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DESIGNING, MODELING, AND EVALUATION OF IMPROVED CROPPING STRATEGIES AND MULTI-LEVEL INTERACTIONS IN INTERCROPPING SYSTEMS IN THE NORTH CHINA PLAIN

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Abbreviations and acronyms

A	Agressivity
A.D.	Anno domini
AIC	Akaike information criterion
ALMANAC	Agricultural Land Management Alternative with Numerical Assessment Criteria
ANOVA	Analysis of variance
APSIM	Agricultural Production Systems Simulator
AR(1)	First-order autoregressive model
ASA	American Society of Agronomy
BBCH	Biologische Bundesanstalt für Land- und Forstwissenschaft, Bundessortenamt und Chemische Industrie
B.C.	Before christ
C_3	Plants with C_3 carbon fixation
C_4	Plants with C_4 carbon fixation
Ca	Calcium
CERES	Crop-Environment Resource Synthesis
cm	Centimetre
CO_2	Carbon dioxide
cohort1retranslocationwt	Change in retranslocation cohort 1 dry matter
CR	Nutrient competitive ratio
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSSA	Crop Science Society of America
DAS	Days after sowing
DFG	Deutsche Forschungsgemeinschaft
dlt_dm	Actual above-ground dry matter
dlt_lai_pot	Potential change in live plant leaf area index
dlt_lai_stressed	Potential change in leaf area index allowing for stress
dlt_leaf_no	Change in number of leaves
dlt_leaf_no_pot	Potential leaf number
dm	Dry matter

DSSAT	Decision Support System for Agrotechnology Transfer
e	East plot border
e.g.	For example
ep	Plant water uptake
esw_layr(1, 2, 3)	Extractable soil water in different soil layers
et al.	Et alii (and others)
etc.	Et cetera
Exp	Exponential model
FAO	Food and Agriculture Organization of the United Nations
FASSET	Farm Assessment Tool
Fe	Iron
Fig.	Figure
g	Gram
G1	Kernel number per unit weight at anthesis
G2	Kernel weight under optimum conditions
G2	Potential kernel number
G3	Potential kernel growth rate
G3	Standard stem and spike dry weight at maturity
GAPS	General-purpose simulation model of the Atmosphere-Plant-Soil system
Gau	Gaussian model
GDP	Gross domestic product
grain_n	Nitrogen in grain
grain_no	Grain number
grain_size	Size of each grain
grain_wt	Weight of grain
H	Plant height
H^+	Hydron
ha	Hectare
IBSNAT	International Benchmark Sites Network for Agrotechnology Transfer
i.e.	That is
IE	Internal efficiency of nitrogen use
inter	Intercropping

INTERCOM	Ecophysiological model for crop-weed interactions
IRTG	International Research Training Group
Jr.	Junior
K	Potassium
kg	Kilogram
KJ	Kilo joule
KMS	Simplified Kubelka-Munk equations model
K_2O	Potassium oxide
LAI	Leaf area index
leaf_no_sen	Number of senesced leaves per square meter
LER	Land equivalent ratio
LV	Linear variance model
m	Metre
m^2	Square metre
MJ	Mega joule
mm	Millimeter
Mn	Manganese
MOE	Ministry of Education of the People’s Republic of China
mono	Monocropping
N	North
N	Nitrogen
N_2	Molecular nitrogen in the atmosphere
NCP	North China Plain
n_demand	Nitrogen demand of plant
n_demanded(1, 2)	Nitrogen demand of plant
NE	Northeast
n.m.	Not measured
N_{min}	Soil available mineral nitrogen
no.	Number
NO_3^-	Nitrate
no3_demand	Demand for nitrate
no3_tot	Nitrate available to plants
n_supply_soil	Nitrogen supply

