in Kalimantan. Site three in southern Sumatra was affected by regular water deficiency where annual rainfall distribution was strongly seasonal (Figure 3) compared to the other sites. At site five in Central Kalimantan, water stress was due to low rainfall and soil (sand) with a very low PAWC.

Management-related yield gap, i.e. the difference between water-limited yield and observed BMP and REF yields, is smallest at site 6 (Figure 7). At this site, yields in many BMP and a few REF blocks match the potential production zone. Here, management already operates at the upper limit of production and differences between BMP and REF are not very pronounced. Therefore, further gains through improved management are not possible according to PALMSIM results. A similar situation is found for site one, where both BMP and REF yields are close to the production limits. At site three, FFB yields are low mainly due to the age of the palm stand. However, it was possible to increase yield close to water-limited yield by implementing BMP. Further yield gains are unlikely as water limits yield at that site more than at others. Site two offers a large yield gap. BMP implementation improved this, but there is still potential for exploitation. A major reason might be the poorer planting material (high dura contamination), which cannot be changed in the short run. The same reason might also explain the larger yield gap at site five.

To sum up the simulation, analysis suggests that sites one and six already operate at the upper limit of production, and at site three could be improved by replanting. For sites two, four and five, a larger management-related yield gap is present. Such analysis might help to understand better field trial results evaluating best management practices. There is a strong focus on nutrient caused yield gaps in oil palm research (Dubos et. al., 2010; Rafflegeau et. al., 2010; Webb, 2008; Webb et. al., 2011), but there is limited literature about climate-related yield gaps for specific sites. Few studies aim to relate production to the weather conditions (Adam et. al., 2011; Caliman and Southworth, 1998; Combres et. al., 2013; Dufrêne et. al., 1990; Legros et. al., 2009). The current expansion of oil palm in Africa and South America with different climates to those in Southeast Asia will certainly increase interest in the climate-productivity relationship with oil palm. This study illustrates that even within Southeast Asia, differences in potential and water-limited yield can be found. However, these simulation results have to be used carefully, as data input for the model such as PAWC and, in particular, the simulated weather data cannot assure detailed accuracy. The recent attention on yield gap studies based on simulation modelling is so far limited to annual crops, as also stated by van Ittersum et. al. (2013) as model and input data are rather scarce for tropical plantation crops (van Oijen et. al., 2010).

The approach in this study using the low data input model PALMSIM showed some useful insights and provided the first yield gap analysis based on simulation modelling. However, this contains a certain amount of uncertainty as several factors, such as temperature, rainfall distribution within a month, and nutrient effects, are not captured. Despite these challenges, yield gap studies based on simulation modelling can potentially be even more beneficial for tropical plantation crops. Field trials for perennials are financially and logistically difficult to conduct; for uncultivated land it is missing. Oil palm climate change studies based on modelling analysis are so far lacking. Simulation modelling could help to evaluate whether a certain region is still suitable for the crop in 20 or 30 years, taking into account that this investment has to be made now.

4.3 Challenges for yield benchmarking in oil palm

For both proposed strategies of sustainable intensification - i.e. expansion into degraded land only and increasing productivity of land already under cultivation - yield benchmarking as shown above can be used as a valuable and supportive tool. However, defining water-limited yield is challenging in perennial crops. Such crops are heavily affected by long-term weather, which is not only restricted to one year. Instead, several years of weather define water-limited yield for a specific site (Carr, 2011).

In this study we dealt differently with this challenge: for the creation of the oil palm yield map of Kalimantan only average weather data was used. In the yield gap assessment, 99 years of possible weather scenarios were used for simulating water-limited yield. This first approach might be sufficient to give an overview on which sites are superior to others. However, for a better understanding of the potential productivity of a given site it is necessary to know about the range of possible production. To reflect this, we developed the concept of water-limited production zones (Figure 7), which represents the mean plus/minus the standard deviation of FFB yield as an output from 99 simulations. However, this approach is still far away from the accuracy of yield gap analysis in annual crops. This is firstly due to the simplicity of

PALMSIM, especially in terms of the water balance, and secondly the lack of information in terms of long-term observed weather data.

5. Conclusion

To balance the large environmental impact of oil palm plantations and the increasing demand for palm oil, sustainable intensification – by expansion only into degraded sites and by the increase of productivity per unit land in existing cultivated areas - is highly desirable. For both strategies, yield benchmarking by simulation modelling can be a useful supportive tool. Therefore, we used the simple physiological oil palm model PALMSIM to set yield targets in two case studies illustrating these two options for sustainable intensification. Such a quantitative pathway towards benchmarking yield is - to our knowledge - a novel approach to oil palm production.

Acknowledgement

More information about the model including the source code is available from: http://www.uni-goettingen.de/en/palmsim/499488.html.

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IV. Crop modelling based analysis of site-specific production limitations of winter oilseed rape in northern Germany[3]

1. Introduction

The average yields of winter oilseed rape (Brassica napus L.) have reached 4000 kg ha-1 in many northern states in Germany since 2000 with the most favourable sites regularly yielding above 5000 kg ha-1 (Statistisches Bundesamt, 2014). Under optimal growing conditions (optimal nutrient and water supply, absence of pest and diseases, no weeds) a potential grain yield of 6500 kg ha-1 has been suggested by Berry and Spink (2006). However, under rainfed conditions winter oilseed rape production in Germany is frequently affected by water stress, indicated by national yields below 3000 kg ha-1 in years with a dry spring period as observed in 2003 and 2011 (Statistisches Bundesamt, 2014). Indeed, oilseed rape is a water demanding crop (Gerbens-Leenes et al., 2009) with studies showing that > 300 mm of water must be available from flowering to maturity to support high yields of more than 4000 kg ha-1 (Berry and Spink, 2006; Rathke et al., 2006). Available soil moisture at flowering is therefore critical to support the crop under conditions where rainfall is limited. Shallow, sandy or constrained soils with low plant available water capacity (PAWC) therefore have a limited ability to buffer a crop during periods of low rainfall, and it is on these soil types that yields are most severely limited.

Another limiting factor in oilseed rape production is that N-application is restricted by the EU Nitrate Directive in Germany to limit average annual N-balance (N applied minus N removed by harvest) to a three year average of 60 kg ha-1. N-balance measured after winter oilseed rape usually exceeds this limit, and is frequently above 100 kg ha-1 (Henke et al., 2007). Large surpluses arise due to typical fertiliser rates in the range of 160 to 200 kg N ha-1 in spring. A low harvest index (HI; ratio harvested organ/total biomass) of oilseed rape, typically 0.3, and N harvest index (NHI; ratio N in harvested organ/ N in total biomass) of 0.6-0.7 result in a large proportion of the applied N remaining in straw residues on the field. The following crop, commonly winter wheat, is not able to take up the mineralising N in autumn. Despite this overall trend, the N-balance for the same N-fertiliser rate can differ strongly from site to site (Sieling and Kage, 2010), when factors, which are largely beyond the scope of management, such as water supply, solar radiation and temperature, limit growth. Matching

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[3] This chapter has been published as Hoffmann, M.P., Jacobs, A., Whitbread, A.M., (2015) Crop modelling based analysis of site-specific production limitations of winter oilseed rape in northern Germany. Field Crops Research, 178, 49-62.

fertiliser application rates to site-specific attainable yield may help to adapt management practices and improve the N-balance.

In the last twenty years, field trials have been widely conducted in Germany to define site-specific best management practices by setting targets for site-specific yield and improved N use efficiency (Lickfett, 1993; Henke et al., 2008a, 2008b; Rathke et al., 2006). However, field trials are expensive and time consuming and, more importantly, results and also N-response curves statistically derived from these trials are difficult to extrapolate to other sites and years due to the complex nature of the interaction between crop physiology, N-uptake and distribution, temperature driven growth duration, intercepted radiation and water supply (rainfall amount, distribution and storage in the soil) (Henke et al., 2007; Schulte auf‘m Erley et al., 2011). For other crops, mechanistic plant growth models have been successfully used to develop complementary insights into soil and climate specific fertiliser practices (e. g. for wheat: Asseng et al., 2000).

During the 1990’s, few models for oilseed rape have been developed in Europe and Australia. However, so far, no model has been evaluated for simulating the growth of rainfed oilseed rape limited by N. For example, the respective LINTUL version developed by Habekotté (1997a, 1997b, 1997c) takes only solar radiation and temperature into account and assumes optimal conditions for growth where water and N are not limiting. It further ignores the autumn and winter development phases of winter oilseed rape. A second example is that of the CERES-Maize model adapted for winter oilseed rape in France, but only tested for non-water stressed plants (Gabrielle et al., 1998). For Mediterranean conditions in Italy, a winter oilseed rape model was adapted within the DSSAT framework (Deligios et al., 2013). For conditions in Australia, a canola model was incorporated into APSIM (Robertson et al., 1999) and mainly used to assess temperature effects on plant phenology (Farre et al., 2002). Both models - DSSAT rapeseed and APSIM canola - were developed for warmer climates than the growing conditions of central and northern Europe. Although both models have not been tested for crop N-uptake, they make use of intensively tested modules for soil N and water dynamics, which make them suitable as a basis for model development and adaptation.

Against this background, this study aimed to (1) collect rainfed field trial data from multiple sites and years to (2) adapt the existing APSIM canola model for winter oilseed rape production in Germany and (3) to evaluate the performance of the calibrated model in terms of total biomass, grain yield, leaf area index (LAI), N-uptake and soil mineral N (SMN) dynamics against these field trial data and (4) explore the scope for site-specific N-management in northern Germany for improving the productivity (represented by yield) and reducing the risk of exceeding the N-balance.

2. Material and methods

2.1 Field experiments

Data for the calibration and the evaluation of the model derived from N-rate x variety field trials conducted at Reinshof in 2010/11, at Rosdorf in 2012/13 (Lower Saxony, Germany, University of Göttingen) and a at third experimental site, at Harste in 2006-2012 (Institute of Sugar Beet Research). These three sites are located in the vicinity of Göttingen. The region is located in the transition between maritime and continental climate. Average annual precipitation is 637 mm and average daily temperature is 9.17°C (Figures 1 and 2). Daily weather data (including solar radiation, maximum and minimum temperature and rainfall) were obtained from the German weather service station in Göttingen around one km from the Reinshof field trial and five km from the trial at Rosdorf. For Harste, meteorological data were taken from a nearby weather station (Wetterstation Göttingen, 2014).

Figure 1: Map of Germany presenting the selected sites: Magedburg (1), Göttingen (2), Bad Salzuflen (3) and Leck (4).

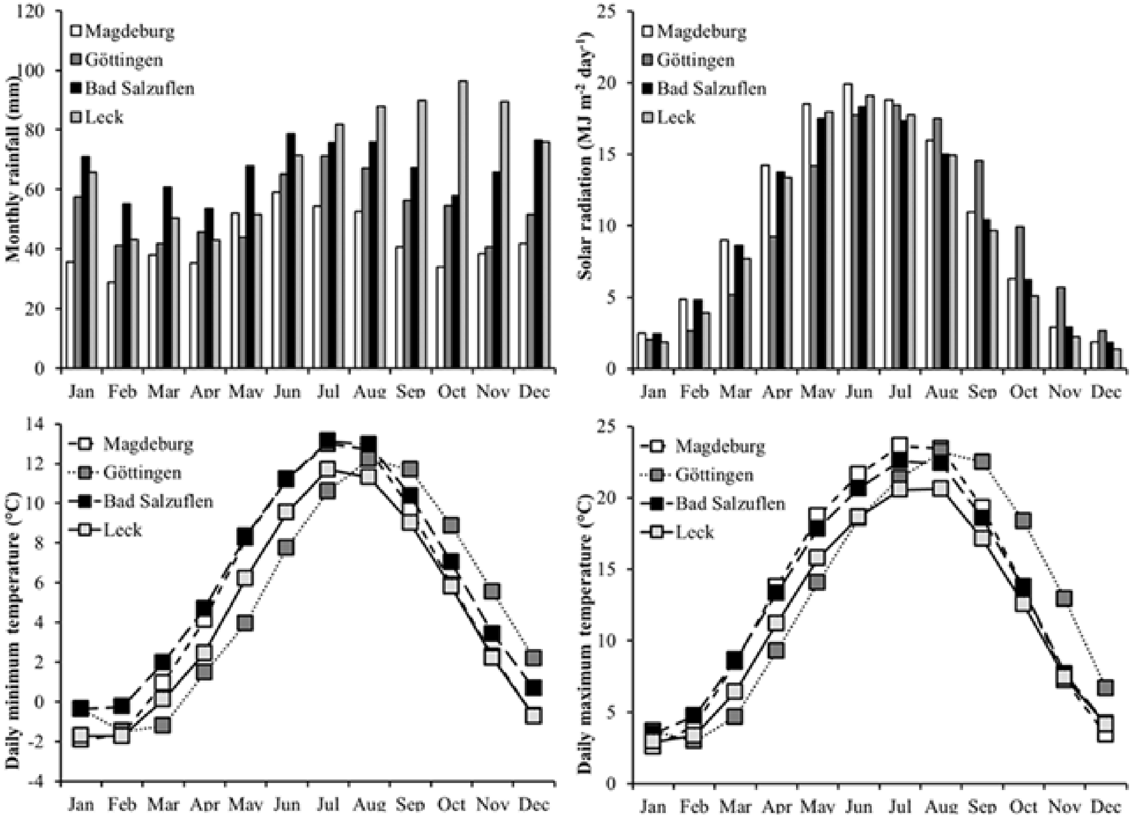

Figure 2: Climate data (monthly mean rainfall, monthly mean solar radiation (SR), mean minimum and maximum daily temperature based on the years 1961-2012: Magdeburg (annual rain 510 mm; annual SR 3847 MJ m^{-2}, annual mean daily Temp 9.4°C); Göttingen (637 mm; 3656 MJ m^{-2}, 9.2°C); Bad Salzuflen (809 mm; 3641 MJ m^{-2}, 9.7°C; Leck (847 mm; 3503 MJ m^{-2}, 8.2°C). Source: German Weather Service.

a) Reinshof

The soil was a Pseudogley with organic carbon content (OC; 0-10 cm) of 1.8 % (Table 1). Soil texture was a clayey silt and the pH value was 7 (0.01 M CaCl2; VDLUFA, 1991). Phosphorus (P; 7 mg 100 g-1 soil; CAL method), potassium (K; 12 mg 100 g-1 soil; CAL method) and magnesium (Mg; 9 mg 100 g^{-1} soil; CaCl2 method) were measured at field trial start and found in sufficient supply (VDLUFA, 1991). The field trial was carried out from 08/2010 to 07/2011. In this study we used data from a factorial experiment with four replicates of three hybrids (cvv. PR46W31, PR46W20, PR46W26) and three N-levels (0, 100, 200 kg ha-1). N-fertiliser was applied in two equally split doses at recommencement of growth after winter dormancy in spring and four weeks later. The crop was sown on 20/08/2010 at a planting density of 50 plants m^{-2}. Soil characterisation including hydrological properties needed to parameterise the soil water balance model in APSIM were taken from Jung (2003) with an assumed rooting depth of 150 cm. SMN (0-90 cm) was low with 30 kg ha-1 before sowing (Nmin method, Wehrmann and Scharpf, 1979). Aboveground residues of the preceding wheat crop were removed. 40 kg ha-1 of sulphur (S) were applied as Kieserite on 08/02/2011. Biomass production, N-uptake and SMN were recorded before winter, after winter, at flowering and at harvest (including grain yield and N-uptake). The main phenological development stages were monitored according to the BBCH scale (Lancashire et al., 1991). All biomass values from the field trial, same for Rosdorf and Harste, were presented as dry weight.

Table 1: Soil properties (Bulk density, LL = Lower limit of plant available water capacity, DUL = Drained upper limit, SAT = Saturation, OC = Organic carbon) for Rosdorf, Harste and Reinshof used for the parameterization of APSIM.

Site	Soil layer (cm)	Bulk density (g cm^{-3})	LL (mm mm^{-1})	DUL (mm mm^{-1})	SAT (mm mm^{-1})	OC (%)
Reinshof	0-10	1.5	0.19	0.43	0.44	1.8
	10-30	1.5	0.19	0.43	0.44	1.8
	30-60	1.5	0.20	0.39	0.42	1.0
	60-90	1.5	0.18	0.34	0.38	0.4
	90-120	1.5	0.16	0.28	0.33	0.2
	120-150	1.5	0.16	0.28	0.33	0.1
Rosdorf	0-15	1.4	0.06	0.33	0.37	1.7
	15-30	1.5	0.10	0.33	0.37	1.5
	30-60	1.5	0.25	0.39	0.43	0.8
	60-90	1.5	0.24	0.34	0.38	0.5
	90-120	1.5	0.18	0.28	0.31	0.2
	120-150	1.5	0.28	0.32	0.35	0.1
Harste	0-15	1.4	0.14	0.37	0.48	1.0
	15-30	1.4	0.12	0.34	0.45	0.9
	30-60	1.5	0.11	0.32	0.44	0.4
	60-90	1.5	0.11	0.32	0.44	0.4
	90-120	1.5	0.11	0.32	0.44	0.2
	120-150	1.5	0.11	0.31	0.44	0.1
	150-180	1.5	0.10	0.31	0.43	0.1

b) Rosdorf

The soil was a Pseudogley with OC (0-15 cm) of 1.7 % (Table 1). Soil texture was a clayey silt and the pH value was 6.5 (0.01 M CaCl2). The nutrient status (5 mg P 100 g^{-1} soil (CAL method), 10 mg K 100 g^{-1} soil (CAL method), 6 mg Mg 100 g-1 soil (CaCl2 method) was tested prior to sowing and found in sufficient supply (VDLUFA, 1991). The field trial was conducted from 08/2012 to 08/2013. The hybrid Visby and the variety line Adriana were tested with three N-levels (0, 100, 200 kg ha^{-1}; replicates = 4). N-fertiliser was applied in two equally split doses at recommencement of growth after winter dormancy in spring and four weeks later. The crop was sown on 24/08/2012 at a planting density of 45 plants m-2 for cv. Visby and 50 plants m^{-2} for cv. Adriana. Hydraulic soil characterisation was done following Dalgliesh and Foale (1998). The lower limit of plant extractable water (known as CLL, similar to permanent wilting point) was assessed by setting a rain out shelter over the flowering oilseed rape. Soil moisture samples measured at harvest under the rain out shelter give the CLL of plant available water capacity. Drained upper limits (DUL, similar to field capacity) were defined by soil moisture samples taken after excessive rainfall. SMN (0-90 cm) was 70 kg ha^{-1} at sowing (Nmin method, Wehrmann and Scharpf, 1979). All residues from preceding wheat crop were incorporated by ploughing. S (40 kg ha^{-1}) was in spring 2013 as Kieserite to ensure that it was not limiting. Biomass production, N-uptake as well as SMN (0-90 cm) were monitored before winter, in spring, at flowering and harvest (including grain yield, and grain N-uptake). Furthermore, LAI was measured five times around flowering. Phenological development was monitored according to the BBCH scale (Lancashire et al., 1991).

c) Harste

The soil is a Stagnic Luvisol with OC content (0-15 cm) of 1.0 % (Table 1). Soil texture is a clayey silt and pH value was 7.1 (0.01 M CaCl2). Hydraulic soil characterisation was based on soil texture analysis using pedotransfer functions following Tsuij et al. (1994) (Table 2). The available data for testing the model derived from a long-term crop rotation experiment with three replicates (2006-2012). Winter oilseed rape was planted every year and, thus, the data set included grain yield from 2006 to 2012 and final total biomass for 2011 and 2012. SMN (0-90 cm) was measured before winter and in spring (Nmin method, Wehrmann and Scharpf, 1979). From 2006 to 2009 the hybrid Mika was planted and from 2010 to 2012 the cv. Visby. Sowing date was late August/early September. Planting density was 45-50 plants m^{-2}. N-fertiliser splitting (2-5 times, including pre-winter application) and amount (185-260 kg ha-1) differed from year to year and was managed according to SMN levels in spring. Before sowing, 109 kg P ha^{-1}, 142 kg K ha^{-1}, 45 kg Mg ha^{-1} and1143-1400 kg CaO ha^{-1} were applied. In spring, 20 kg S ha^{-1} and 15 kg Mg ha^{-1} as Bittersalz were applied. All residues from preceding wheat crops were incorporated by deep cultivation.

2.2 APSIM setup

APSIM is a widely used farming system model that simulates crop growth and development upon incoming radiation limited by temperature stress, water supply and N availability (Keating et al., 2003). Management decisions such as sowing date, fertiliser application, etc. can be specified in a manager module. APSIM (version 7.5r3008) was configured with the modules for canola, soil water (SOILWAT), soil N (SOILN) and surface organic matter (represents residues of the preceding crop) as follows:

2.2.1 Soil and surface organic matter setups

The SOILWAT module was parameterised following standard practices using APSIM: The two parameters that determine first (U) and second stage (Cona) of soil evaporation using the Taylor-Priestly approach were set to 4 and 2 mm day–0.5 for loam soils, similar to Hunt and Kirkegaard (2011). Runoff is linked to the setting of the USDA curve number and was defined for all sites as 73. The fraction of water drained to the next soil layer under saturated conditions per day (SWCON) is 0.5 for all layers in the three soils following standard parameterisation for loam. For soil water content below DUL, water movement depends upon the water content gradient between adjacent layers and the soil's diffusivity, defined in APSIM as diffusivity constant and diffusivity slope. For all sites the default values of 88 (diffusivity constant) and 35 (diffusivity slope) were used to represent loam soils.