NTRM-MSC	Nitrogen Tillage – Residue Management Model – Multiple Species Competition
n_uptake	Nitrogen uptake
obs.	Observed
P	Phosphorus
p./pp.	Page/pages
P1	Growing degree days from emergence to end of juvenile phase
P1D	Sensitivity to photoperiod
P1V	Sensitivity to vernalization
P2	Photoperiod sensitivity
P_2O_5	Phosphorus pentoxide
P5	Cumulative growing degree days from silking to maturity
P5	Grain filling duration
PAR	Photosynthetically active radiation
PHINT	Phylochron interval
PR	People’s Republic
R^2	Coefficient of determination
REI	Relative efficiency index
REML	Restricted maximum likelihood
RLO	Relative land output
RMSE	Root mean square error
RNT	Relative nitrogen yield total
root_depth	Root depth
RYT	Relative yield ratio
s	Second
S	Shading
senescedwt	Senesced dry matter
sim.	Simulated
Sph	Spherical model
SPRI	Shandong Peanut Research Institute
SRAD	Daily solar radiation
SSSA	Soil Science Society of America
Stage	Growing stage

STICS	Simulateur mulTIdisciplinaire pur les Cultures Standard
SUCROS	Simple and Universal Crop growth Simulator
sw_deficit(1, 2)	Soil water deficit in different layers
sw_demand	Soil water demand
sw_supply	Soil water supply
t	Ton
TAB	Büro für Technikfolgen-Abschätzung beim Deutschen Bundestag
Tab.	Table
TDR	Time domain reflectometry
TKW	Thousand kernel weight
UN	United Nations
UNEP	United Nations Environment Programme
US/USA	United States of America
VDLUFA	Verband Deutscher Landwirtschaftlicher Untersuchungs- und Forschungsanstalten
Vs	Version
vs.	Versus
w	West plot border
Zn	Zinc
α	Probability
t	Spatial trend effect
y	Yield
μ	Intercept (column effect)
β	Fixed effect for the position
ε	Error/nugget
σ^2	Variance
°C	Degree centigrade
°E	Degree east/longitude
°N	Degree north/latitude
3D	Three-dimensional space
%	Percent
vol %	Volume percent

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1 Introduction

Modern agriculture has to work out the balancing act between economy and ecology. On one hand, there is a growing demand for food supply, food access and food quality. On the other hand, there are constrains on environmental protection issues and income certitudes for farmers within a global market. High yield and sustainability are the catchphrases of production in the 21st century – and agronomy research has to provide solutions in increasingly briefer terms. In fast developing countries like China, those issues have become even more severe. Agriculture production rates and tremendously increased production levels aiming to feed the nation coming along with severe environmental pollution need adopted cropping systems for Chinese production circumstances. Thus, improved cropping strategies, which are based upon common, widespread and traditional cropping systems like intercropping, need to be developed. Taking modeling and simulation tools into account could help both to accelerate research attainments and to give a better understanding of cropping systems.

Within the last decades the Chinese agricultural development has been accompanied by serious **environmental degradation problems** (Wen et al., 1992). Exaggerated verbalized, agriculture nowadays is an attack on the environment, attacking anything that could be cut down, plowed up, pumped over, dug out, shot dead, or carried away (Hinton, 1990, p. 21). Fulfilling the premise of high productivity and food self-sufficiency within a country where the average population density is four times higher than global population density (Prabhakar, 2007) and, in contrast, the land per capita is only 0.11 ha (EarthTrends, 2003) (Figure 1) resource use efficiency takes on a dimension beyond sustainability. That is what Evans (1998) called the sustainability dilemma when agriculturists are often torn between their concerns about the need for greater food production and the need to conserve what is left of nature and of the resources of agriculture for future generations.

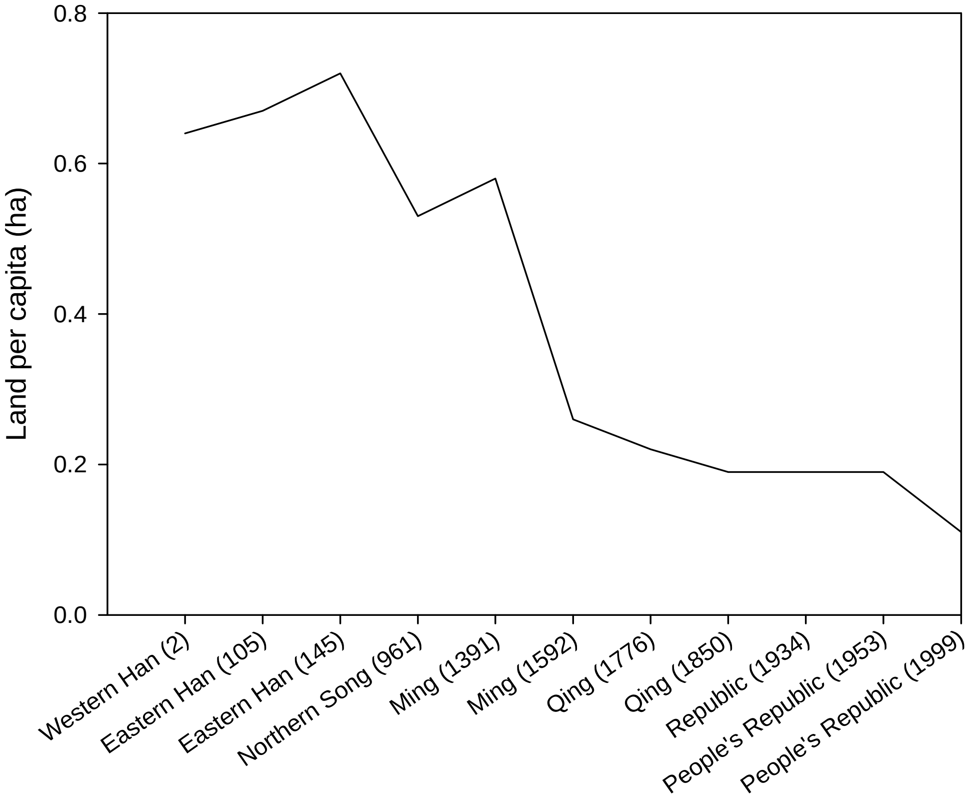

Figure 1: Development of the ratio of land per capita in China throughout the centuries (EarthTrends, 2003; Netting, 1993).

THE PARADIGM OF SUSTAINABILITY

Looking upon soil erosion, degradation and desertification in China as an example, five billion tons of soils are eroded each year, resulting in a loss of nutrients associated with organic matter equal to twice the national production of chemical fertilizers (Tong et al., 2003). 1/6 of the total land area and 1/3 of arable land in China are presumed to be eroded; the total soil loss in one year was 20 % of the total soil loss in the world, and deserts are expected to expand at a rate of 1560 km² per year (Wen et al., 1992; Yunlong and Smit, 1994).

In addition, China ranks first in the world with respect to the amount of nutrient fertilizers used. In the North China Plain, the N fertilizer application rate for a maize/wheat double cropping system is 400-600 kg N ha^{-1} per year (Fang et al., 2006). For peanut (legume-) production, recommended fertilizer amounts range between 3.75-7.5 t farmyard manure combined with additional 60-100 kg N (Liang, 1996; Cai et al., 1996) or, for a peanut/wheat relay intercropping, 60 m³ farmyard manure combined with 300-375 kg urea or 15-22.5 t farmyard manure combined with 150 kg urea provided as second application in spring (Zhang et al., 1996). As a result, nitrate leaching is a big issue in China. Fang et al. (2006) reported that 35 % of total N application in 1987 was lost due to leaching. A survey in northern China indicated that the maximum nitrate content in ground and drinking water of 109 mg l^{-1} exceeded accepted health standards by an average of 50 mg l^{-1} (Wang et al., 2009; Zhang et al., 1996).