The OC content which was only measured for the top layer, was assumed to decrease exponentially with depth. FINERT and FBIOM, the different pools of the organic matter are defined according to typical default values (FBIOM; 0-10 cm: 0.05; 10-30: 0.045; 30-60: 0.035; 60-90: 0.015; 90-120: 0.01; FINERT: layer 0-10: 0.4; 10-30: 0.5; 30-60: 0.7; 60-90: 0.8; 90-120: 0.95; unit less, fraction of total OC; Probert et al., 1998; Luo et al., 2014).

Straw remaining from the preceding wheat crop was set according to the values measured and a C:N ratio of 60 was assumed. The amount of straw in the field trials ranged from 6000 to 8000 kg ha^{-1}. The relative potential decomposition rate was 0.05 d-1 according to the application of APSIM in the Netherlands by Asseng et al., (2000). Recorded tillage events were implemented in the management script. An annual N-deposition of 24 kg ha-1 as suggested by the Deutsches Umweltbundesamt (2013) was evenly distributed over the year on a monthly basis (2 kg ha-1 mo-1) in the simulation runs.

2.2.2 Plant module calibration

As the APSIM canola model was not previously tested for the study region, we calibrated the model with data from three treatments of the Reinshof trial (cv. PR46W26 at 0, 100, 200 kg N ha-1, respectively). These treatments were excluded from the evaluation of the model afterwards. An existing cultivar in the APSIM data base, cv. French Winter, was selected as a base cultivar which was assumed to be closest to cultivars found in northern Europe. The model output of these calibration runs was compared to observed results. It showed that the N-uptake was overestimated in relation to total biomass production. APSIM's N-uptake is regulated by supply and demand. The demand side is determined by a value for minimum, critical and maximum concentration (%) for the different organs and plant stage. Based on the measured N-concentration in vegetative biomass and grain before winter, at vegetation start, flowering and harvest and in accordance with literature (Barlog and Grzebisz, 2004), the APSIM-standards for N-concentrations for leaf, stem, pod and grain were adjusted (Table 2). Values are close to the ones used by Deligios et al. (2013) for an oilseed rape model built for the Mediterranean climate in the DSSAT framework. Adjusting the threshold N-concentration levels in the model led to a good match between simulated N-uptake with the observed N-uptake in the calibration treatments.

Table 2: Minimum, critical and maximum N-concentrations (%) for different organs of winter oilseed rape derived in this study for the calibration of the APSIM winter oilseed rape model. Original values in brackets.

		Plant Stage						
Organ	Level	emergence	Juvenile	flower initiation	flowering	start grain filling	end grain filling	maturity
Leaf	min	5.5 (5.5)	2.5 (5.0)	2.5 (4.0)	1.4 (3.0)	0.5 (0.5)	0.5 (0.5)	0.5 (0.5)
Leaf	critical	6.5 (6.5)	3.6 (6.0)	3.0 (5.5)	3.1 (5.0)	1.5 (5.0)	1.5 (0.5)	0.8(1.0)
Leaf	max	8.0 (8.0)	7.5 (7.5)	6.5 (6.5)	5.5 (5.5)	5.5 (5.5)	5.5 (5.5)	1.0 (2.0)
Stem	min	5.5 (5.5)	2.0 (5.0)	2.0 (3.5)	1.4 (3.0)	0.5 (0.3)	0.5 (0.3)	0.3 (0.3)
Stem	critical	6.5 (6.5)	2.7 (6.0)	2.7 (5.0)	2.5 (4.0)	1.5 (4.0)	1.5 (4.0)	0.5 (0.5)
Stem	max	8.0 (8.0)	5.5 (7.5)	5.5 (5.5)	4.5 (4.5)	4.5 (4.5)	4.5 (4.5)	1.5 (2.5)
Pod	min				3.5 (4.0)	2.5 (3.0)	0.5 (2.0)	0.3 (0.5)
Pod	critical				4.0 (5.0)	3.5 (4.0)	1.5 (3.0)	1.0 (1.0)
Pod	max				5.5 (5.5)	4.5 (4.5)	2.6 (3.5)	1.5 (1.5)
Grain	min							2.8 (2.8)
Grain	critical							3.3 (4.0)
Grain	max							4.5 (4.5)

Two further adjustments were made in the model setup: First, recent work with the APSIM canola model in Australia suggested greater leaf size for modern cultivars than the default ones in the release version of the model (APSIM 7.5r3008). Leaf size was increased to 2000, 7000, 15000, 18000 and 19000 mm2 (original vales 1500, 4000, 11000, 14000, 15000) which is set in APSIM according to leaf number (1, 3, 5, 9, 13, 16, respectively) (McCormick et al. accepted). Secondly, senesced leaves were set to be dropped at a daily rate of 1% (original value 0 %) by calibrating the model with the observed total biomass values before and after winter.

After these general canola module calibration, which is the same for all cultivars, cultivar specific parameterisations (HI and thermal time requirements for the specific development stages) were done as follows (Table 4): cv. PR46W26 was paramterised by observed HI for the 200 kg N ha^{-1} treatment and thermal unit requirements, which were adapted from observed flowering and harvest day. For differentiating the other cultivars, we used the 200 kg N ha^{-1} treatments at Reinshof for cv. PR46W31 and cv. PR46W20. For cvv. Visby and Adriana, we used the 200 kg N ha-1 treatment at Rosdorf. The cv. Mika was assumed to be similar to Visby.

Table 3: Cultivar parameter for APSIM.

APSIM Parameter	Acronym	Unit	Cultivar					
			French Winter (default)	PR46W 26	PR46W 31	PR46W 20	Adriana	Visby
Harvest Index	hi_max_pot	-	0.30	0.20	0.24	0.25	0.27	0.28
<u>Thermal time requirements:</u>								
End of juvenile to floral initiation	tt_end_of_juvenile	◦C days	900	900	900	900	900	900
Floral initiation to flowering	tt_floral_initiation units	◦C days	250	250	350	350	350	350
Flowering to start grain	tt_floweringunits	◦C days	200	350	300	300	250	300
Start grain filling to end grain filling	tt_start_grain_fill	◦C days	1000	650	750	750	950	950

2.3 Analysis of model performance

For statistical analysis of model evaluation, the observed data of biomass, yield, grain N, biomass N and soil mineral N, and LAI were compared with the corresponding predicted values. To assess the goodness of fit of these simulated - measured comparisons the root mean square error (RMSE) between predicted and observed data was calculated as follows:

$$\text{RMSE} = [(\sum (\text{O} - \text{P})^2/n)]^{0.5}$$

Where O and P are the paired observed and predicted data and *n* is the total number of observations. Additionally, for comparison, the traditional r^2 regression statistic (least-squares coefficient of determination) forced through the origin was calculated.

2.4 Simulation experiment

The scope for site-specific N-fertiliser management was investigated using a simulation experiment for four locations across northern Germany (Figure 1). For a transect running from Göttingen to Leck, long-term (1961-2012) daily historical weather data (solar radiation, minimum and maximum temperature and rainfall) of four sites were obtained from the German Weather Service (Figure 1). The highest average annual rainfall (847 mm) and coolest mean daily temperature (8.16 °C) is recorded for Leck. During the critical growing period for oilseed rape growth from flowering to maturity 53 % of all season provide more than 200 mm rain. Contrary, in Magdeburg, a continental dry site (510 mm average annual rainfall), only 16 % of all seasons have rainfall > 200 mm, while more than half of the seasons (57 %) have less than 150 mm rainfall during that period (Figure 8).

A generic loamy soil - of varying depth - similar to a Parabraunerde (USDA classification, Cambisol) was used to represent a common highly productive arable soil in northern Germany. While information on soil texture is easily available, there is often a lack of knowledge concerning the rooting depth of the specific soil. Rooting depth can differ due to subsurface hardpans or rocks and it is correlated strongly with PAWC and, thus, crop growth. Therefore, we applied four different rooting depths to illustrate the effect on crop growth at each site: A rooting depth of 180 cm resulted in a PAWC of 237 mm, which was categorised as high according to AG Boden (1994). Rooting depths limited to 140 (PAWC 187 mm), 90 (PAWC 123 mm) 50 cm (PAWC 58 mm) are considered to represent moderate, low and very low PAWC respectively according to AG Boden (1994). To single out rooting depth effects, CLL and DUL were not changed. All parameters of the SOILWAT module were kept constant (first (U) and second (cona) stage evaporation 4 and 2 mm day–0.5, respectively; runoff 73; SWCON 0.5 for all layers; diffusivity constant 88; diffusivity slope 35. We used a typical OC content in the topsoil of 1.4%. Characterisation of the soil organic matter pools followed the convention as described above.

The simulation experiment was set up for the site-specific climate data and repeated for each year (1961-2012) and each PAWC category. The sowing date was fixed to 30th August and cv. Visby was planted at a density of 50 plants m^{-2}. The APSIM surface organic matter module was initialised with wheat straw of 6000 kg ha^{-1} and with SMN (0-90 cm) of 50 kg ha^{-1}. Surface organic matter and soil-N (including SMN) were reset annually on 20th August. Soil water was set only in the starting year, and from then on APSIM calculated soil water dynamics. A deposition of 24 kg N ha^{-1} year^{-1} was included (Deutsches Umweltbundesamt, 2013). For each combination, twelve levels of N-fertiliser rates (from 0 to 220 kg N ha^{-1} at an interval of 20 kg ha^{-1}) were tested for their effect on grain yield and N-balance. Fertiliser application followed standard practice in the region split into two equal doses both applied in spring. After winter, the first N-dose was applied if the Julian day of the year was > 30 and < 182 and when the six preceding days > 6 oC (daily average). This rule resulted in N-application during February/March. The second dose was applied four weeks later.

3. Results

3.1Evaluation of the model

Field trial data covered a wide range of grain yield (1348-4754 kg ha-1), total biomass (1001-16608 kg ha^{-1}), and N-uptake (37-204 kg ha^{-1}) (Table 4; Figure 3a) and therefore offered the opportunity for detailed testing of the model. At harvest, observed grain yields matched predicted ones with a RMSE of 243 kg ha^{-1} against an observed average of 3274 kg ha^{-1} (% RMSE 7.4) (Figure 3a). Similar results were found for total biomass (% RMSE 6.4) and N-uptake (% RMSE grain-N 9.8; biomass-N 12.8 %) (Figures 3 b, c, d). The regression line forced through the origin indicated an almost perfect match for predicted and observed grain yield, grain N-uptake and total biomass (Figures 3 a, b, c). As shown in Figure 3d, total N-uptake at harvest was slightly over predicted.

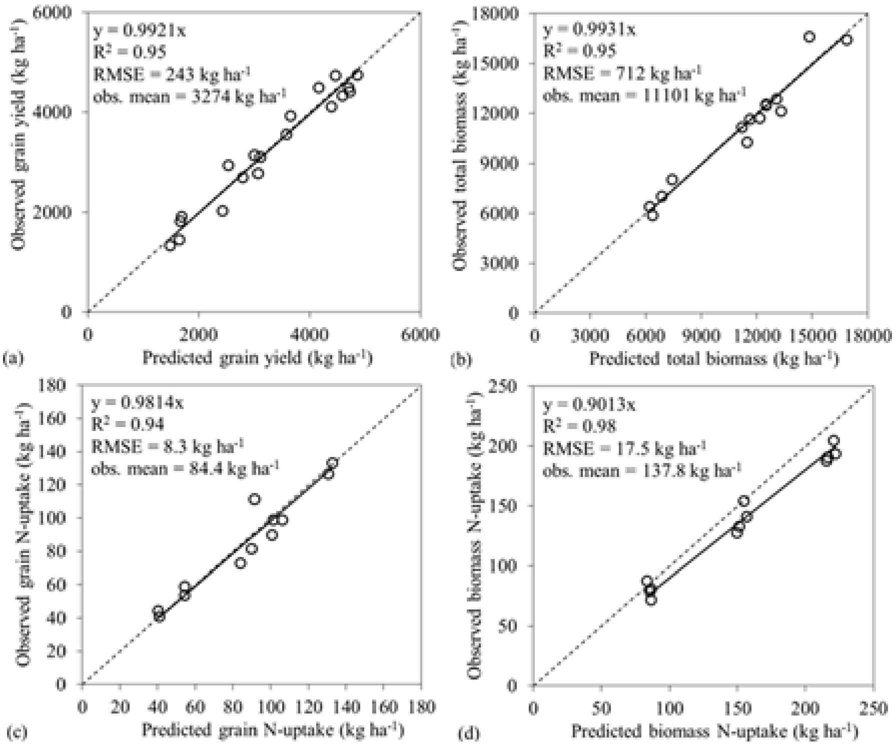

Figure 3a-d: Observed versus predicted (a) grain yield, (b) total biomass, (c) grain nitrogen (N-) uptake, and (d) biomass nitrogen (N-) uptake at harvest. The dotted line represents the 1:1 line. The straight line represents the regression line forced through the origin.

Taking all observed points of the whole growing period, the RMSE for total biomass was 884 kg ha^{-1} against an observed average of 4996 kg ha-1 (Table 4). Growth simulated over time for Rosdorf and Reinshof is presented exemplary for two cultivars in Figures 4a-g. Predicted total biomass was close to the four measured points (before and after winter, around flowering and maturity) at both sites (Figures 4a, b). However, around flowering predictions slightly under estimated production for the zero N-fertiliser treatments at both sites. For total N-uptake across all data points, a RMSE of 16.5 kg ha^{-1} against an observed average of 83.6 kg ha^{-1} was found (Table 4). For the trial at Reinshof, the observed values at flowering exceed the predicted ones (Figure 4c). For the zero N-fertiliser treatment, this was consistent with the underestimation of biomass at that stage. For the other treatments, the model under predicted N-uptake at that site and development stage. However, despite this exception, the model accurately simulated the N-uptake at the different sampling dates (Figures 4c, d).

Table 4: Summary of the APSIM winter oilseed rape model evaluation at Rosdorf, Reinshof and Harste in Germany taking all measured points across the whole growing period into account. Performance at harvest only is presented in 3a-d.

Model attribute	Unit	Number of paired data points	Observed range	Observed mean	R^2	mb	RMSE
Total Biomass	kg ha^{-1}	50	1001 - 16608	4996	0.96	1.01	884
N-uptake	kg ha^{-1}	48	37 - 204	83.6	0.94	0.90	16.5
LAI		30	0.34 -4.94	2.63	0.88	1.04	0.55
Soil mineral N (0-90 cm)	kg ha^{-1}	48	5.4 - 121.5	19.9	0.93	1.91	16.4

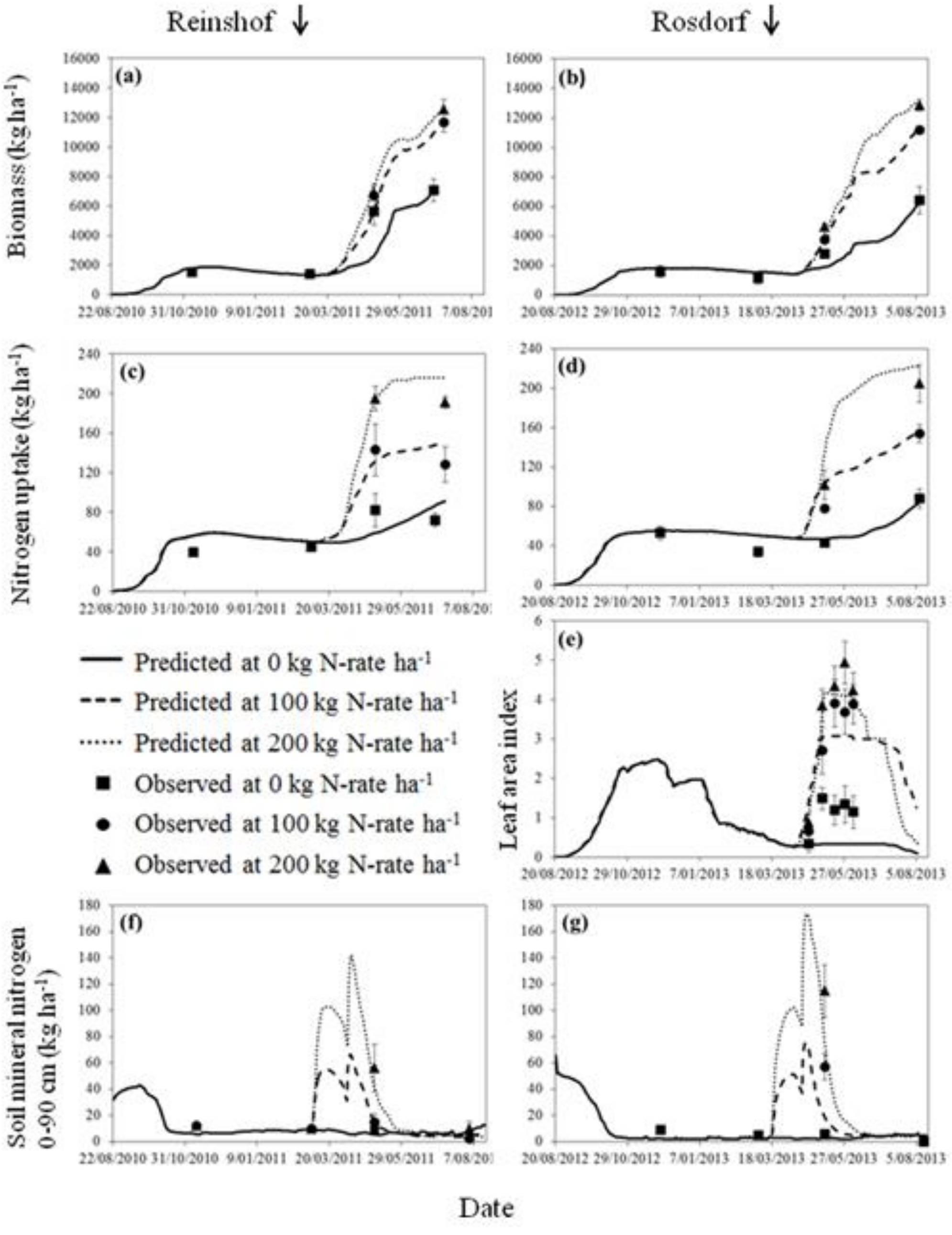

Figure 4a-g: Simulated (as lines) and observed (as points) (a) total biomass growth, (c) N-uptake, and (f) soil mineral nitrogen (0-90 cm) for the treatments with the cultivar PR46W20 as affected by 0, 100, 200 kg nitrogen fertiliser ha^{-1} at Reinshof (2010/2011). Simulated (as line) and observed (as points) (b) total biomass growth, (d) nitrogen uptake, (e) leaf area index, and (g) soil mineral nitrogen (0-90 cm) for the treatments with the cultivar Visby as affected by 0, 100, 200 kg nitrogen fertiliser ha^{-1}at Rosdorf (2012/2013). Bars represent standard deviation (n=4).

Observed LAI values reflected the strong increase in growth during the first weeks in spring with values below 1 at end of March/early April to values of 5 at end of May for the 200 kg N ha^{-1} treatment at Rosdorf (Figure 4e). The model simulated LAI with a RMSE of 0.55 against an observed average of 2.63 (Table 4). However, for the run with the zero N-fertiliser application, the model under predicted LAI by about 1 (Figure 4e). Taking all samples into account, SMN was modelled with a RMSE of 16.4 kg ha-1 against an observed average of 19.9 kg ha-1. However, observed values ranged widely from 5.4 to 121.5 kg ha^{-1} (Table 4) and the R2 forced through the origin showed an agreement of 0.93. The simulated SMN dynamics reflected the observed pattern with a decrease of N before winter and the increase through fertiliser application in spring (Figures 4f, g).

3.2 Simulation experiment

In the simulation experiment, grain yield and N-balance were strongly affected by N-fertiliser application. Grain yields were around 1100 kg ha-1 with zero fertiliser and increased to 4000 kg ha^{-1} for most of the sites with high PAWC when 220 kg N ha^{-1} was applied (Figure 5). However, the yield gain from additional N-fertiliser diminished at higher N-rates. The average N-balance increased with the amount of N-fertiliser applied and exceeded the EU Nitrate Directive in Germany of 60 kg ha^{-1} for all sites and PAWCs when 160-180 kg N ha^{-1} was applied (Figure 6).