Taking these two aspects – soil erosion and N use efficiency – into consideration, it is obvious how important it is to develop technically feasible agricultural systems, which are friendly towards the natural environment and which are predisposed towards farmers' adoption and use (Sanders, 2000). The question is how to combine the welcome reduction in hunger and malnutrition, how to earn cash and how to reduce the threats to ecological sustainability over time? Prabhakar (2007, p.18) pointed out that revising the existing cropping patterns and systems is needed, and as monocropping means higher risk, in terms of income security, nutritional diversity in rural areas, and possibility of severe impacts to large areas due to pest and disease outbreak in changing climate, mixed and intercropping practices are the only alternative that has multiple benefits.

In the **intercropping** research context the following benefits appear repeatedly (Knörzer et al., 2009): maximized land use, several harvests per year, yield stability, increased resource use efficiency, reduced soil erosion and leaching, and reduced pests and diseases. As a scale unit for maximized land use, the land equivalent ratio (LER) is most commonly used. It defines the ratio of land for monocropping necessary in comparison to intercropping. In his appendix, Innis (1997) gave a compilation of the results of several hundred experiments, which have been done on intercropping using the LER. In most of those studies, maize or legumes or even both were involved. In some of them, the LER of monocrops, which is 1, was almost doubled for intercrops, showing that intercropping had higher yield expectancies than its monocropping equivalents for the same proportion of land. Not only yield in total might be higher in intercrops, but yield stability also, as one crop failed because of climatic or pest and disease reasons, there was still another crop left. In addition, relay intercropping, where the maturing annual plant is interplanted with seeds of the following crop, allows an additional harvest within the growing season as the overlapping growing period elongates the growing period of the second crop. In the Northern and North-Eastern provinces of China, relay intercropping systems with wheat/maize (Li, 2001; Li et al., 2001; Yamazaki et al., 2005; Wang et al., 2009), wheat/peanut (Cai et al., 1996; Liang, 1996; Zhang et al., 1996) and wheat/cotton (Li, 2001; Zhang et al., 2008) are widely and successful practiced, indicating that intercropping is not restricted to cereal/legume combinations or maize as a major component. Indeed, the species spectrum within intercropping systems in China is extensive and includes wheat, maize, cotton, green manure, soybean, sweet potato, rape, peanut, broomcorn millet, bean, buck wheat, millet, tobacco, sorghum, rice, cassava, garlic and a great variety of vegetables (Meng et al., 2006; Li, 2001).

Literature gives evidence that the advantage of intercropping compared to monocropping is the increased nutrient and light use efficiency (Fukai and Trenbath, 1993; Inal et al., 2007; Li et al., 2003; Song et al., 2007; Vandermeer, 1989; Zhang et al., 2004). Competition and facilitation could be balanced by choosing appropriate components and a mutually beneficial timing. Permanent covered soil is less susceptible to erosion, and as example from the middle reaches of Heihe River in the Hexi Corridor region showed, a switch to intercropping intimated a reduction in soil wind erosion and a halt in sand entrainment (Su et al., 2004). In this region it occurs that dust transport from farmlands is about 4.8 to 6.0 million tons per year and consequently higher than that of sandy desert dust transport in the same region. In addition, several studies indicated that intercropping reduced nitrate leaching (Li et al., 2005; Song et al., 2007; Ye et al., 2005).

For Chinese farmers the reasons for intercropping are more driven by basic principles than by sophisticated aspects like sustainability or protection of environment. On the one hand there is a long tradition of those systems being passed on from generation to generation, and on the other hand there is China’s situation of land shortage and abundant labor – and intercropping systems in China are extremely labor intensive. Average farm size is 0.1-0.5 ha with fields being extremely small. Farmers have to make the most of their small plots in space and time which are carefully economized in the Chinese Intensive System (Netting, 1993). First priority is maximizing land use and income security. Agricultural landscape is fragmented leading to the term “noodle fields” (Netting, 1993) (Figure 2). This **smallholder farming** in combination with labor and time intensive cropping systems are stigmatized to be old-fashioned and less efficient than those agro-industries in the United States of America or Australia.