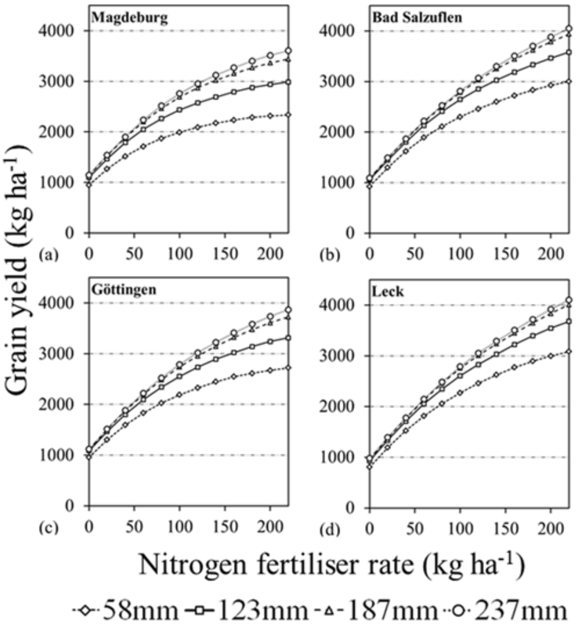

Figure 5: Nitrogen fertiliser rate versus mean grain yield for (a) Magdeburg, (b) Bad Salzuflen, (c) Göttingen, and (d) Leck and for different plant available water holding capacities (PAWC) (i) 58 mm, (ii) 123 mm, (iii) 187 mm and (iv) 237 mm based on an APSIM simulation experiment for the years 1961-2012.

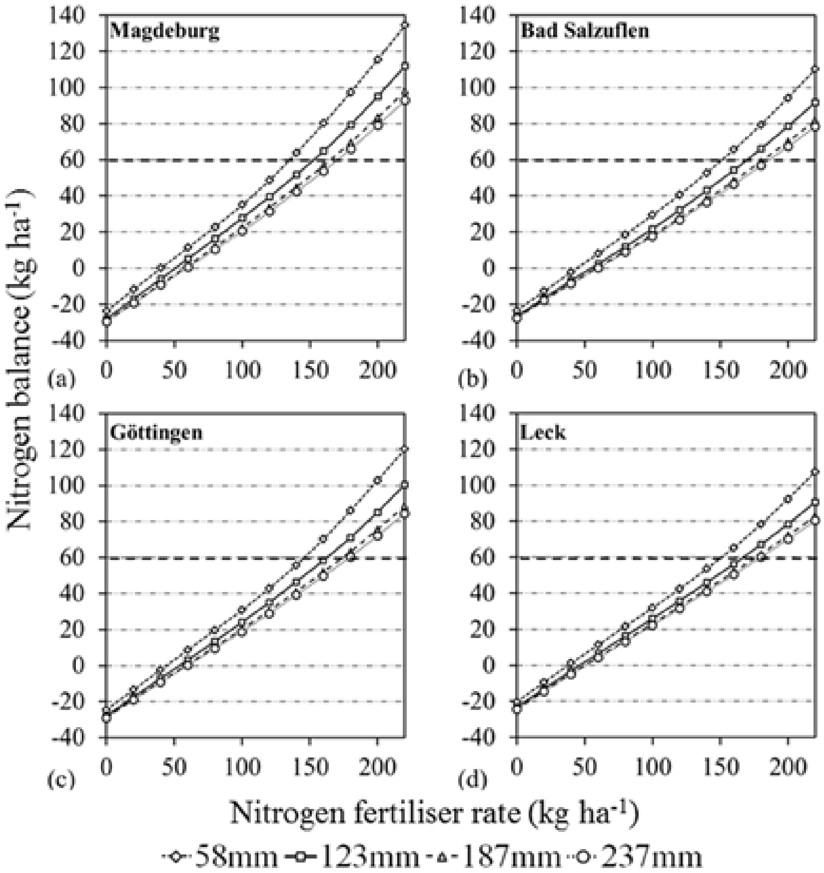

Figure 6: Nitrogen fertiliser rate versus mean nitrogen balance for (a) Magdeburg, (b) Bad Salzuflen, (c) Göttingen, and (d) Leck and for different plant available water holding capacities (PAWC) (i) 58 mm, (ii) 123 mm, (iii) 187 mm and (iv) 237 mm based on an APSIM simulation experiment for the years 1961-2012. The 60 kg N ha^{-1} threshold for the nitrogen balance defined by the EU Nitrate Directive in Germany is marked in bold.

Comparing sites for the zero fertiliser run, simulated grain yields were highest in Magdeburg (1146 kg ha^{-1}) and lowest in Leck (980 kg ha^{-1}) (Figure 5). Differences were in the range of 200-300 kg ha^{-1}. Contrary, for all runs with fertiliser rates > 160 kg N ha^{-1}, the grain yield was highest in Leck and lowest in Magdeburg. Generally, at these high fertiliser rates, mean grain yields were larger at higher rainfall sites (Bad Salzuflen and Leck) than at low rainfall sites (Göttingen and Magdeburg) (Figures 2 and 5). At all sites, simulated grain yields reflected the four different PAWC levels (Figure 5). Although the magnitude differed from site to site, the very low PAWC of 58 mm resulted in average 500 kg ha-1 lower yields than the low PAWC of 123 mm. The mean yield difference between the 123 mm PAWC and the 187 mm was around 300 kg ha^{-1}. However, this difference was more pronounced at lower rainfall sites. The mean yield gap between the moderate and the high PAWC soils was marginal at all sites. Seasonal yield variability was largest for the low PAWC (58 mm), especially in Magdeburg and Göttingen (for 180 kg N-fertiliser rate ha^{-1}); yield ranged at these sites from 1000 to 3000 kg ha^{-1} (Figure 7).

The N-balance exceeded the critical threshold of 60 kg ha^{-1} at all PAWC categories in Magdeburg when > 180 kg ha^{-1} was applied (Figure 6). At all other sites, this was only true for the low and very low PAWCs while it stayed close to this limit at the moderate and high PAWC soils (Table 5).

For this 180 kg ha^{-1} N-fertiliser rate, higher NHI and N-uptake were generally simulated for the moderate and high PAWC across sites (Table 5). However, N-concentrations in vegetative and reproductive parts of the crop decreased with higher grain yields and PAWC. For some sites, the model suggested a good relationship between water supply from flowering to maturity (extractable soil water at flowering plus rainfall until maturity) and yield (Figure 7). In Magdeburg, a lower correlation was simulated for the low PAWC soil and highest for PAWC 237 mm (Figure 7a). At the other sites, the very low and the low PAWC showed the best relationship between water supply and yield, respectively. At Leck only a weak relationship was suggested (Figure 7d).

Taking the inter-annual variability into account, the N-balance differed strongly from year to year. Figure 8 shows that the N-balance with a fertiliser rate of 180 kg N ha^{-1} was always above the critical threshold of 60 kg N ha^{-1} in dry seasons (rainfall from flowering to maturity < 200 mm) at all sites. For rainfall > 200 mm and PAWCs of 123, 187 and 237 mm the N-balance was already close to the critical threshold. The difference between the sites is defined mostly (beside stored soil water at flowering) by the frequency of the rainfall class (< 150, < 200, <250, >250 mm); in Magdeburg, more than half of the seasons (57 %) fell into the category of < 150 mm, in Leck only 20 % of all seasons had less than 150 mm rainfall. We further explored the water limitations by plotting the mean and standard deviation of the water stress factor for photosynthesis (no water stress = 1, severe water stress = 0) in APSIM (Figure 9). In Magdeburg, winter oilseed rape suffered strongly in almost all years indicated by the high standard deviation, even at high PAWC values. In Leck, a stress factor of below 0.8 was hardly reached for the PAWC 187 and 237 mm. Across all sites with the exception of Magdeburg, mean water stress was strongest during flowering (Thermal time units 1750-2050 degree-days).

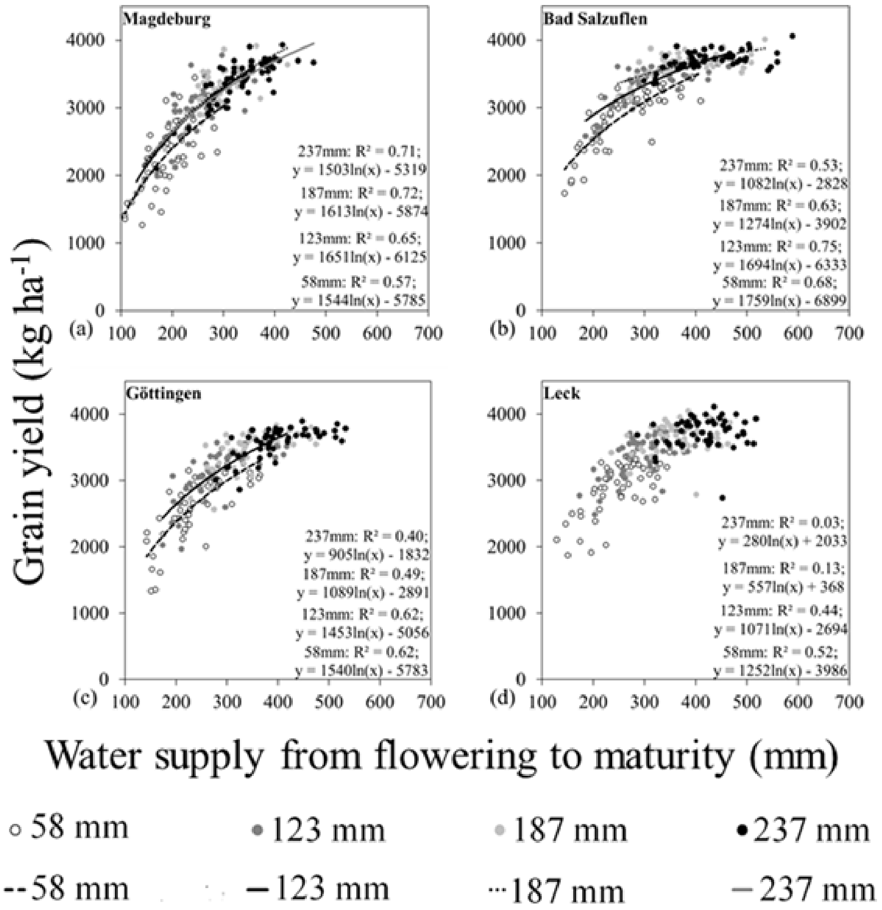

Figure 7: Water supply from flowering until maturity (extractible soil water at flowering and rainfall from flowering until maturity) versus grain yield for (a) Magdeburg, (b) Bad Salzuflen, (c) Göttingen, and (d) Leck and for different plant available water holding capacities (PAWC) (i) 58 mm, (ii) 123 mm, (iii) 187 mm and (iv) 237 mm based on a simulation experiment for the years 1961-2012 for each site. N-fertiliser rate was 180 kg N ha^{-1}. Regression line was only drawn for R2 ≥ 0.55.

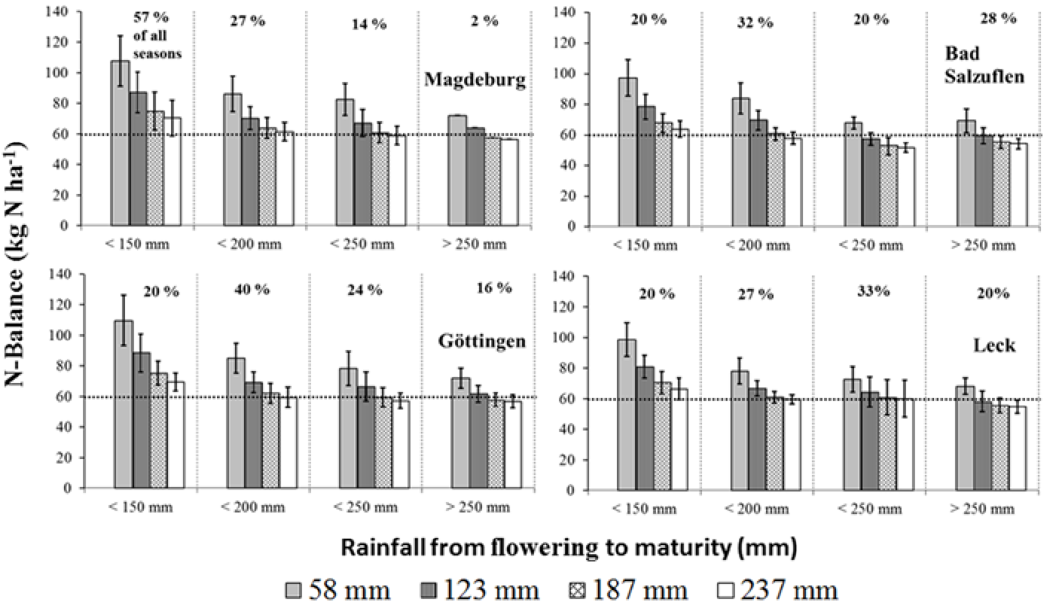

Figure 8: Simulated N-balance averaged according to years with rainfall classes for the period from flowering to maturity: < 150, < 200, < 250 and > 250 mm. Frequency of seasons out of all season (1961-2012), which fall into the respective rainfall class, are presented as percentage. Results based on a simulation experiment for the years 1961-2012 for each site and plant available water capacity (PAWC 58, 123, 187 and 237 mm). N-fertiliser rate was 180 kg N ha^{-1}.

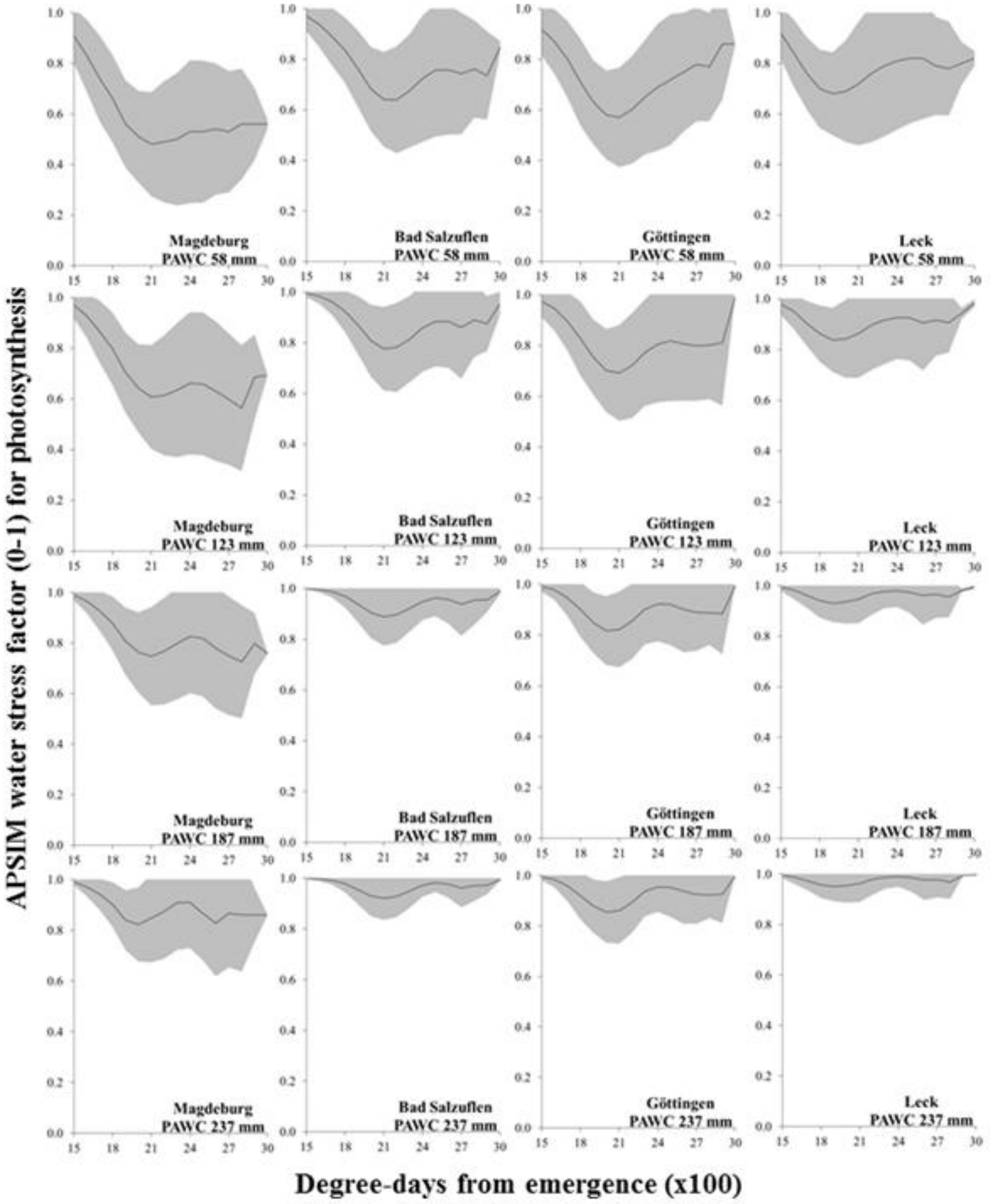

Figure 9: Simulated factor for mean water stress for photosynthesis as the mean (dotted line; 0= severe stress, 1= no stress) and the standard deviation (grey). Results based on an APSIM simulation experiment for the years 1961-2012 for each site and plant available water capacity (PAWC). N-fertiliser rate was 180 kg N ha^{-1}.

Table 6: Simulated mean winter oilseed rape grain yield, N-balance, total plant N-uptake, grain N-uptake, N harvest index (NHI), N-concentration in the straw and the grain, and the harvest days after emergence at four different sites and four categories of plant water holding capacities (PAWC). The simulation scenario using APSIM based on a fertilisation rate of 180 kg N ha-1 rate. Mean (n = 50) and standard deviation (in brackets).

Site	PAWC	Grain yield	N-balance	Total N-uptake	Grain N uptake	NHI	N-straw	N-grain	Harvest day after emergence
	(mm)	(kg ha-1)	(kg ha-1)	(kg ha-1)	(kg ha-1)		(%)	(%)	(days)
Magdeburg	58	2284 (526)	97 (19)	149 (12)	83 (19)	0.55 (0.10)	1.1 (0.5)	3.6 (0.1)	324 (8)
	123	2876 (449)	79 (14)	162 (10)	101 (14)	0.62 (0.07)	0.8 (0.3)	3.5 (0.2)	324 (8)
	187	3268 (384)	70 (12)	167 (10)	110 (12)	0.66 (0.05)	0.7 (0.2)	3.4 (0.2)	324 (8)
	237	3404 (336)	66 (11)	169 (10)	114 (11)	0.67 (0.05)	0.6 (0.2)	3.4 (0.2)	324 (8)
Bad Salzuflen	58	2832 (429)	79 (14)	158 (9)	101 (14)	0.64 (0.07)	0.8 (0.3)	3.6 (0.1)	320 (7)
	123	3333 (302)	66 (10)	168 (8)	114 (10)	0.68 (0.04)	0.6 (0.1)	3.4 (0.2)	320 (7)
	187	3623 (188)	59 (7)	173 (7)	121 (7)	0.70 (0.03)	0.6 (0.1)	3.3 (0.1)	320 (7)
	237	3702 (143)	57 (6)	175 (7)	123 (6)	0.71 (0.02)	0.5 (0.1)	3.3 (0.1)	320 (7)
Göttingen	58	2612 (483)	86 (17)	154 (12)	94 (17)	0.61 (0.09)	0.9 (0.4)	3.6 (0.1)	326 (7)
	123	3140 (393)	71 (12)	165 (9)	109 (12)	0.66 (0.06)	0.7 (0.2)	3.5 (0.2)	326 (7)
	187	3475 (275)	63 (9)	170 (8)	117 (9)	0.69 (0.04)	0.6 (0.1)	3.4 (0.2)	326 (7)
	237	3581 (218)	60 (7)	172 (8)	120 (7)	0.70 (0.03)	0.6 (0.1)	3.3 (0.2)	326 (7)
Leck	58	2894 (401)	78 (14)	155 (11)	102 (14)	0.66 (0.07)	0.7 (0.2)	3.5 (0.2)	336 (8)
	123	3396 (304)	67 (11)	164 (11)	113 (11)	0.69 (0.04)	0.6 (0.1)	3.3 (0.2)	336 (8)
	187	3650 (239)	62 (9)	168 (12)	118 (9)	0.70 (0.03)	0.5 (0.1)	3.2 (0.2)	336 (8)
	237	3720 (227)	60 (9)	170 (12)	120 (9)	0.71 (0.02)	0.5 (0.1)	3.2 (0.2)	336 (8)

4. Discussion

4.1 Model performance

The performance of the model taking all observed points for total biomass and N-uptake into account was excellent (Table 5, Figures 3a-d) and comparable to other model evaluations (e.g.: Asseng et al., 2000). LAI was well simulated, but only few measurements from one site were available (Figure 4e).

Observed biomass growth and N-uptake before winter for both sites were in a typical range for conditions in Germany (Henke et al., 2008b) and were well simulated (Figure 4a-d). In Germany, the winter period is characterized by biomass and N-losses of oilseed rape plants due to frost. In the model, frost effects induced by critical temperature values resulting in leaves dropped at a constant rate. N-content in senesced leaves is fixed by the default model setting at 1.5 %. Biomass production during winter is reduced due to low radiation and the critical minimum temperature value of 0°C. This framework for winter conditions worked sufficiently indicated by a good match between simulated and observed biomass and N-uptake at vegetation start in spring (Figure 4a-d). Simulated LAI was 2.5 before winter and dropped to 0.5 which is a commonly observed value for winter oilseed rape at vegetation start in spring (Grosse et al., 1992) (Figure 4e).

In the period after winter when temperatures stay continuously > 0 °C, winter oilseed rape grows rapidly: Over a period of 3 to 4 weeks, it produces most of the aboveground biomass (Malagoli et al., 2005). Observed biomass increased from 1500 kg ha^{-1} at vegetation start to more than 6000 kg ha^{-1} at flowering for the 200 kg N ha^{-1} fertilisation treatment at Reinshof (Figures 4a, c). The simulation runs captured this development well for biomass and N-uptake (Table 4). LAI increased from 0.5 in early spring to 5 m m-2 at flowering for the highest N-fertiliser simulation run in Rosdorf (Figure 4e). The underestimation of the model of LAI and biomass production at flowering for the zero N-fertiliser treatment at Reinshof indicates that the model may overestimate the effect of N stress at low N-fertiliser rates when decomposing organic material was the major source of N (Figure 4a). Simulated and observed SMN contents were high in spring due to the fertiliser application (Figures 4f, g), but due to the high demand of the plant for its rapid growth, N was taken up at a very high rate. As shown in Figures 4f and g, the model captured the dynamics; however due to the fast N-uptake rate, differences of just a few days result in higher error terms (RMSE) for SMN (Table 4) as for example also observed in Asseng et al. (2000).

During grain filling, oilseed rape drops most of its leaves. This was reflected by the model in the decreasing LAI (Figure 4e). Dropped leaves were compensated by grain production in terms of total biomass of a plant. From the leaves, N was then re-translocated to the grains leading to overall decreasing N-content in the vegetative biomass in the field and in the simulation (Figures 4a-d). While the prediction of N-uptake in grains by the model was generally good, the amount of N (kg ha^{-1}) in the vegetative parts at harvest was overestimated (Figure 3d). We conclude that the N-loss via leaves dropped during the period from flowering to maturity was higher in reality than predicted by APSIM. This process needs further consideration, in particular via testing against measured N-content and total amount in the senesced leaves, when the model is used to investigate post-harvest soil N-dynamics.

Further possible improvements in model performance may be achieved by better simulating plant dormancy during the winter periods. Especially in warmer winters with temperatures > 0°C over a long period, the current setup could lead to an overestimation of total biomass production as the current model parameter will result in growth. However, we consider that this overestimation is of little consequence for total biomass and grain yield at harvest since winter oilseed rape produces most of its biomass in spring. Generally, after a comprehensive test against a wide range of data points for total biomass, grain yield, N-uptake, LAI, and SMN, the model showed excellent correlation with observed data (Table 4, Figures 3a-d). Based on these results, we concluded that it was valid to use APSIM canola for simulation experiments investigating the relationship between fertiliser application, grain yield and grain N-uptake.

4.2 Simulation experiment

The purpose of the simulation experiment was to explore soil and climate related production limitations for winter oilseed rape cultivation across northern Germany and assess how such limitations can be related to N-fertiliser rate, yield and N-balance. As presented in Figure 4, the model suggested that mean yields at all sites differed strongly with rooting depth and therefore PAWC. Furthermore, long-term mean yields under higher N-fertiliser rates (> 160 kg N ha^{-1}) were related to the average annual rainfall (Figures 1 and 5). For example, yields were highest in Leck (average rainfall 847 mm) and lowest in Magdeburg (average rainfall 510 mm). Simulated yields for these sites reflected generally the finding that winter oilseed rape yields are higher in the cooler, and high rainfall areas of far northern Germany than in more central locations with drier and warmer continental climate (Statistisches Bundesamt, 2014; Leck: 4000 kg ha-1; Magdeburg: 3500 kg ha-1; Figure 2). These observed and simulated values confirm results from Saskatchewan (Canada), where Kutscher et al. (2010) showed that district average canola yields follow precipitation patterns.

Figure 7 presents the relationship between water supply and yield, and, indeed, for most sites with the exception of Leck a good correlation (R2 > 0.62) was found. While the coefficient decreased for Bad Salzuflen and Göttingen with higher PAWC, the coefficient increased for Magdeburg. This indicates for Magdeburg that the water stress for the low PAWC was already severe before flowering (mean 0.83 at 1600 Degree-days; Figure 9) and looking only at the period from flowering to maturity might not be sufficient to explain the productivity at that site. According to the simulation results, high yielding winter oilseed rape (> 3500-4000 kg grain yield ha^{-1}) is frequently affected by water limitation, even on fertile loamy soils with some rooting depth restriction. It is acknowledged that oilseed rape has a high demand for water (Gerbens-Leenes et al., 2009), but literature, which takes water stress into account when developing fertiliser strategies for oilseed rape, is limited in Germany. Nevertheless, it is addressed in extension material (Alpmann, 2009) and is mentioned for oilseed rape for soils of low PAWC (Rathke et al. 2006). As average yields have risen now to levels where water stress can likely occur (> 3500-4000 kg ha^{-1}), the simulation experiment demonstrates the importance of taking rainfall amount and distribution as well as the PAWC of a soil into account to determine the attainable yield of a site. For the N-balance, APSIM simulations ranged from 50 to 125 kg N ha^{-1} for 180 kg N-fertiliser ha^{-1}; such variability was observed under field conditions as well (Henke et al., 2008a and b). The N-balance of 60 kg N ha^{-1} was exceeded in average at fertiliser rates of more than 160 kg N ha^{-1}. For soils of a low PAWC, this was already the case for 140 kg ha^{-1}. Nevertheless, the N-balance differed from year to years according to seasonal rainfall (Figure 8). For instance, for the 180 kg N ha^{-1} rate, the N-balance was hardly exceeded for the PAWC > 187 mm when rainfall was > 200 mm. The main difference between the sites was that in Leck more than 53 % of all seasons provided sufficient rainfall (> 200 mm) from flowering to maturity to remain below the critical threshold for the N-balance for the PAWC > 123 mm, while in Magdeburg, it occurred only in 16 % of all seasons. This shows that crop modelling using weather forecast data in spring has the potential to provide improved N-fertiliser recommendations (e.g. Asseng et al., 2012). However, in-season decision making in fertiliser rate is difficult in winter oilseed rape cultivation as the application takes place early in spring to meet the high N-demand during the juvenile phase (Rathke et al. 2006). In the future as reliability of these seasonal forecasts improves, better N-management may be possible.

While we found in the simulation experiment that N-balance was well related with the PAWC of a soil, a relationship between N-balance and sites was less obvious and needed a more integrative interpretation (Figure 6). For example, the model suggested a trend of higher yields in Leck than in Göttingen, but the N-balance was the same for both sites at high PAWCs and at the 180 kg N ha^{-1} fertiliser rate. Mean simulated N-uptake was almost the same at Göttingen (172 kg ha^{-1}) than at Leck (170 kg ha^{-1}) (Table 5). For Göttingen, the model simulated around 5-10 kg more N mineralised per hectare and per growing season (data not shown) due to higher temperatures than for Leck (Figure 2). However, in Göttingen, biomass production is more limited by water, although the overall N-uptake is similar. Thus, the N-concentration in the plant is higher in Göttingen than in Leck where mean N-concentrations in the grain (3.2%) and in the straw (0.51%) were below critical values (Tables 2 and 5). Therefore, the plant suffered from N-stress more frequently in Leck than in Göttingen. This resulted in more efficient translocation of the available N into the grains indicated by the slightly higher NHI of 0.71 to 0.70 which are typical values for winter oilseed rape in Germany (Sieling and Kage, 2010). Nevertheless, all these differences are very small. According to the model, reduction of the average N-balance in Leck would only be possible by a high soil N-mineralisation which would result into a higher yield and N-content in the grain without additional fertiliser application or by improved HI due to breeding progress. Currently, semi-dwarf varieties have been bred which are supposed to have a higher HI and should be theoretically able to reduce the N surplus. Interestingly, Sieling and Kage (2007) did not find differences to conventional varieties in terms of yield or N-utilisation over a series of field trials at one location near Kiel (northern Germany). However, crop modelling could provide a better understanding under which circumstances (weather, soil) such varieties perform better. At present, the APSIM canola model simulates HI ultimately on a fixed term (Table 4). An improvement by including the yield determining parameters (grain weight, grain numbers) in the model and how they are affected by climate and management would be needed to better capture the HI (Weymann et al., 2015).

The presented simulation experiment does, however, illustrate the complex relationship between yield, N-balance, soil depth, PAWC, temperature and precipitation. By integrating cultivar specific differences (for instance, HI and root growth (nitrogen uptake capacity) of semi-dwarf varieties) stronger into the model, such an approach could be even more effective in analysing the N-balance. Surprisingly, so far, there is limited literature on a systematic approach trying to connect the different factors (management, soil, climate, genotype) for improving the N-balance (Sieling and Kage, 2010, 2007).

5. Conclusion

We presented the first evaluation of a winter oilseed rape model for central and northern Europe, which includes simultaneous growth limitation by water and N-supply. The model evaluation showed sufficient to excellent results for biomass, N-uptake, SMN and LAI. Thus, it was used to analyse grain yield and N-balance as affected by different N-fertiliser rates at four sites in northern Germany and at four different rooting depths of a loamy soil. Simulated yield was well related with water supply from flowering to maturity at low PAWC and low rainfall sites. Such analysis helps to identify site-specific yield targets which can be reached by an appropriate fertiliser rate. We suggest such an approach complementary to field trial activities for developing site-specific management strategies, which maintain high grain yield levels and improve N-balance in winter oilseed rape cultivation.

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V. Assessing the potential for zone-specific management of cereals in low rainfall South-eastern Australia: Combining on-farm results and simulation analysis[4]

1. Introduction

The Mallee of south-eastern Australia is a major grain growing region of Australia. However it is constrained by several challenges, which might potentially exacerbate under climate change; low and erratic rainfall (annual average rainfall 250 to 350 mm) and distinctive soil types within large fields (>100 ha) reflecting the typical Dune-Swale landscape with higher elevated sandy areas and clay soils at the bottom, which leads to high variation in soil fertility, subsoil constraints and consequently plant available water capacity (PAWC) (Connor 2004). The attainable yield can differ strongly within a field and also from season to season. In certain years, low water supply can result in terminal drought, which may be accelerated by large crop biomass due to high early nitrogen (N) supply ('haying off') (Herwaarden et al. 1998; Sadras 2002) or in higher rainfall years a lack of N-supply limiting cereal yield and profit (Monjardino et al. 2013). In risky environments, farmers most often respond to these limitations by adapting a risk averse strategy with inputs well below yield maximising rates (Sadras and Rodriguez 2010; Sadras et al. 2003b). High N use efficiency (NUE) is achieved at the expense of low WUE, as attainable yield levels in good rainfall years are not reached (Sadras and Rodriguez 2010). However, water supply is not only determined by rainfall, but also by the capacity of the soil to store available water for the plants (PAWC), which is related to texture, subsoil constraints and the organic matter content. The large heterogeneity in PAWC due to texture and subsoil constraints, as high salt concentration, across one field causes large variability in the attainable yield of a certain season. In particular, in such an environment, dividing the field into different zones according to PAWC, soil fertility and texture and matching input to the attainable yield of that zone appears to be a promising strategy to increase the resource use efficiency and profitability of farming (Oliver and Robertson 2013; Rab et al. 2009). Several methods to define attainable yield have been developed.In southern Australia the attainable yield is often estimated by using the French & Schultz (1984) boundary function, where yield is result of in-season rainfall minus a fixed evaporation of 110 mm, which is multiplied by a transpiration efficiency factor of 20 kg/mm/ha. Sadras and Angus (2006) modified this equation suggesting an evaporation term of 60 mm and a transpiration efficiency of 22 kg/mm/ha. However, such simple linear rainfall-

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yield relationship cannot address yield differences caused by soil variability. Zoning the field into high performing and low performing patches is challenging, as usually such information is based on just a few years of yield results and are restricted to the specific grown crop, so that patterns in seasonal variability in yield in this region is not captured. Closely linked to this point, this method does not provide much explanation about the complex interaction between water supply and N-application and the final determination of yield. Therefore, decisions on fertiliser application based only on this information are difficult to make (Lawes et al. 2009a and b). Long-term field trials on experimental sites, which would help exploring the attainable yield dynamics of certain zones, are rarely conducted due to labour and financial constraints.

Another method that has developed into a commercially offered service over the past decade is electromagnetic soil mapping (EM38). EM38 measures the apparent electrical conductivity (ECa), which is correlated to soil water, texture and salt concentrations. Although found to be effective in the Mallee landscape (Llewellyn et al. 2008), such soil properties can be difficult to relate to yield performance in many situations (Rab et al. 2009).

Conducting simulation experiments with validated process-based crop models can help to address many of the above limitations by analysing yield variability and its driving factors over multiple seasons for such zones. Monjardino et al. (2013) suggest, based on combining crop simulation knowledge of the variation in PAWC and economic analysis for one site in the Mallee (Karoonda), that a higher economic return is possible by using higher N-fertiliser rates for sandy soils than what are typically used by farmers - this assumes that other abiotic and biotic stresses are minimised. Wong and Asseng (2006) also used crop modelling to analyse the long-term agronomical performance of EM38 soil zones in western Australia. They concluded that under non-constrained soil types the PAWC is positively correlated to yield. Rainfall (annual average 327 mm) in their study site at edge of the wheat cropping belt of West Australia is concentrated (75 to 86 percent) in the growing period from April to October. While the total rainfall is similar, the share of precipitation in the April to October period is less pronounced (60-65 percent) in the Mallee.

While mechanistic crop models have been shown useful to define site-specific attainable yields, it is necessary to test these models for such constrained soils in the low-rainfall Mallee. In this environment a high sensitivity of APSIM to the characterisation of the soil water parameter, namely first and second stage evaporation can be expected (Hunt and Kierkegaard, 2011).

A range of simple versus more complex zoning methods are used in the Mallee environment that usually result in zones largely based on dune, mid-slop and swale soils (Robertson et al. 2013). It is not the intended purpose of this study to test zoning methods but instead examine the approach to better understanding differences in zone behaviour and their management. Against this background we used crop simulation modelling to analyse the seasonal-spatial dynamic nature of the attainable yield at five farmer fields characterised by the swale-dune system in the Mallee. Thereby, we explore whether it is possible to identify simple linear yield relationship (such as PAWC-yield or In-season rainfall-Yield) for establishing zones in the region or whether more sophisticated soil considerations such as those included in the crop simulation models are of value. To achieve this we went through following steps:
(i) describe the chemical and physical soil properties of the swale, mid-slope and dunes at five sites and how they define PAWC; (ii) setup the crop model APSIM for these zones, (iii) evaluate simulated crop yield against observed; and (iv) finally using a simulation experiment with historical weather data to explore the factors determining the yield variability and potential zoning.

2. Material and methods

2.1 Sites

Four fields from commercial farming operations, in the Victorian and South Australian Mallee were selected for an EM38 survey, which was conducted before sowing in 2006; these included Bimbie (34°27’ S, 142°58’ E), Carwarp (34°27’ S, 142°12’ E), Pinnaroo (35°20’ S, 140°54’ E) and Loxton (34°29’ S, 140°34’ E). In 2007 an additional site at Cowangie (35°13’ S, 141°23’ E) was also surveyed and included in this study. The EM38 surveys were repeated in 2007 for the original 4 sites. Annual average rainfall is 311 (Bimbie), 290 (Carwarp), 319 (Cowangie), 274 (Loxton) and 337 mm (Pinnaroo). The larger share of the rainfall is between April and October, which covers most of the growing season (Bimbie 189; Carwarp 175; Cowangie 206; Loxton 171; Pinnaroo 219 mm). Average daily temperature is similar at all sites and highest in January (24.3-22.7°C) and lowest in July (9.6-9.9°C).

2.2 Soil sampling and zoning

Based on an EM38 survey, Llewellyn et al. (2008) presented a zoning of one farmer field at each above mentioned site. They could show that these EM38 defined zones are constant over seasons (measurements 2005-2007) and reflect the typical landscape of dune-swales. This allows differentiating the field into three zones: dune, mid-slope and swale. For soil samples collected prior to sowing (April 2006) at Bimbie, Carwarp, Loxton and Pinnaroo, soil chemical and textural analysis was undertaken. Samples (n=9) were collected using a stratified transect sampling pattern across each field to a depth of 110 cm (0-20, 20-40, 40-60, 60-80 and 80-110 cm horizons) and averaged according to the subsequent zoning based on the EM38 surveys. In 2007 only one sample was taken from the site in Cowangie to a depth of 110 cm for each zone. All samples were analysed as follows: organic carbon (OC) was analysed using the combustion method after a pre-treatment with dilute acid to remove inorganic carbon. Soil pH was measured in a 1:5 soil/0.01 M CaCl2 suspension and EC 1:5 was measured in a 1:5 soil/water suspension (Rayment and Higginson 1992). B was determined using 0.01M CaCl2 extracting solution and immersion in a 98°C water bath (Rayment and Higginson 1992). Chloride (Cl) was measured in a 1:5 soil:water extract. Exchangeable sodium percentage was calculated following measurement of cation exchange capacity using 0.1 M ammonium Cl with 0.1 M barium Cl extractant (method 15E1) outlined in Rayment and Lyons (2011). Soil samples were further analyzed for Colwell extractable phosphorus (P) and extractable sulphur (S) using 0.25 M potassium Cl at 40°C (Rayment and Lyons 2011). Soil textural analysis of proportions of sand, silt and clay were determined using the pipette method, after sieving to remove gravel as described in USDA (1982).

PAWC of each zone was characterised by drained upper limit (DUL), crop lower limit (CLL) and rooting depth. DUL was determined at a point within each zone using the techniques described by Dalgliesh and Foale (1998). CLL was determined for each zone using the lowest soil moisture values measured at the harvest of wheat crops in 2006 (nine cores across the three soil classes) and in 2007 (27 cores across the three soil classes). Soil OC, initial soil mineral N content and water content were measured prior to sowing in 2006 and 2007.

2.3 Management and harvest

Since these experimental sites were all part of commercial farming operations, all sowing and management was undertaken by the farmer. Wheat (cvv. Janz and Yitpi) and barley (cv. Sloop) were sown in April/ May along with the typical application of starter fertiliser (N 5-20 kg/ha; P 7-16 kg/ha). In 2006 soil mineral N at sowing was lower in the dune zones followed by the mid-slope in Bimbie (0-90 cm 15 kg/ha dune, 23 kg/ha mid-slope, 80 kg/ha swale), Carwarp (0-90 cm 45 kg/ha dune, 75 kg/ha mid-slope, 80 kg/ha swale), and Loxton (0-90 cm 34 kg/ha dune, 45 kg/ha mid-slope, 57 kg/ha swale) than in the swale systems. In Pinnaroo, the results were opposite (0-90 cm 64 kg/ha dune, 41 kg/ha mid-slope, 39 kg/ha swale). In 2007 the same pattern was found again: Bimbie (0-90 cm 18 kg/ha dune, 32 kg/ha mid-slope, 85 kg/ha swale) , Carwarp (0-90 cm 57 kg/ha dune, 98 kg/ha mid-slope, 105 kg/ha swale), and Loxton (0-90 cm 35 kg/ha dune, 56 kg/ha mid-slope, 78 kg/ha swale). Similar results were observed for Cowangie (0-90 cm 25 kg/ha dune, 57 kg/ha mid-slope, 55 kg/ha swale). In Pinnaroo again it was different (0-90 cm 44 kg/ha dune, 43 kg/ha mid-slope, 38 kg/ha swale). The harvest was done for the entire field using a commercial combine header fitted with a yield monitor. Yield data was extracted from a 50-100 m sweep for the locations within the field where soil sampling had been undertaken. All yield data is represented as dry weight calculated from harvested grain weight and assumed to be at 10 percent moisture content.

2.4 APSIM parameterization and validation

APSIM is a widely used farming system model that simulates crop growth and development upon incoming radiation limited by temperature stress, water supply and N availability (Keating et al. 2003). Management decisions such as sowing date, fertiliser application, etc. can be specified in a manager module. APSIM (version 7.5r3008) was configured with the wheat and barley module, the soil water module SOILWAT, and the soil N module SOILN, Surface OM and Manager. APSIM was widely tested in Australia. For the Mallee region evaluation can be found in Hochman et al. (2009), Hunt et al. (2013) and Yunusa et al. (2004). Every site and soil zone was represented by an individual soil file to represent the soil chemical (Table 1) and physical characteristics (Figure 2). Potential rooting depth was assumed to be 140 cm across all sites and zones. Sub-soil constraints were taken into account by using the measured CLL value. Runoff is based on the USDA-Soil Conservation Service procedure known as the curve number technique and the values used reflected the effect of texture (Sand and Loam = 68; Clay = 73). Potential evapotranspiration (Priestley and Taylor) is calculated using an equilibrium evaporation concept: Soil evaporation is assumed to take place in two stages: the constant (U), or first stage and the falling rate (Cona) or second stage. Cona and U are considered to be soil specific (Ritchie et al. 2009) and therefore the values were defined according to texture similar to Hunt and Kirkegaard (2011). If the top layer was clay, U was set to 6. For loamy and sandy top layers this value was set to 4. If clay occurred in the next layer up to 40 cm, the value was set to 3.5, otherwise to 2 (Table 1). Flow between adjacent layers under unsaturated conditions is defined by two parameters (diffusivity constant, diffusivity slope), which were parameterised following standard practice according to soil texture (Diffusivity constant: Sand 250; Loam 88; Clay 40; Diffusivity slope: Sand 22; Loam: 40; Clay 16).