On a political level, Netting (1993, p. 21), who studied smallholder systems very briefly, stated for both, the socialists and the communists on the left and the free-market capitalists on the right, the agreed-upon path to agricultural development has been the large-scale, mechanized, energy-dependent, scientific, industrialized form. In contrast, tradition or cultural values are said to be responsible for economic irrationality. Accordingly, is intercropping in its existing form a dwindling system? The paradigms of sustainability and biodiversity convey not only the resource protection consciousness of industrialized countries' society, but also their forms of agricultural practice. Netting (1993, p.151) argued that the productivity of land declined sharply on large farms and the risks of deforestation, erosion, and possibly permanent environmental degradation increased. In the past, only the smallholder intensification increased output per unit of land, while conserving natural resources. Nowadays, China's smallholders face rapidly developing agricultural production with high chemical fertilizer and pesticides input, mechanization and monocropping of cash crops. The combination of scarce land, cash and technological progress shows an ever increasing trend to deforestation, erosion, and potentially permanent environmental degradation. Across China's long agricultural history it has always been assumed that farming activities should be in accordance with seasons, climate, soil conditions, and nutrient input. And it has been in that long agricultural history that intercropping developed and always played an important role. This does not mean that Chinese agriculture has to go back to its roots, but it shows the potential and the importance of typical Chinese cropping systems to be improved, adapted, and refined.

Figure 2: Chinese agricultural landscape is extremely fragmented leading to the term "noodle fields" (Netting, 1993) (picture: T. Feike, 2008).

ECOLOGICAL AWARENESS AND RESEARCH

Within the last two decades, there is an increasing awareness of environmental pollution and degradation due to agricultural production in China. Studies on agricultural development and land use in China mostly open with the problem of China's population density and its lack in arable land: Chinese farmers have to feed 22 % of the world's population with only 7 % of the world's arable land (Li, 2001; Liu et al., 2001; Tong et al., 2003; Wen et al., 1992). Those studies outline the serious challenges China will face on its still long way to truly sustainable agriculture having enormous environmental costs to carry on its shoulder. Thus, agricultural research aims to cope with those constraints leading to a vast variety of national and international projects such as the International Research Training Group (IRTG) “Sustainable Resource Use in the North China Plain”, within which this research was based.

The project is entitled **“Modeling Material Flows and Production Systems for Sustainable Resource Use in Intensified Crop Production in the North China Plain”** and was established by the Deutsche Forschungsgemeinschaft (DFG) and the Chinese Ministry of Education at the Universität Hohenheim (Stuttgart) and the China Agricultural University (Beijing) in June 2004. It will run until 2013. With a background of high level production intensities, raising productivity, increasing food demand of a growing population with increasing living standards and coincidently a lack of sustainability the IRTG’s aims were to develop environmentally, economically and socially sustainable cropping and management systems. This requires clearly identifying, measuring, and modeling the related material flow effects in cropping systems on field, farm, and regional levels (https://rtgchina.uni-hohenheim.de/start.html?&L=1). Eleven subprojects from various disciplines (soil science, plant nutrition, plant ecology, plant production, plant breeding, weed science, agricultural engineering, farm management, agricultural informatics and rural policy) are involved and several dissertations on those fields have been released so far.

Research has been focused on the North China Plain (NCP), also known as the Huang-Huai-Hai Plain (Figure 3). It is the so called granary of China, where approximately one-fourth of the country’s total grain yield is produced, with wheat, maize and cotton as major crops. It is located in the country’s North-East (32°-40°N, 100°-120°E) and composed of the piedmont diluvial-alluvial plains of Taihang Mountains and Yanshan Mountains and the alluvial plains of the Huanghe and Haihe River (Liu et al., 2001; Xi, 1989). The climate is characterized as a continental monsoon climate with an average temperature ranging between 10-14°C and an average precipitation between 500-800 mm (Liu et al., 2001). The NCP is a major base of agricultural production in China and plays a vital and strategic role in the development of the national economy (Xi, 1989, p. 16). Therefore, the region could be ranked as a hot spot for pollution caused by agricultural production as the problems herein reach a certain point of culmination.