When water content in any layer is below SAT but above DUL (saturated water flow), a fraction of the water drains to the next deepest layer each day, which is described by the SWCON value in APSIM, which is set according to texture (Sand 0.7; Loam 0.5; Clay 0.3). Measured OC levels were used to parameterise the model. The amount of inert OC fraction (Finert) for each layer followed the convention set by Probert et al. (1998) where soil OC concentration in the deeper layers is assumed to be inactive and also represents the quantity of Finert in all layers.

Finally, for every sampled point a simulation run (in total 135 simulation) was carried out based on measured initial soil N and water content. Soil OC and hydrological soil characterisation for each simulation setup was used zone-specifically (3 zones at each site) (Figure 2). Management decisions such as sowing date, cultivar choice etc. were the same for each simulation run within one site (see section 2.3).

2.5 Analysis

Observed yields and predicted yields (based on dry matter) for every core were grouped according to the zone (low, moderate or severe) they were located. Averages of the cores located within these zones are presented. To assess the goodness of fit of these simulated - measured comparisons the root mean square error (RMSE) between predicted and observed data was calculated as follows:

$\mathrm{RMSE} = [(\Sigma\ (O - P)2/n)]0.5$

where O and P are the paired observed and predicted data and n is the total number of observations. Additionally, for comparison, the traditional r2 regression statistic (least-squares coefficient of determination) forced through the origin was calculated.

2.6 Simulation experiment

To explore the response of the different zones to N-fertiliser and a simulation experiment was conducted: For every site and soil zone (5 sites x 3 site-specific soil types), long-term simulations were devised using historical weather data (01/01/1959 to 31/12/2012) with different N-rates (0, 15, 30, 60, 120 kg/ha) applied at sowing. Wheat sowing was triggered by first rainfall within the time from 20th April to 10th July. The common wheat cultivar Yitpi was planted at a density of 150 plants/m2. Surface organic matter and initial mineral N (25 kg/ha) was reset annually on April 1st. After initialisation soil water was not reset to allow fallow rainfall (Nov-April) to influence winter grown crops. The first three simulated years (1959-1962) were discarded to avoid errors by set initial water content in the first year of simulation. Historical climate data for the period were obtained from the Silo Patched Point Data Set (http://www.bom.gov.au/silo).

3. Results

3.1 Soil profiles

The landscape pattern of the Mallee was reflected in the physical (soil texture and CLL), and soil chemical properties (OC, S, ESP, electric conductivity, B, Cl) (Table 1, Figure 1 and 2) with swale, mid-slope and dune. There was a dominant trend that the dunes zones had a relatively high proportion of sand, while the swale zones had a higher clay proportion (Figure 2). However, across zones and sites, available P concentration ranged from 22-41 mg/kg, indicating adequate to high P availability as a result of many years' fertiliser application, and high exchangeable K (208-409 mg/kg). For available S differences between zones were observed; for the dunes, S was below 6 mg/kg, which is the defined critical concentration in the soil, at all sites and almost all soil horizons. Only in Bimbie and Pinnaroo, higher values of 10-12 could be found in the soil layer below 60 cm. For the mid-slope zones only Cowangie and Loxton had values below the critical threshold. The swale zones had a low S content of 4-6 mg/kg in the top soil, but in the layers below values of 96-233 mg/kg. Only in Cowangie again the swale zone had low S values of 4-12 mg/kg across soil layers. Similar to available S, the lowest values for OC were found in the dunes (range 0.71 to 0.86 %, Figure 2) while the mid-slope zones ranged from 0.82 to 1.15% and the swale zones had the highest OC content from 1.08 to 1.3 %. Soil pH CaCl2 was 7.5 to 8.6 across sites and zones. Soil pH measured in water is about 10-12% higher than the pH measured in CaCl2, but shows the same pattern. Cation exchange capacity (CEC) followed the trend of OC and S, lowest in the dune (across sites and soil horizons: 13 meq/100g), medium in the mid-slope (17 meq/100g) and highest in the swale zone (24 meq/100g). For sodicity of the soil, expressed here as exchangeable sodium percentage (ESP), there was again the trend that ESP was low in the dune zones, and highest in the swale zone. However, large differences between sites existed; The dune zone in Loxton, Cowangie and also Carwarp could be classified as non sodic soils, even in the subsoil, in Bimbie and Loxton this zone was already moderately sodic in the upper layers, while very strongly sodic in the subsoil (Table 1). The mid-slope zone only in Bimbie (2-43%), Carwarp (1-36%) and Pinnaroo (13-37%) could be classified as very strongly sodic, while the swale zone, at least in the subsoil, was very strongly sodic, across sites. EC 1:5, Cl and B were higher in the swale, fine textured soils. Largest B (3.2-29.7 mg/kg) and Cl (33-499 mg/kg) accumulations were found in the swale zone in Pinnaroo, the highest ECa (0.7-1.4 dS/m) in Bimbie. Cowangie was affected to a lesser extent by these constraints in comparison to the other sites. For EC1:5 values above 0.4 dS/m, for B 10-14 mg/kg and for Cl 1000 mg/kg, constraints in terms of crop water uptake could be expected. A good relationship between these parameters and the crop lower limit had been found (Figure 1a-d) indicating higher CLL with increasing subsoil constraints.

Table1: Chemical soil properties of the dune, mid-slope and swale constrained soil zones sampled 2006/2007 near sowing for (a) Bimbie, (b) Carwarp, (c) Cowangie, (d) Loxton and (e) Pinnaroo. For the surface layers, averages are presented from at least 4 cores falling in the specific zone. Characterization of layers below based on 1- 9 core sample. Standard error of the mean was calculated if possible and presented in brackets.

		Zone (determined by EM38 measurements)											
		Dune				Mid-slope				Swale			
	Depth	ESP %	Conduc dS/m	Boron mg/kg	Cl mg/kg	ESP %	Conduc dS/m	Boron mg/kg	Cl mg/kg	ESP %	Conduc dS/m	Boron mg/kg	Cl mg/kg
Bimbie	20	1 (0)	0.0 (0.02	0.7 (0.1)	11 (2)	2 (1)	0.1 (0.01	0.6 (0.0)	6 (1)	21 (5)	0.7 (0.22	1.7 (0.1)	793 (285)
	40	11 (5)	0.1 (0.01	1.5 (0.0)	12 (2)	13 (3)	0.3 (0.07	2.7 (0.7)	130 (90)	36 (1)	1.3 (0.17	9.6 (0.4)	1441 (216)
	60	22 (5)	0.3 (0.05	7.0 (1.8)	27 (7)	26 (5)	0.4 (0.08	10.3 (2.6)	175 (75)	43 (1)	1.5 (0.09	14.2 (1.8)	1405 (178)
	80	31 (3)	0.4 (0.04	12.3 (2.2)	50 (15)	37 (3)	0.6 (0.04	18.3 (2.6)	244 (61)	49 (1)	1.4 (0.11	18.4 (1.9)	1508 (146)
	110	34 (0)	0.5 (0.01	12.5 (0.5)	94 (2)	43 (4)	0.7 (0.06	20.0 (1.4)	340 (58)	53 (0)	1.4 (0.12	20.3 (1.6)	1645 (161)
Carwarp	20	0 (0)	0.1 (0.01	0.7 (0.1)	7 (2)	1	0.1	1.0	16	9 (3)	0.5 (0.22	1.8 (0.4)	440 (220)
	40	2 (1)	0.1 (0.00	1.0 (0.1)	8 (1)	4	0.1	1.8	20	30 (1)	0.9 (0.05	6.9 (0.8)	874 (58)
	60	6 (3)	0.2 (0.03	3.0 (1.2)	17 (8)	19	0.4	6.6	66	37 (0)	1.1 (0.10	10.7 (1.1)	1046 (131)
	80	14 (6)	0.2 (0.06	5.5 (2.3)	31 15)	31	0.5	13.3	63	41 (1)	1.1 (0.13	13.8 (0.4)	1065 (108)
	110	20 (6)	0.3 (0.06	6.3 (1.8)	26 (10)	36	0.5	16.7	75	43 (2)	1.2 (0.09	14.6 (1.9)	1027 (108)
Cowangie	20	1	0.1	0.6	9	1	0.1	1.0	5	6	0.2	0.9	8
	40	1	0.1	0.7	4	1	0.1	1.3	19	11	0.2	1.1	10
	60	1	0.1	0.9	3	3	0.1	2.1	12	18	0.3	2.8	99
	80	1	0.1	0.8	3	12	0.2	8.7	46	29	0.8	13.1	790
	110	1	0.1	0.7	2	22	0.4	16.7	91	37	1.0	20.8	1456
Loxton	20	1 (0)	0.0 (0.02	0.4 (0.0)	6 (1)	0 (0)	0.1 (0.01	0.5 (0.1)	6 (0)	1 (0)	0.1 (0.00	0.9 (0.0)	6 (0)
	40	1 (0)	0.1 (0.00	0.6 (0.1)	5 (1)	1 (0)	0.1 (0.01	0.9 (0.1)	5 (1)	8 (4)	0.2 (0.05	2.1 (0.4)	34 (19)
	60	0 (0)	0.1 (0.00	0.6 (0.0)	5 (0)	2 (1)	0.1 (0.01	1.4 (0.3)	6 (1)	29 (7)	0.6 (0.21	12.1 (4.9)	367 (115)
	80	1 (0)	0.1 (0.00	0.6 (0.0)	4 (1)	5 (3)	0.1 (0.05	3.4 (1.9)	9 (3)	39 (3)	1.0 (0.21	13.6 (6.5)	785 (268)
	110	1 (0)	0.1 (0.00	0.7 (0.1)	3 (0)	12 (6)	0.2 (0.08	5.9 (4.1)	25 (18)	41 (3)	1.1 (0.21	18.9 (0.8)	993 (295)
Pinnaroo	20	15 (4)	0.2 (0.01	1.8 (0.3)	73 (0)	13 (4)	0.2 (0.05	1.7 (0.6)	75 (31)	3 (1)	0.2 (0.03	3.2 (0.8)	33 (8)
	40	25 (5)	0.4 (0.07	12.0 (1.2)	69 (2)	23 (6)	0.5 (0.12	10.9 (3.2)	207 (84)	17 (4)	0.5 (0.10	13.2 (5.3)	240 (56)
	60	29 (5	0.5 (0.04	16.1 (0.3)	83 (16)	30 (8)	0.7 (0.17	20.2 (5.6)	259 (109)	32 (3)	0.7 (0.06	23.6 (5.3)	375 (26)
	80	31 (2)	0.5 (0.06	13.5 (0.1)	78 (21)	31 (6)	0.7 (0.18	17.6 (3.8)	334 (140)	40 (1	0.8 (0.02	28.6 (1.9)	456 (37)
	110	38 (0)	0.5 (0.00	14.3 (0.0)	124 (49)	37 (5)	0.8 (0.14	16.0 (1.0)	393 (170)	42 (1)	0.9 (0.02	29.7 (1.7)	499 (29)

The overall and the top layer PAWC was largest at the five sites in the swale, followed by mid-slope and smallest in the dune zones (Figure 2). Although CLL is higher in the swale zones in comparison with the mid-slope and the dune zones, the DUL of this zone type was also substantially higher, which led to the overall high PAWC. Despite this general pattern, the absolute PAWC for each zone type differs from site to site. For instance, the low constrained zone in Loxton had a PAWC of 72 mm, while the low constrained zone of Cowangie had a PAWC of 134 mm. To sum up, across sites soil sampling showed a pattern of increasing OC, PAWC and subsoil constraints from the dune zones to the swale.

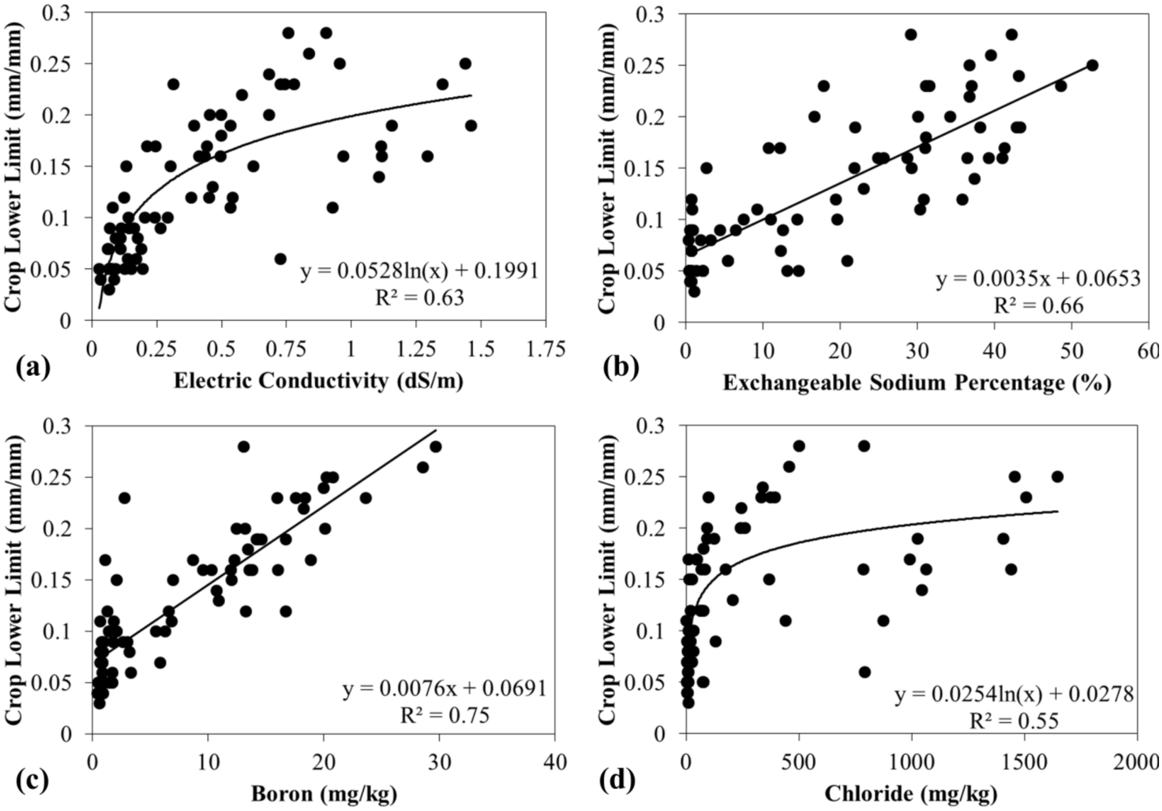

Figure 1: Relationship between measured Crop lower limit and soil chemical properties (a) Electric conductivity, (b) Exchangeable Sodium Percentage, (c) Boron and (d) Chloride.

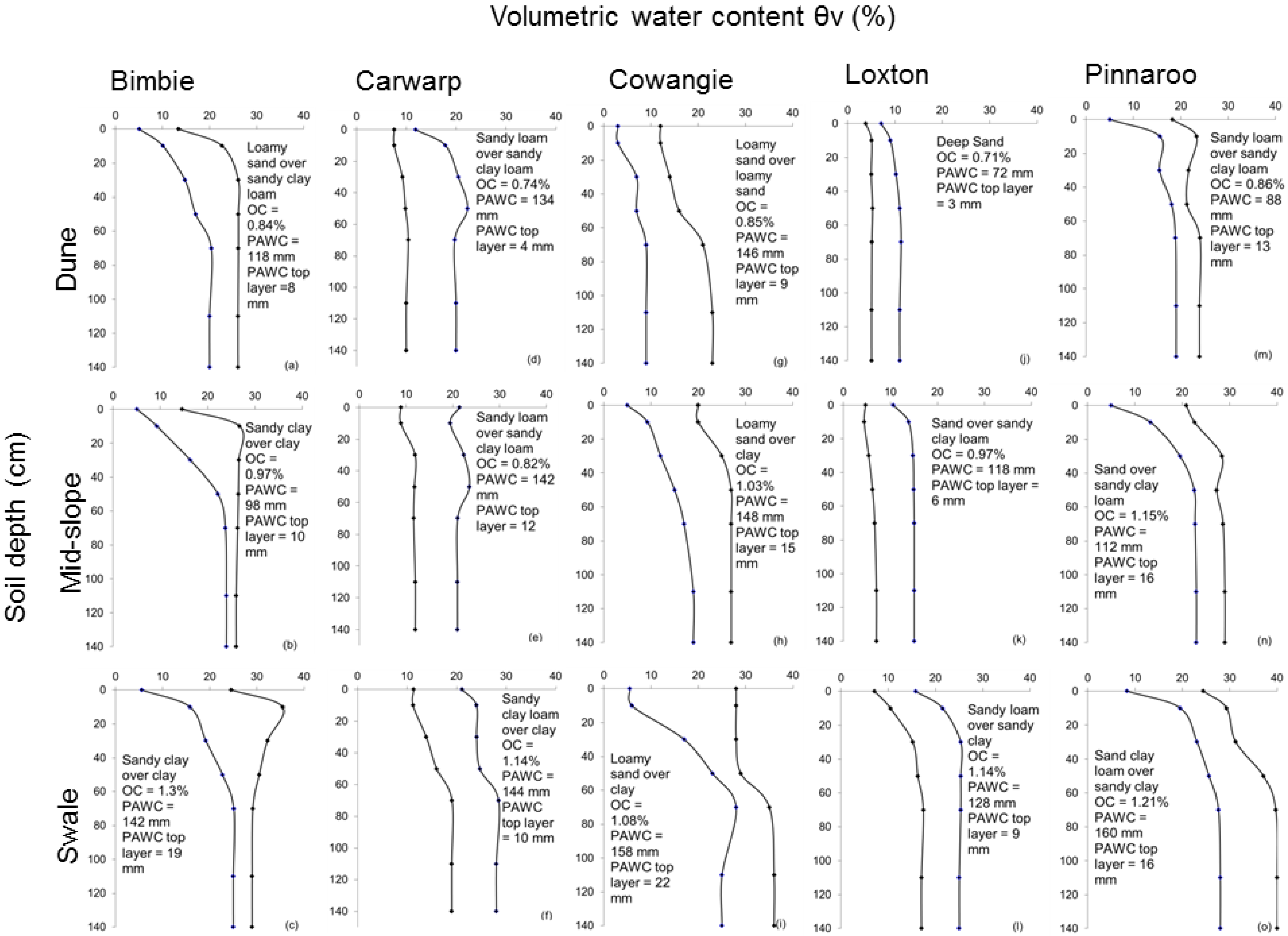

Figure 2: Plant available plant capacity profiles until a depth of 140 cm plus soil texture and organic carbon (OC) in the top soil as measured for the different zones and sites.

3.2 Observed yield performance of the zones and APSIM validation

In-crop rainfall in 2006 ranged between 78-107 mm representing a season in the lowest deciles of historical seasonal rainfall and consequently resulting in grain yields of almost zero in the swale zone at Carwarp and 849 kg/ha in the dune zone at Pinnaroo (Figure 3). In-crop rainfall in 2007 was relatively better ranging between 117-180 mm with yields ranging from 410 kg/ha (low constrained zone Loxton) to 1986 kg/ha (severely constrained zone Cowangie) (Figure 3). Extractible soil water at sowing (esw-sowing) was lower in 2006 (range 15-61 mm) than in 2007 (range 42-160 mm). In 2006 the yield decreases in all sites from the dunes to swales. In 2007, for Bimbie and Carwarp this trend can again be observed, however, in Loxton and Pinnaroo the mid-slope zones and in Cowangie the swale zone were highest yielding. A good relationship was found for observed yields and the corresponding water supply (which includes in-crop rainfall plus soil water at sowing) for the moderate and severe zone (r2: 0.68 and 0.67) across sites (Figure 4). As shown in Figure 4 yields were higher for the dune zone under low water supply. Yields for the mid-slope and swale zones with a water supply of less than 150 mm were below 500 kg/ha. However, when water supply was above 300 mm, yield reaches levels of more than 1000 kg/ha.

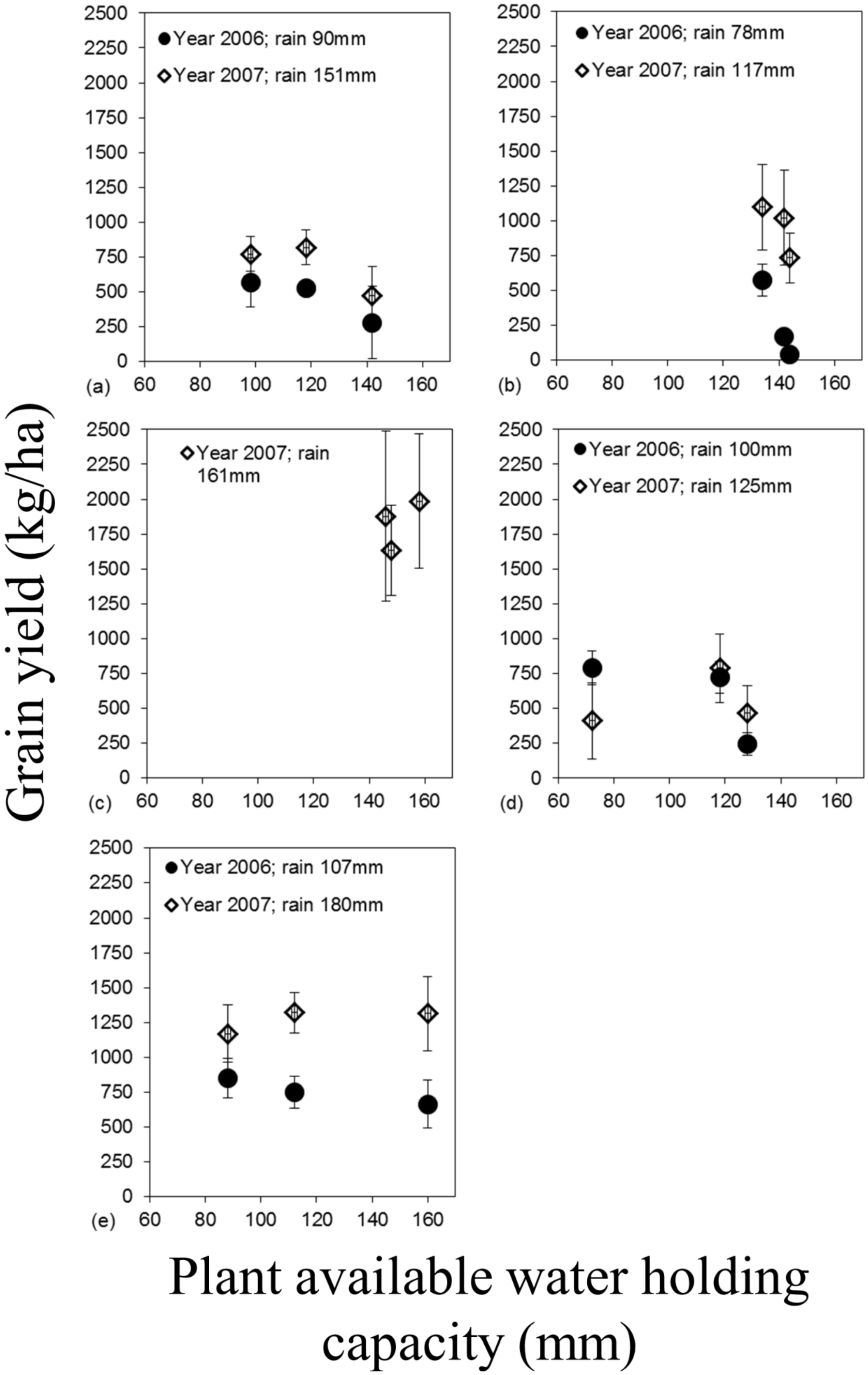

Figure 3: Observed dry grain yield in relation to the PAWC for the five study sites for the years 2006 and 2007. Rain is growing season rainfall.

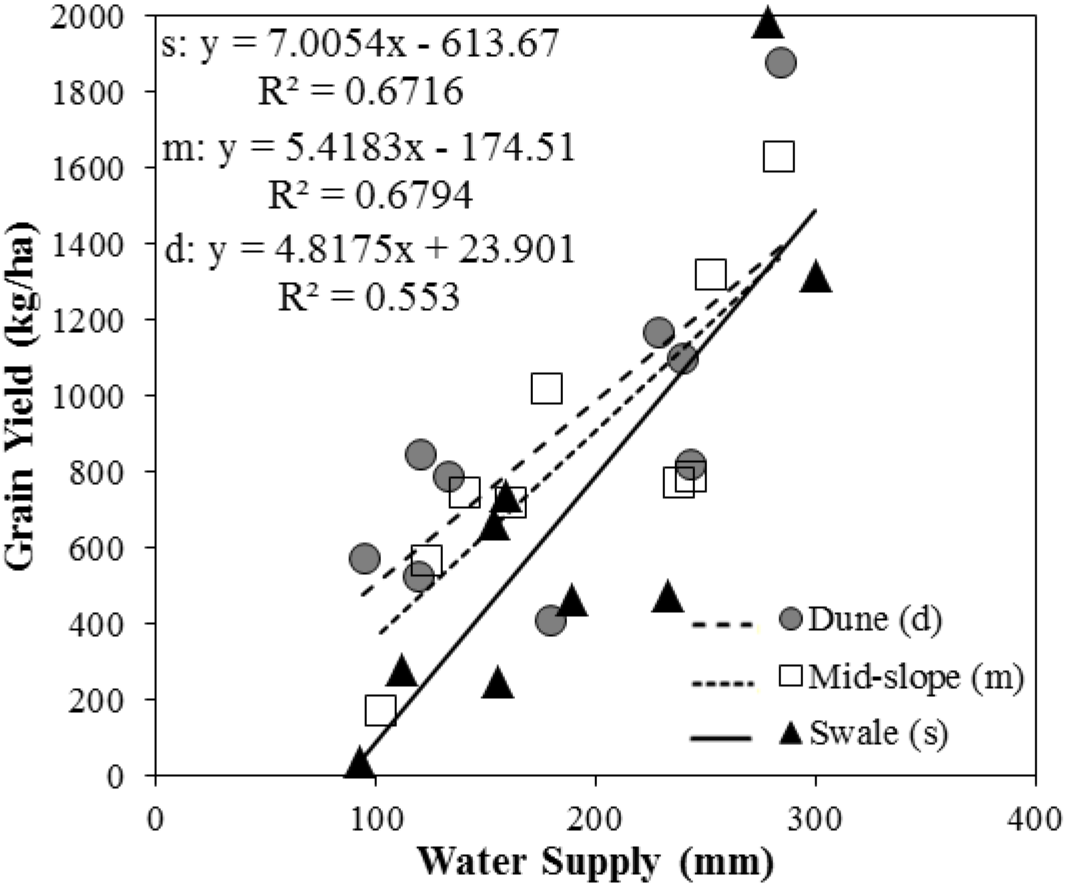

Figure 4: Water supply (extractible soil water at sowing plus in-crop rainfall) vs. observed yield (years 2006/2007) for the zones across sites.

The prediction of grain yield compared with observed yields (n = 26) is considered good with a RSME of 320 kg/ha against an observed mean of 820 kg/ha (Figure 5). Observed yields ranged from 38 to 1986 kg/ha, which is reflected in the simulation results (Figure 1; r2 = 0.71). As expected with a model that does not account for other biological constraints such as weeds and disease, the model predicted slightly higher yield levels than those observed.

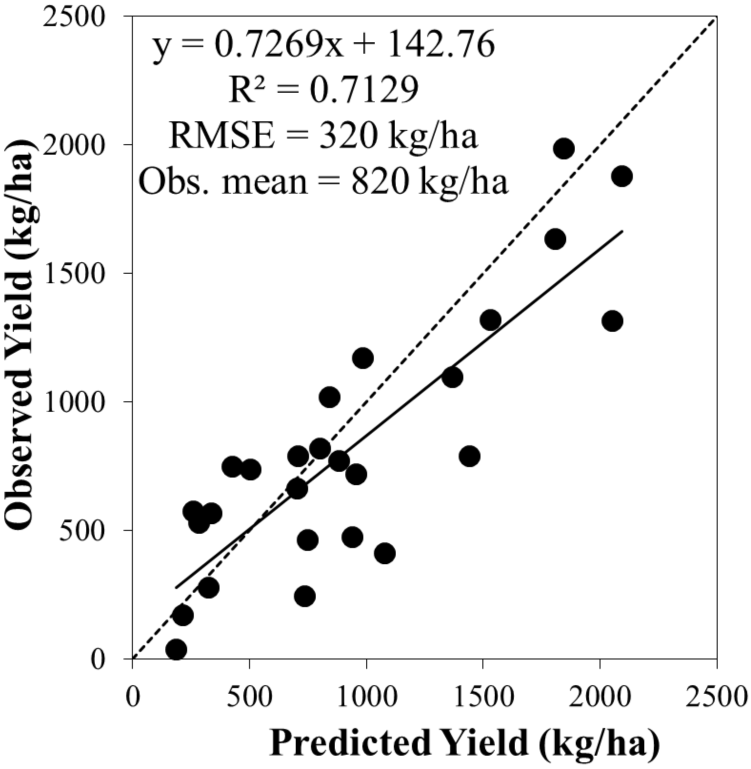

Figure 5: Predicted vs. observed grain yield. Dotted line represents the 1:1 line.

3.3 Simulation experiments

In the simulation experiment across all sites, mean yields when no N-fertilisers were applied were highest in the mid-slope zones, followed by the swale zone, and lowest in the dune zone (Table 2). However, the swale zones had greater amplitude of possible yields indicating a higher risk, followed by the mid-slope zones. In the dune zones yields were relatively stable across seasons for low fertiliser application rates.

Overall, no relationship between PAWC and yield could be detected. In Loxton for instance the dune zone had a low PAWC of 72 mm but had still high average l yield of 1916 kg/ha at 120 kg N/ha. Contrary, in Pinnaroo the swale zone with a PAWC of 160 mm yielded only 1612 kg/ha at the same N-rate (Table 2).

Generally, all dune zones showed the strongest mean response to the 30 kg/ha N-application taking all years of simulation into account. The response to N was progressively lower at higher N-application rates. However, the coefficient of variance increased as well, indicating a stronger variability in grain yield from season to season even for the dune zones. Yield at 120 kg/ha N-rate was generally the highest in the dune zones followed by the mid-slope and then by the swale zone (Table 2).

Table 2: Simulated mean yield and coefficient of variance (Standard deviation/mean) for different soil zones (constraint D =dune; M=mid-slopee; S=swale) at 5 Sites in the Mallee in response to different N-rates based on APSIM runs from (1916-2012; 94 years).

	Site	Constraint	Fertiliser rates (kg N ha^{-1})									
			0		15		30		60		120	
grain yield (kg ha^{-1})	Bimbie	D	456	(0.19)	723	(0.27)	991	(0.37)	1349	(0.50)	1717	(0.66)
		M	938	(0.43)	1102	(0.49)	1238	(0.56)	1434	(0.64)	1655	(0.75)
		S	723	(0.64)	871	(0.71)	977	(0.75)	1082	(0.85)	1189	(0.96)
	Carwarp	D	582	(0.11)	900	(0.19)	1182	(0.27)	1602	(0.40)	1979	(0.56)
		M	1417	(1.01)	1433	(1.01)	1441	(1.02)	1448	(1.01)	1443	(1.01)
		S	1041	(1.08)	1054	(1.08)	1064	(1.09)	1071	(1.09)	1071	(1.10)
	Cowangie	D	997	(0.11)	1315	(0.13)	1621	(0.18)	2103	(0.29)	2652	(0.43)
		M	1839	(0.24)	2063	(0.30)	2163	(0.36)	2365	(0.42)	2664	(0.52)
		S	1332	(0.45)	1492	(0.52)	1551	(0.60)	1666	(0.69)	1949	(0.77)
	Loxton	D	462	(0.19)	784	(0.22)	1097	(0.25)	1524	(0.35)	1916	(0.46)
		M	1052	(0.45)	1204	(0.51)	1301	(0.54)	1422	(0.60)	1528	(0.69)
		S	684	(0.59)	814	(0.66)	920	(0.72)	1032	(0.80)	1096	(0.92)
	Pinaroo	D	516	(0.21)	791	(0.27)	1073	(0.34)	1471	(0.49)	1831	(0.62)
		M	1206	(0.47)	1420	(0.52)	1548	(0.57)	1719	(0.64)	1956	(0.72)
		S	958	(0.51)	1181	(0.56)	1288	(0.65)	1434	(0.76)	1612	(0.86)

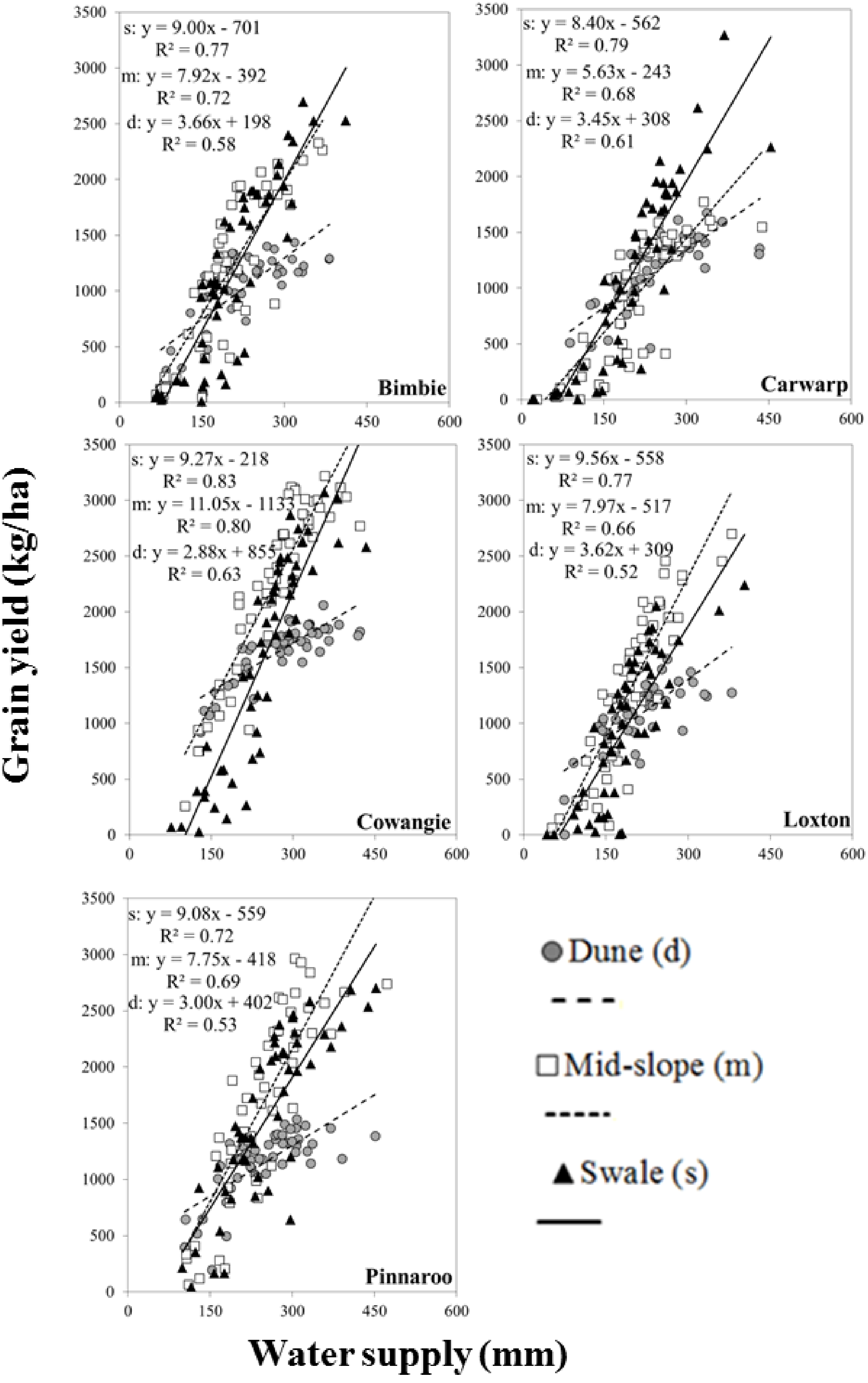

Figure 6: Water supply (extractible soil water at sowing plus in-crop rainfall) vs. simulated mean grain yield (years 1963-2012). The crop was annually fertilized with 30 kg N /ha.

Comparing the simulated yields at 30 kg N/ha versus water supply (the sum of esw-sowing at sowing plus in-crop rainfall) showed a good relationship for the swale zone across sites (Figure 6). Yields were lower than at the dune zone with water supply being less than 200 mm. For such a low water supply the dune zone was generally superior in terms of yield performance than the other zone types. However, with higher water supply when N becomes more limiting, yield at the dune zone remained at around 1500 kg/ha, only in Cowangie did yield reach 2000 kg/ha on the dune. Yields for the mid-slope and swale where there is greater soil N supply reached levels of 3000 kg/ha with a water supply of above 300 mm.

Esw-sowing for the 30 kg N ha-1 rate increased with higher summer rainfall (Figure 9). It was highest in the dune zone followed by the mid-slope zone and lowest at the swale zone for in-fallow rainfall to 200 mm. In case of high summer rainfall (>200 mm) the mid-slope and the swale zones contain more water at sowing. In-fallow soil evaporation was by far the most important source of water loss from the system at low rainfall seasons (< 200 mm) (Figure 7a). For instance, for 100 mm of rainfall there was a mean evaporation of 60-90 mm across sites and soil zones. Generally, in the dune zone, the evaporation was lower than in the other zone types. However, at high rainfall the importance of soil evaporation was reduced in relation to the remaining esw-sowing and drainage and runoff become more important (Figure 8). In particular, in the dune zone the amount of rainfall could exceed the relatively low PAWC.

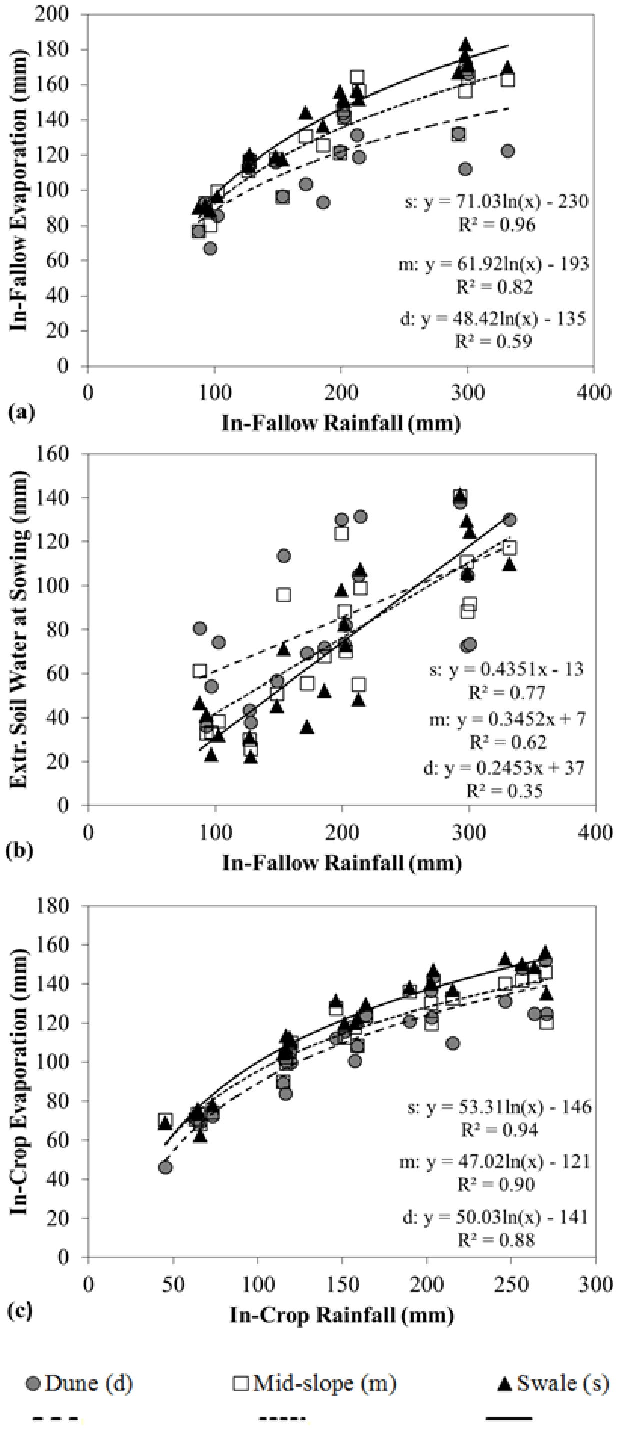

Figure 7: Relationship between (a) in-fallow rainfall and simulated in-fallow evaporation, (b) in-fallow rainfall and simulated extractible soil water at sowing, and (c) in-crop rainfall and simulated in-crop evaporation for each zone averaged across sites. Simulation based on the years 1963-2012 and an annual fertilizer application of 30 kg N/ha. Simulated data is presented as mean average for in-fallow rainfall, respectively in-crop rainfall <100, <150, <200, >200mm. The crop was annually fertilized with 30 kg N ha^{-1}.