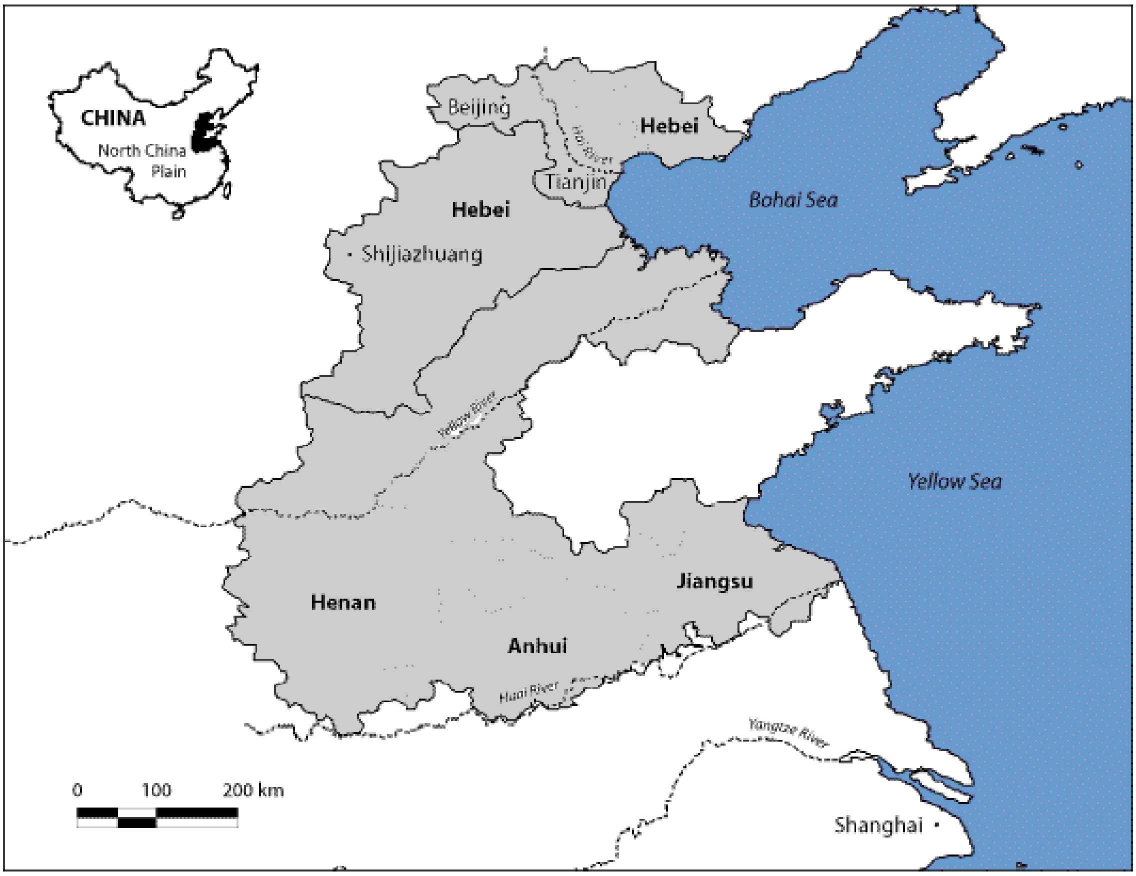

Figure 3: IRTG study region 'North China Plain' (www.cossa.csiro.au/aciar/book/Overview.html).