Mean evaporation during crop growth (in-crop-es) across soil zones was highest in Pinnaroo (140 mm), Bimbie (121 mm) and Cowangie (120 mm) followed by Carwarp (113 mm) and Loxton (109 mm) (Table 3). When in-crop-es was grouped according to in-season rainfall, the comparison of the means showed strong differences between seasons (Figure 7c). Evaporation terms increased from roughly 60 mm across zones and sites when there was less than 100 mm in-season rain to more than 150 mm when there was more than 250 mm rain. However, the ratio between in-crop-es and in-crop rainfall declined with increasing rainfall (Figure 7c). The zone-specific in-crop-es differs from site to site; while in Loxton and Carwarp in-season es was on average lowest in the low constrained zone, it was lowest in Bimbie, Cowangie and Pinnaroo for the mid-slope zone (Table 3). However, highest in-crop-es was simulated for the swale zone, which was also reflected in the relationship between in-crop rainfall and in-crop evaporation (Figure 7c).

Table 3: Simulated in-season evaporation and coefficient of variance (Standard deviation/mean) for different soil zones (constraint D =dune; M=mid-slope; S=swale) at 5 Sites in the Mallee in response to fallow rain based on APSIM runs. The crop was annually fertilized with 30 kg N ha^{-1}.

	Site	Constraint	in-season rainfall (mm)				
			< 100	< 150	< 200	< 250	>250
(mm)	Bimbie	D	66 (0.29)	103 (0.14)	120 (0.14)	137 (0.14)	155 (0.15)
		M	64 (0.32)	102 (0.14)	116 (0.13)	131 (0.13)	147 (0.14)
		S	67 (0.33)	109 (0.14)	125 (0.13)	142 (0.14)	156 (0.14)
	Carwarp	D	66 (0.15)	96 (0.14)	109 (0.11)	122 (0.14)	136 (0.11)
		M	61 (0.42)	103 (0.13)	126 (0.11)	138 (0.15)	154 (0.15)
		S	56 (0.50)	108 (0.13)	129 (0.11)	141 (0.14)	160 (0.14)
	Cowangie	D	72 (0.09)	93 (0.13)	113 (0.11)	123 (0.12)	133 (0.12)
		M	73 (0.07)	94 (0.12)	112 (0.10)	121 (0.10)	129 (0.10)
		S	79 (0.09)	107 (0.12)	129 (0.11)	141 (0.10)	146 (0.12)
	Loxton	D	52 (0.39)	83 (0.17)	101 (0.12)	110 (0.11)	124 (0.13)
		M	63 (0.36)	100 (0.14)	121 (0.13)	133 (0.11)	147 (0.10)
		S	59 (0.39)	104 (0.14)	126 (0.13)	142 (0.11)	153 (0.09)
	Pinaroo	D	72 (0.04)	109 (0.14)	130 (0.13)	150 (0.12)	160 (0.14)
		M	74 (0.03)	108 (0.14)	129 (0.14)	148 (0.12)	152 (0.12)
		S	76 (0.02)	115 (0.12)	136 (0.13)	154 (0.11)	159 (0.15)

Water losses from the system other than evaporation, namely runoff and drainage were important only at higher rainfall levels (> 300 mm) for the swale zone (Figure 12). For the dune zones runoff was of less importance, but drainage was a major pathway of water loss at high rainfall. For rainfall > 300 mm the mean drainage loss across sites was substantial (> 50 mm).

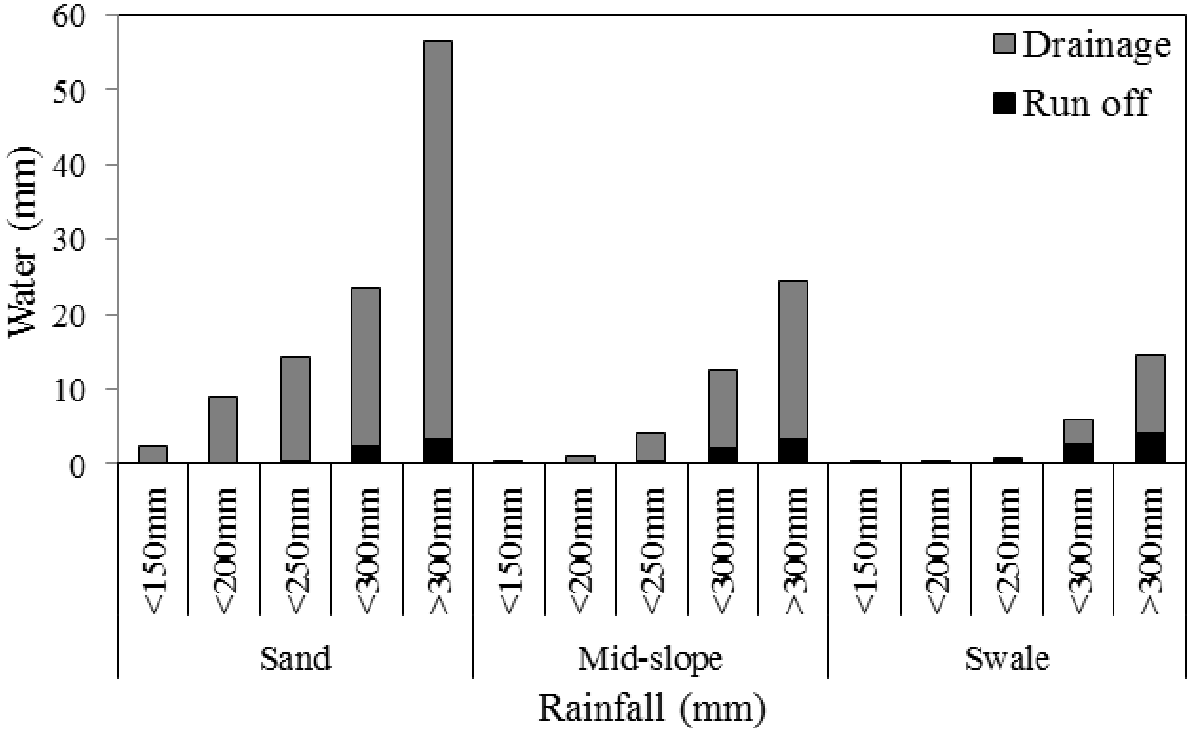

Figure 8: Mean simulated in-crop drainage and runoff losses for different rainfall quantities averaged across sites for the three soil zones. Simulation based on the years 1963-2012 and an annual fertilizer application of 30 kg N/ha.

4. Discussion

4.1 Soil properties

The three soil zones reflected the different soil properties in a typical Mallee Dune-Swale landscape. The fine textured zone was constrained by salt concentrations (Table 1). Across sites ESP, B, Cl and EC were very high, which influenced water uptake ability of the crop. A good relationship existed between these soil properties and the CLL (Figure 1), which is supported by other studies (Hochman and Dang 2007; Rodriguez et al. 2006). However, the extent of the influence of these constraints on CLL remained unclear, as fine textured soils have typically higher CLL than course textured ones. Despite this limitation, the swale zones had the highest OC content, which could be explained by the formation of typical stable clay-organic matter aggregates (Tisdall and Oades 1982). Due to the finer soil texture the swale zones had the highest overall PAWC across sites despite the high CLL. This was reflected in the evaporation sensitive top-soil layer, where the PAWC was again highest (with the exception of Carwarp) in the swale zones (Figure 2). Contrary to this, the dune zones were sandy soils with very low OC content (all below 1%) and low PAWC. In Pinnaroo, PAWC in the dune zone was almost only half of the swale zone (Figure 2). The K and P status in all soils was high due to regular fertilisation and could be assumed not being yield limiting. S is a highly mobile nutrient, and due to the low clay content of the course-textured soils they are prone to S leaching. Therefore in the low constrained zone S deficiency (< 6 mg/kg) could occur for higher growth rates, but was not observed in the generally low rainfall years of the field measurements (Peverill et al. 1999).

4.2 Use of APSIM on constrained soils in low-rainfall environment

Setting APSIM up for the constraint soil zones with high salt and B concentrations is assumed to be a challenge as it is difficult to quantify the effect of the constraints on water uptake by the plant. However, it is acknowledged that these affect the ability of the crop to take up water against low levels of soil moisture (Hochman and Dang 2007). Hochman and Dang (2007) tested an approach modifying the water-extraction coefficient (kl) in APSIM based on subsoil constraint indices for Vertisols. Rodriguez et al. (2006) discussed possible changes of the rooting depth in the simulation setup due to soil constraints as sodium and Cl. However, they did not come to a final conclusion about the best representation of these processes in modelling frameworks. Whitbread et al. (in prep) could show that for two sites in the Mallee lab measured lower limits by suction plates lead to overestimations of the lower limit of the PAWC. They found the best match between observed and predicted yield and soil moisture using the crop lower limit measured as described by Dalgleish and Foale (1998). Here, the subsoil constraints were assumed to directly influence CLL. This study supported such an approach as B, Cl, ESP and EC are well correlated with CLL at the research sites (Figure 1). In line with this result, this study used the measured CLL (Figure 2). Based on the PAWC field characterisation and the simple rule for the setting of Cona and U, the soil water balance model within APSIM was parameterized and resulted in reasonable predictions of yield (RMSE 311 kg/ha; Figure 5). This level of error was comparable to other studies in this low yielding farming system (Hochman et al., 2009; 500 kg/ha). The slight overprediction by the model under higher rainfall conditions as in 2007 might potentially be due nutrient limitations other than N or other biological constraints, as the model does not capture these growth limitations. However, the validation exercise showed that the production for the different zones can be successfully simulated.

4.3 Long-term performance of the different zones based on crop modelling results

In the simulation experiment across all sites the yield was lower in the dune zones than in the mid-slope and swale zones when no N fertilisers were applied in the simulation run (Table 2). Because yields were limited in many seasons by the availability of N, the coefficient of variation for this zone type was lower than in other zones. This finding reflected the limited native N-supply because of the low soil OC content (Figure 2). Consequently, these dune zones showed the strongest response to fertiliser applications indicating the strong N-limitation of the sandy zones (Table 2). Despite the lower PAWC of the dune zones, maximum achievable yield at 120 kg/ha N-rate was higher than for the other two zone types. Nevertheless, the production risk (indicated by the variance of the mean; Table 2) increased with N-rates of 120 kg/ha also for the dunes to high levels. Therefore such maximum yield is rather a theoretical construct and not relevant as an economic yield target for a farmer (Monjardino et al. 2013).

However, with a locally typical input of 30 kg N/ha a good linear relationship between water supply and yield for the mid-slope and swale zones was simulated (Figure 6). For the dune zone this relationship was much weaker. In high rainfall years the mid-slope and swale zones had higher yields, while in low rainfall years the dune zones perform better. One reason for this finding is the lower N-supply, which reduced the growth rate on the sandy soils. In good rainfall years this led to lower yields than for the other zones, but in the low rainfall years it prevented the crop from being affected by the haying off phenomena (Herwaarden et al. 1998). A second reason was that in low rainfall years evaporation is by far the major loss of water (Figure 10 and 11). In-crop evaporation was lower on a sandy soil as it stored less water in the evaporation sensitive top layer than the fine textured soils (Figure 2 and Figure 7c, Table 3). In years with low in-fallow rainfall, the coarse-textured zone had again the advantage of lower evaporation and the esw-sowing is usually higher (Figure 7a and 7b). However, with higher rainfall drainage becomes more important for the sandy soils as the PAWC is too low to store the water (Figure 8) (Sadras et al. 2003a). Therefore, esw-sowing was under these conditions less than in the other zones (Figure 7b). The simulation analysis shows a complex interaction between soil type, evaporation, rainfall, overall PAWC, top layer PAWC and N-supply and its effect on growth and yield. In low rainfall years the sandy, low fertility zones perform better, where as in high rainfall years, the fine textured zones with higher organic matter content yield higher due to a higher N-content.

To sum up, crop production differs significantly spatially (site and zone) and seasonally (from year to year) in response to N-application. This finding suggests that defining linear relationships between rainfall and attainable yield is of little help. None of the three zones described in this study can be generally classified as low performing, rather the specific seasonal weather conditions define the suitability of the zone for cropping. Such results are contrary to the Western Australian situation of Wong and Asseng (2006), who simulated on course textured soils with low PAWC low response to fertiliser rates and recommended such zones for land use change. In their study the PAWC was positively related to yield. One reason for this is the very different rainfall patterns between the two regions of study. In the western Australian cropping district of their study 75 - 86 percent of rainfall typically falls between April and October compared to 60 - 65 percent for the same period in a Mallee district. The peak in rainfall distribution in West Australia increases the importance of the storage capacity of a soil to prevent drainage, and reduces the risk of evaporation losses. Contrary, the more even distribution of rainfall in the Mallee cause higher evaporation rates, especially for those soils with high storage capacity in the evaporation sensitive top layers. This different rainfall pattern makes the extrapolation of findings from western Australia (Lawes and Robertson, 2012) for zone-specific management of limited use in the Mallee region of south eastern Australia. Another method used in zone-specific management, yield maps, can be misleading in certain conditions. For example, the highest observed yield in this study was found in a wetter year in the zone at Cowangie with severe subsoil constraints. A further important point is as widely discussed in the literature and also here that N-availability influences attainable yield (Heerwarden et al., 1998). The fact that a higher N-supply can lead to lower yields in low rainfall years, makes clear that the concept of attainable yield has to take N-availability into account. Simple yield models as discussed above define attainable yield independently of N-supply. Therefore, we argue to improve further zone-specific management in this low rainfall region, simulation modelling and long-term field trials/on-farm observation are essential. As in these methods the complexity of the discussed soil-weather-management interaction can be addressed. Finding ways to apply this data input intensive models and determine trigger points for management decisions are promising as shown here, but challenging (Mudge and Whitbread 2010; Hochman et al. 2009).

Based on the soil survey and the simulation analysis following recommendations can be given (i) The dune zones are rather mostly nutrient instead of water limited, especially by nitrogen (section 4.1 and Table 2). Here additional fertilisation (30-60 kg N/ha) would result in gains in almost all seasons. Similar results were found by Monjardino et al., (2013). (ii) The mid-slope zone showed a weak relationship; however, in dry years water limitations can become severe. The input for this zone type might be done during the season. Weather forecast might be of special relevance for managing this zone (Asseng et al., 2012). (iii) The swale zones were poor yielding in dry years, but may perform well in wet years as they are rarely nutrient limited. Additional N-fertilisation should be avoided. However, in-season decision can be made on end use (graze/hay/grain).

5. Conclusions

The study showed the attainable yield in the low rainfall region of south eastern Australia is highly variable spatially (soil type) and temporarily. Fine textured soils perform well in wet years, supported by the higher potential for soil N supply, but perform badly in dry years due to the high evaporation losses of these soils. PAWC alone is not a good predictor of crop performance across these soils. Sandy soils are generally more nutrient-limited than water-limited. Complex models or long-term field observations help to identify patterns within these complex dynamics for zone-specific management. Simpler methods, which ignore soil variability, differences in evaporation characteristics, and N supply might consequently not well equipped for zone-specific management support in this region.

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VI - Synthesis and general discussion

VI. General discussion

Oil palm production in plantations, winter oilseed rape cultivation in crop rotations in central Europe and cereal cropping in the low rainfall region of south eastern Australia are very distinctive in terms of climate, soils, scale and type of management, and socioeconomic context. Applying a common widely used theoretical framework (yield gap analysis) and methodology (crop modelling) across these different production systems should help to critically evaluate this concept and tool.

1. Yield gap analysis

With a growing world population, re-occurring food crises in some countries and climate change, there is an increasing demand for knowledge on how global food production will develop over the following decades, and which exploitable potentials are left. Assessments of potential production gaps have become an important topic in the scientific community in the last ten years (Figure 1). Sumburg (2012) pointed out that the phrase "yield gap" has become a powerful catch-word in policy debates. Finding large yield gaps appears desirable in this context, indicating that there are potential solutions. Small yield gaps are of minor interest. There is a threat that postulating large yield gaps gains more attention than "closed yield gaps". Sumburg (2012) highlights one case study for Africa on how yield gaps are framed and how it matters. He criticized that "despite an association with science and systematic analysis, yield gaps are often purposively and loosely constructed by policy advocates to support particular narratives and policy options. In general, the link between the yield gap and issues addressed by the favored policy options is lacking or at best poorly specified".

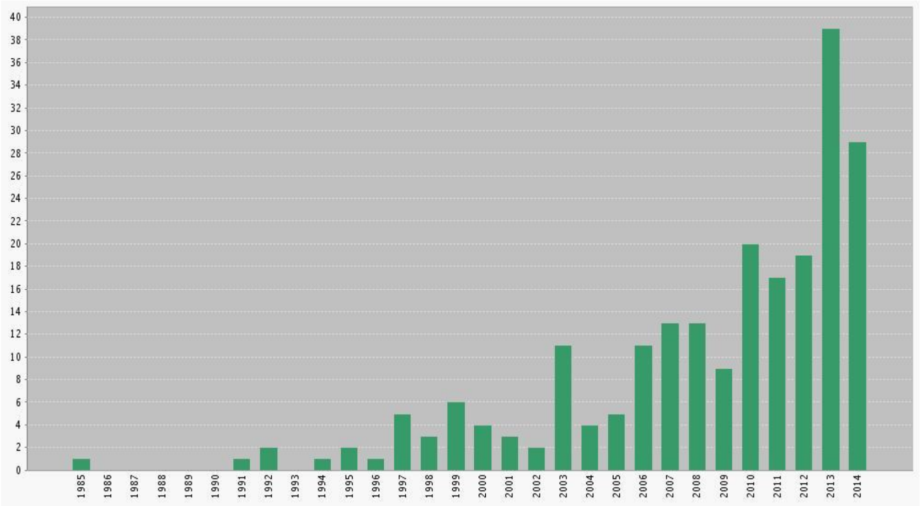


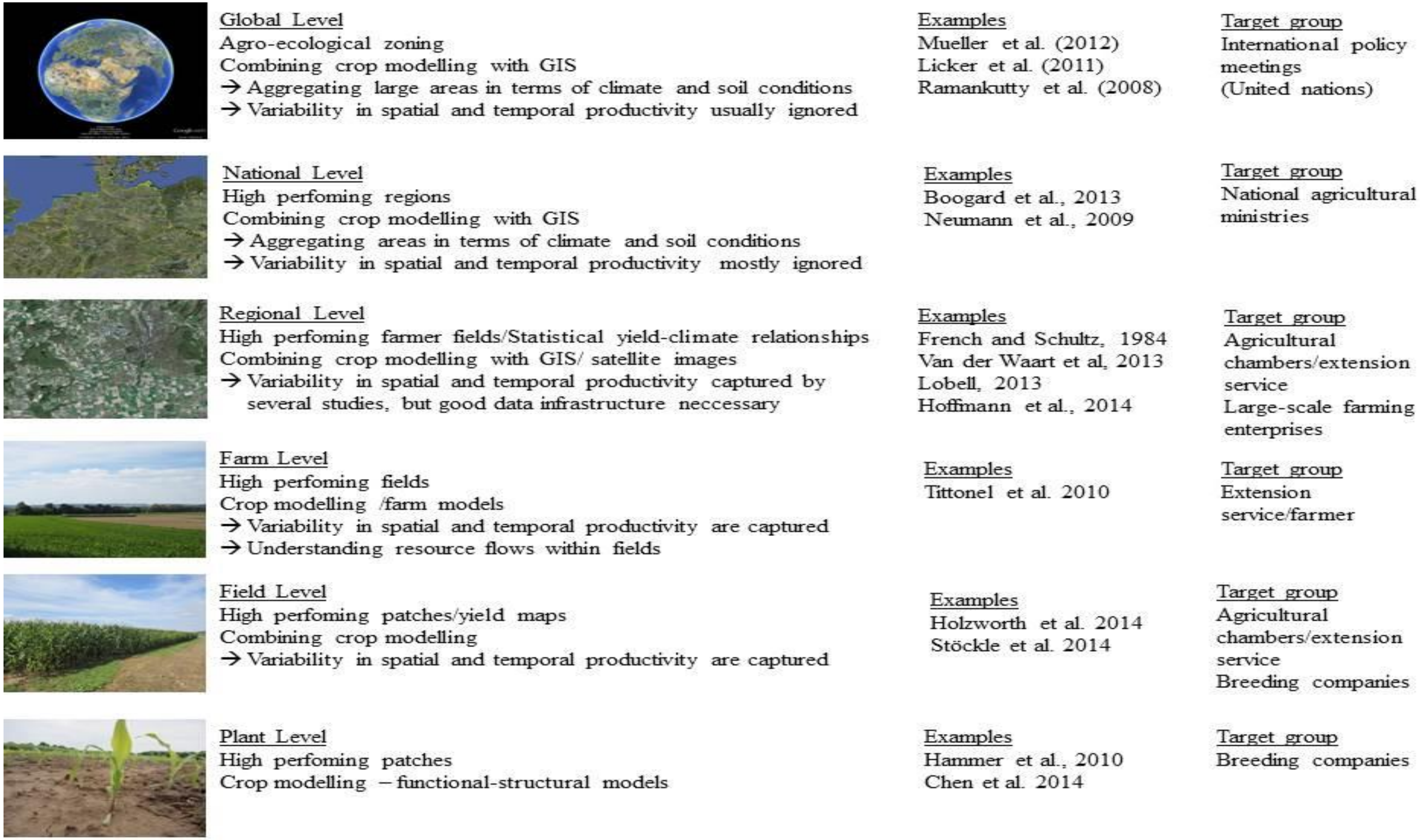
Figure 1: Publications found in the Web of Science using the key word „yield gap"(Web of Science).

Taking up this argument, a closer look at such studies reveals a strong variation in the methodology and scale of assessment (Figure 2).

Studies using an agro-ecological zoning approach are widely sites at a global scale. For instance, Mueller et al. (2012) investigated the yield gap for the major cereals - maize, rice and wheat – and suggested there is a large scope for increasing production through better nutrient and water management. In some parts of the world, especially China, high production levels can be maintained and resource input can even be reduced. For Africa and Eastern Europe a major yield gap would be present, and more intensive farming would lead to a sharp production increase. Such studies are widely discussed in the scientific community indicated by citation rate (citation metrics for Muelller et al., 2012, 97 times cited; web of science; 6.12.2014), blogs and articles in the scientific popular magazines (http://www.nature.com/nature/journal/v490/n7419/nature11420/metrics).

On lower scale from national levels upwards increasingly crop models are used. At low resolution at national scale usually soil maps are used to derive the necessary data plus information from nearest climate station (Figure 2). Such analyses are mostly done in developed countries where the informations are available (Hochman et al., 2013; Boogaard et al., 2013). However, from regional, towards farm level and finally field and plot scale it is possible to increase the resolution and to collect the necessary input parameter by satellite images and field surveys. Detailed crop modeling frameworks such as ASPIM, which can take soil water and nitrogen dynamics into account, can capture differences at these low levels. Simple empirical yield-climate relationships, which are developed for certain regions, cannot address these complexities. A good example is the French and Schultz approach (1984) used in south eastern Australia (Chapter five). Here, a relationship based on in-season rainfall and yield is assumed taking a constant water use efficiency factor and an evaporation term into account. This relationship results in a fixed yield output for a certain region with the same in-season rainfall. However, in chapter six it was shown that the attainable yield is determined by the much more complex relationship between in-season rainfall timing and amount, in-fallow rainfall, and soil conditions and fertility (Chapter V).

A further advantage of using crop models in yield gap studies is related to the point that the gap between attainable yield and actual yield differs from year to year, as weather conditions change; especially, in environments such as southeastern Australia, but also in central Europe in terms of the attainable yield (chapters IV and V). In semi-arid Africa, this variability is framed by the high cost of input (fertilizer, seeds) in comparison to the total income.



Global Level Agro-ecological zoning Combining crop modelling with GIS → Aggregating large areas in terms of climate and soil conditions → Variability in spatial and temporal productivity usually ignored	Examples Mueller et al. (2012) Licker et al. (2011) Ramankutty et al. (2008)	Target group International policy meetings (United nations)
National Level High perfoming regions Combining crop modelling with GIS → Aggregating areas in terms of climate and soil conditions → Variability in spatial and temporal productivity mostly ignored	Examples Boogard et al., 2013 Neumann et al., 2009	Target group National agricultural ministries
Regional Level High perfoming farmer fields/Statistical yield-climate relationships Combining crop modelling with GIS/ satellite images → Variability in spatial and temporal productivity captured by several studies, but good data infrastructure neccessary	Examples French and Schultz, 1984 Van der Waart et al, 2013 Lobell, 2013 Hoffmann et al., 2014	Target group Agricultural chambers/extension service Large-scale farming enterprises
Farm Level High perfoming fields Crop modelling /farm models → Variability in spatial and temporal productivity are captured → Understanding resource flows within fields	Examples Tittonel et al. 2010	Target group Extension service/farmer
Field Level High perfoming patches/yield maps Combining crop modelling → Variability in spatial and temporal productivity are captured	Examples Holzworth et al. 2014 Stöckle et al. 2014	Target group Agricultural chambers/extension service Breeding companies
Plant Level High perfoming patches Crop modelling – functional-structural models	Examples Hammer et al., 2010 Chen et al. 2014	Target group Breeding companies

Figure 2: Different scales of yield gap studies and the methodology used.

Thus, the economic risk for high input is much stronger. Chapters IV and V also clearly show the spatial variability of attainable yield, even within one field large differences can be identified (Chapter V). Improving resource use efficiency and yield will rely on taking this variability and risk element into account. Therefore, yield gap studies, which should be of relevance for the farmer, have to be done where the farmer makes the decision (farm, field, plantation block). Variability needs to be addressed in attainable yield, as production risk is a major decision making determinant. Such studies also reduce the risk of overestimating the potential yield gap. Global assessments such as done using the agro-ecological zoning approach ignore this risk element (Mueller et al., 2012, Licker et al., 2011). For policy makers addressing national fertilizer strategies or identifying regions of high production potential (chapter III) large-scale assessments could be of benefit. However, ground based studies are very important in verifying such results.

2. Crop modelling - Complexity versus applicability

Are the complex and data demanding annual crop models a useful basis for model development for perennial crops? How detailed do the time consuming soil hydrological measurements - needed to parameterize models for subsoil constrained soils, as in the Mallee in south eastern Australia - have to be? What are the constraints of applying a crop model in a different agro-ecological zone for which it was not originally developed? Such questions point out to a general conflict in modelling - the more production levels (potential yield, water limited potential yield, limitations by nitrogen and phosphorous, biotic stress) should be covered, the more input data is needed (Figure 1).

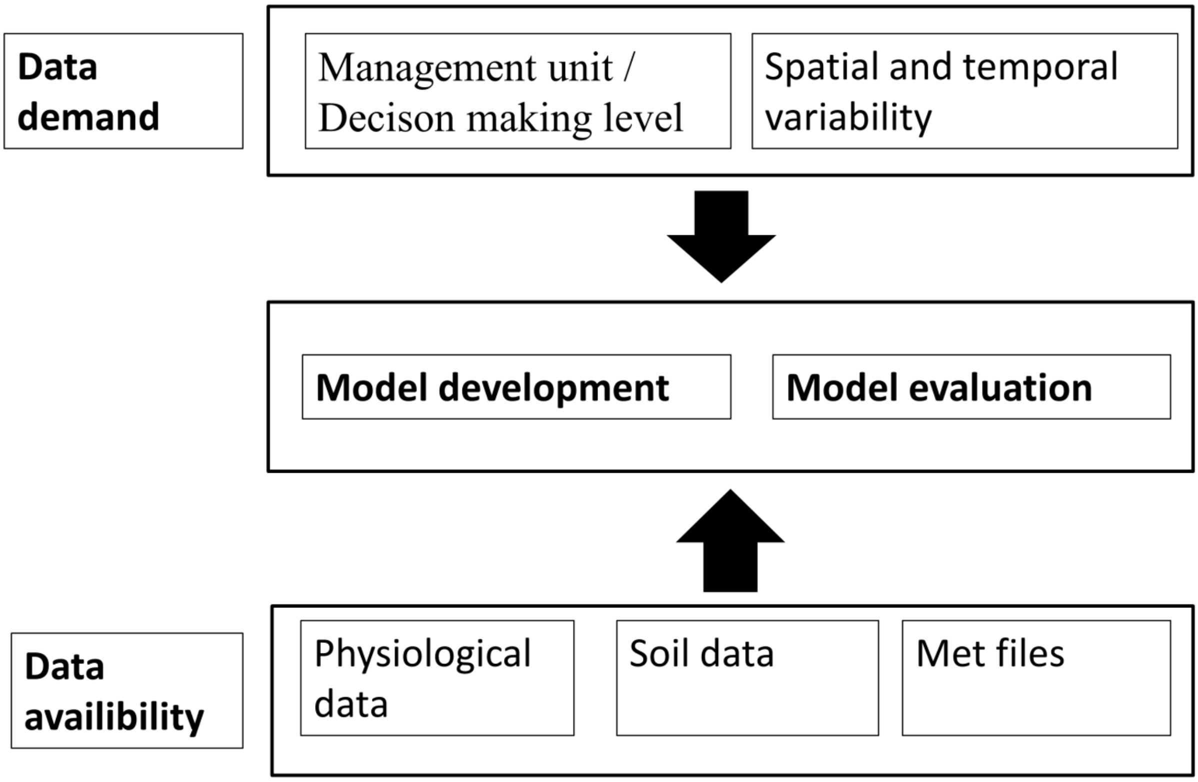


Figure 3: Conceptual diagram of factors affecting model development and evaluation.

Climate data (solar radiation, max and min temperature, rainfall, wind speed, relative humidity) in Asia and Africa on a daily time step is often missing, particularly over longer time periods, which is of major importance to assess the variability of yield over years. Secondly, physiological data for parameterization and evaluation of a model for certain crops, mainly tropical perennials (oil palm, cassava) lacks in particular. These two points made the development of an oil palm model challenging. In chapter II, the presented PALMSIM model follows the idea of being both, simple enough in terms of data input and at the same time incorporates sufficient plant physiological knowledge to be generally applicable across sites with different growing conditions. PALMSIM simulates yield only on solar radiation and rudimentary water deficiency (chapter III). However, by keeping the model this simple it is usable for plantation managers and the large-scale assessment of potential productivity of a certain site as shown in chapter III. The simplification of the models in terms of flower development and the negligence of other production determining factors (nutrients, temperature, planting material, biotic stress) narrow the application to benchmark studies as provided in chapter III. Huth et al. (2014) recently developed a complex oil palm model in the framework APSIM, which fulfills the criteria for crop modelling application in yield gap studies (van Ittersum et al., 2013). Such models might help to investigate a wider range of topics such as planting density, nitrogen management, fruiting cycling. However, they also concluded that it is possible to model perennial plants using a similar approach that employed for annual crops, but the application of the model would be usually limited by the availability of soil and climate data. In the longer term with increasing awareness of the potential applications of crop models, necessary data for running more complex models usied in management may become available. However, short-term, for simple yield benchmarking assessments PALMSIM might be a good compromise between data availability and model usefulness, especially as the smallest management unit in large scale oil palm plantation is block-scale (> 25 ha) (Donough et al., 2009). Spatial variation within a block is ignored. While the most determining factor for oil palm yield in favourable sites in Southeast Asia is solar radiation, the determining factor in the low rainfall region of southeastern Australia is water availability. Fields in this environment show an enormous spatial variability within one field (> 100 ha) (Llleweyn et al., 2008); typically ranging from sand dunes to clay textured soils. Such variability causes large differences in water storage capacity within a field. Managing the field soil type, specifically taking the variable water-limited potential yield into account, appears to be a promising way to increase the profitability (increase of yield and resource use efficiency) of farming in this region. Using a crop model for such conditions needs considerable efforts to parameterize soil conditions and achieve realistic yield ceilings. In chapter V the complex crop model APSIM is setup for such conditions. However, this needs measured crop lower limit (similar to wilting point), drained upper limit (similar to field capacity) and soil organic carbon. With such inputs the model is able to give reasonable estimates on the attainable yield (taking nitrogen and water effects into account) spatially and also temporarily. In chapter IV, the APSIM model is used for an assessment of production limitations of winter oilseed rape production in Germany. As this model was originally developed for canola cultivation in Australia, the model was tested, especially for nitrogen uptake. Based on a detailed data set on nitrogen uptake the model was modified before it could be evaluated and used as decision-making tool. When comparing PALMSIM with APSIM it becomes clear that APSIM is an effective tool for site-specific management up to scales of zones within fields. This takes climate but also nutrient limitations into account. Therefore, such models are very data intensive for parameterization and running. In western countries and for annual crops such data is usually available; therefore model development/adaptation is mainly determined by the specific application question. For tropical perennial crops model input is usually rare, and such conditions limit the model evaluation and application. Improving the modelling infrastructure (climate, soil, and physiological data) will improve the applicability of site-specific models for these crops. However, for yield benchmarking assessments such described in chapter III, simple models such as PALMSIM, might be sufficient. To sum up, in ideal conditions model development and evaluations is only determined by the demand of the decision maker (farmer, plantation manager), but under certain conditions it is a compromise between data availability and data demand.

3. Conclusions

The first objective of this thesis was to develop/ adapt crop model approaches to set yield targets, which are applicable for agronomists, farmers or plantation managers i.e. taking data availability and the socioeconomic context of the crop production system into account. Comparing the three different production systems, it becomes clear that the key constraint for crop modelling of oil palm is the data availability. Modelling oilseed rape in Germany and in Australia was an easier exercise in terms of data and model availability. Furthermore, a wide range of literature is already available. Therefore, despite they depict challenges (only few oilseed rape models are currently available, and setup APSIM for subsoil constraint soils is challenging) these models could be set up for this objective.

It was possible at different levels of accuracy to validate the model approaches including the oil palm one against field data. Finally, this study supports the approach using crop modelling for providing information for sustainable intensification strategies. However, the two chapters about oilseed rape and wheat cropping show clearly that detailed mechanistic crop models which take all production factors into account (solar radiation, temperature, water and nitrogen), which determine attainable yield (van Ittersum et al., 2013) are well suited to offer information for the farmer in terms of management (in particular N fertilizer input). Furthermore, they can capture the seasonal spatial variability of attainable yield and therewith addressing climate risk, which is an important point for decision making at the farm and field scale. PALMSIM (chapter two and three) cannot address this variability so far. Improvements are necessary to further implement production limiting factors. Detailed mechanistic models (Huth et al. 2014) for tropical plantation crops found in the literature are so not well tested so far. Further research especially detailed field trials and further weather monitoring are necessary to improve the modelling of oil palm production.

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Summary

There is a general consensus that world food production has to be increased significantly to fulfill the growing demand until 2050. However, at the same time resource use efficiency has to be improved due to declining resource bases (oil, phosphor) and the environmental effects of inputs (pesticides, nitrogen). Solving this paradox of “producing more with less” will rely, for example, on applying inputs according to attainable yield levels. However, attainable differs from year to year due to different weather conditions (attainable yield and risk relationships). Furthermore, soil conditions affect the water storage for plant uptake. Traditionally, field trials have been conducted to assess attainable yield in a certain regions. In regions with well-developed extension service it was possible to develop simple empirical yield response relationship to climate and fertilizer based on a range of field trials. Such data rich environments are usually restricted to the developed world and mostly lacking in the developing countries. However, simple empirical yield models like for example the French and Schultz approach for southeastern cannot capture the complex interaction between the factors, which determine attainable yield (water, solar radiation, rainfall, nitrogen, soil properties). So that it is not possible to develop site specific management recommendations, which are necessary to improve resource use efficiency and closing the yield gap.

Therefore, crop modelling, mainly in modern simulation frameworks like APSIM or DSSAT has been widely used in the scientific community for setting such yield targets, in particular for wheat and maize. However, for other crops and certain conditions such as soil constraints there is less information found in the literature (Chapter I). With this in mind, the main objective of this thesis was to develop/adapt crop model approaches for oil palm plantations in Indonesia, oilseed rape production in Europe and wheat cropping in southeastern Australia to set yield targets applicable for agronomists, farmers or plantation managers i.e. taking data availability and the socioeconomic context of the crop production system into account. After selection and adaption all model approaches presented in this study were evaluated against field trial data. Finally, challenging the idea of crop usage for sustainable intensification, all three models were applied to typical problems in the respective production systems.

In the first research chapter (chapter II) a new physiological based oil palm model (PALMSIM) is presented. Assessing potential yield in oil palm based on crop modelling depicts a challenge. First of all there are few models available, which are rarely tested against field trial data. Secondly, these models are data input intensive in parameterization and in terms of running them. The high data demand for oil palm modeling is lacking, such as the essential basic and necessary data such as soil information, cultivar parameter and long-term weather records. This makes the application of standard modelling approaches (daily time step, detailed water balance etc.) unlikely. PALMSIM therefore follows the idea of being both simple enough in terms of data and at the same time incorporates sufficient plant physiological knowledge to be generally applicable across sites with different growing conditions. The version presented in chapter II simulates potential yield based on incoming solar radiation only and therefore only gives realistic yield levels for optimal growing conditions. Nevertheless, it was possible to evaluate the model against field trial data from Indonesia and Malaysia. In the next chapter (chapter III), the PALMSIM model is extended by incorporating a simple water balance. This is often used in oil palm cultivation to assess water deficiency. The improved PALMSIM version is then used to exemplify and illustrate the use of crop modelling in oil palm sustainable intensification, the extension into marginal degraded sites, and the increase of productivity in existing plantations. One case study presented in this chapter makes use of a recent report by the World Resource Institute, which aims to identify degraded sites in Kalimantan. PALMSIM was run for water-limited potential on a 0.1°grid for Kalimantan and overlaid with the suitability map produced in the above-mentioned report. Results show that 8.1% of the suitable land has a potential productivity of more than 40 Mg FFB /ha. The largest proportion (35.6% of the suitable land or 115,300 km^2) falls into the category between 35 and 40 Mg FFB ha. In the second case study presented in the paper, PALMSIM was setup for six plantation sites in Indonesia. Long-term weather data was derived using WorldClim data in the stochastic weather generator MarkSim. In all six sites, best management practices were introduced in five blocks. As a comparison, similar blocks were selected and managed following standard practice in the plantation. The potential and water-limited yield was then simulated for each plantation. This shows that potential yields are generally higher in Sumatra than in Kalimantan due to higher solar radiation. Water deficiency was a problem at two sites, either due to low rainfall or soil constraints. The gap between water-limited yield and actual yield differs from location to location, and therefore requires a site-specific analysis of the factors causing the yield gap. To sum up, in the two case studies the scope for sustainable intensification at regional and at plantation level was explored in a quantitative manner - a novel approach to oil palm production.

While the scale of decision making for oil palm is often regional, plantation or the smallest unit the block level, the scale and the challenges for German oilseed rape production is field scale (typically 1-4 ha) and needs a more powerful approach in terms of factors which are taken into account. Winter oilseed rape production is typically characterised by low nitrogen (N) use efficiency. Defining site-specific fertiliser strategies based on field trials and crop modelling may help to improve the ecological efficiency of this crop. However, no model has been evaluated for winter oilseed rape that simulates the growth of the plant as limited by the interaction of water and N. In this chapter the APSIM canola model, originally developed for the temperate regions of Southeast Australia, was adapted for conditions in Germany and tested successfully against measured data (biomass, grain yield, leaf area index, N-uptake and soil mineral N) from three sites around Göttingen and with different N-fertiliser rates. In the second part of the study the evaluated model was used in a simulation experiment to explore site specific climate and soil related production limitations to match fertiliser rates to these yield targets. Simulation results indicates that water supply plays a critical role when maintaining high N use efficiency and simultaneously grain yields of 4000 kg ha^{-1}.

In the last chapter ASPIM was again used to develop site-specific recommendations; here for a case study from southeastern Australia. (annual average rainfall of 250-300 mm). Field productivity shows enormous spatial variation. Since these differences are largely related to soil variation in fertility, subsoil constraints (high salt, Boron levels) and plant available water capacity, three distinctively different zones - low subsoil constrained sandy zone, moderately subsoil constrained zone, and severe subsoil constrained, clay soil - were defined for one field at five sites in the Mallee. To assess the scope of zone-specific management, zone specific yield and soil properties were surveyed for each site in 2006 and 2007. Additionally, the crop model APSIM was parameterised for these challenging soils (taking subsoil constraints into account), successfully tested against the observed yield data and finally used to carry out a long term simulation experiment investigating the response of the three zones to nitrogen fertilisation over multiple seasons (50 years). For the severe constrained zone, simulated and observed yields were well related to rainfall, indicating that this soil zone is limited by water. Nitrogen fertilisation above the standard rate (30 kg/ha) should be avoided, especially in low rainfall years. Simulated and observed yields for the low constrained zone showed a weaker relationship with rainfall. Simulation analysis suggested a potential increase of production on these sandy soils due to higher N-input as evaporation rate and the organic matter content (lower N-supply) are lower than for the other two soil zones.

Across the three case studies, crop modelling has provided useful insights for setting yield ceilings. However, the development and the application of crop models have to be system specific. Currently, we are not able to simulate tropical plantation crops in a similar manner to annual crops like maize and rice, due to missing data in terms of validation, but even more so in terms of input data (soil and especially weather data). A compromise might be for the current situation the PALMSIM model, which still gives useful information despite its low

input demand. However, in contrast it was relatively easy to develop for the annuals oilseed rape and wheat site-specific simulation analysis, which can serve as blueprint to improve perennial crop modelling.

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Letztendlich wären alle Schritte undenkbar gewesen ohne meine Familie, im Besonderen ohne meine Eltern und meine Partnerin Mercedes. Danke für alles!

Publications

Journal publications:

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

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Conference contributions:

<u>Oral:</u>

1) Hoffmann, M.P., Jacobs, A., Whitbread, A.M., (2014) Modelling winter oilseed rape (*Brassica Napus* L.) in Germany to develop site-specific nitrogen fertiliser strategies. ESA conference, 25.-29. August, Debrecen, Hungary.

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DECLARATIONS

1. I, hereby, declare that this Ph.D. dissertation has not been presented to any other examining body either in its present or a similar form. Furthermore, I also affirm that I have not applied for a Ph.D. at any other higher school of education.

Göttingen, ...

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(Signature)

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(Name in block capitals)

2. I, hereby, solemnly declare that this dissertation was undertaken independently and without any unauthorised aid.

Göttingen,...

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(Signature)

.... (Name in block capitals)