Within the IRTG project, the subproject 'crop production' was included. Based on a process-oriented modeling approach, the subproject emphasis' was on the evaluation of cropping system prototypes with special regard to intercropping (Project Proposal, 2007). Several crops were involved: spring maize (*Zea mays*), winter wheat (*Triticum aestivum*), peanut (*Arachis hypogaea*), and pea (*Pisum sativum*). The aim was to explore the potential and the possibilities of intercropping and the competition and facilitation effects of those systems in order to create new methodologies for a better understanding of and improvement of existing cropping systems. Necessary methods and basic approaches for the description of the relevant indicator parameters were designed and transferred into a thorough modeling approach (Project Proposal, 2007) for the simulation of intercropping experiments. Datasets collected from both, German and Chinese field experiments 2007-2009, were used to develop a shading algorithm to be incorporated into the DSSAT (Decision Support System for Agrotechnology Transfer) crop growth model (Jones et al., 2003). So far, the current version of DSSAT aims to simulate monocrop production systems (Jones et al., 2003) and does not take interspecific competition into account. Intercropping could not be modeled or simulated.

DECISION SUPPORT SYSTEM

> “This decision support system is designed to answer “what if” questions frequently asked by policy makers and farmers concerned with sustaining an economically sound and environmentally safe agriculture. Sustainable agriculture requires tools that enable decision makers to explore the future. A decision support system must help users make choices today that result in desired outcomes, not only next year, but 10, 25, and 59 or more years into the future (Tsuji et al., 1994)”.

In their introduction for the 3rd DSSAT volume manual, Tsuji et al. (1994) clearly pointed out, that nowadays agriculture and agriculture research are strongly related to sustainability and consequential relevant decisions for the future. Since the outcomes of crop growth models in the late 1960s and early 1970s (Acock, 1989; Jones, 1998), research questions and topics changed from “what is the explanation for what has been” to “how can the knowledge be applied for predicting future scenarios”. **Computer simulation models** of the soil-crop-atmosphere system can make a valuable contribution to both furthering the understanding of the processes determining crop responses and predicting crop performance in different areas and different cropping systems (Project Proposal, 2007). Understanding the underlying processes of plant growth within a given environment and a given management system can be used for prediction of plant growth in different environmental conditions, even with respect to climate change, the introduction of new species into a cropping system, and different management strategies. Understanding and prediction might be the push back factors for managing and controlling and hence, offering the opportunity for change and improvement.

There are various types of models: statistical and kinetic, static and dynamic, empiric and mechanistic, deterministic and stochastic as well as one-dimensional and multi-dimensional. For modeling and simulating cropping systems, process-oriented crops growth models are preferred, such as the DSSAT model, which was used predominantly for this study, as well as the APSIM model (Agricultural Production Systems Simulator) (McCown et al., 1995, 1996).

Process-oriented means a programming paradigm that separates the concerns, shares logically data structures and the concurrent processes that act upon them (Ericsson-Zenith, 1992). As a result, process-oriented models are suitable for large scale applications that partially share common data sets. In agricultural practice, both crop growth and applied management strategies such as rotations, tillage, fertilizers, and plant protection are important elements of success. Thus, a systems approach is needed, where a system is defined as a part of reality which can be delimited from its surroundings, for example soils, plant canopies, and atmosphere. Within those environmental and biophysical plant-soil-atmosphere models, various single heat- and mass-transfer mathematical models are combined to map the exchange processes between organisms and their surroundings (Campbell and Norman, 1998).

The **DSSAT** Vs 4.5 is able to simulate crop growth development of 30 different species for uniform areas of land under prescribed or simulated management as well as dry matter- and grain yield. It can also simulate changes in soil water, carbon and nitrogen stocks and fluxes (Jones et al., 2003). It is organized in different and independent acting modules which operate together. In its center the crop simulation models with underlying genotype characteristics are placed surrounded by weather and soil models as well as experimental conditions and measurements options each with individual databases defining and describing basic conditions, dependencies and functions.

Jones et al. (2003) provided a comprehensive list of modeling and simulation studies wherein the DSSAT model has proven to be a robust model to simulate monocropping situations and experiments in uniform, spatial as well as modified environments all over the world. In addition, there are various models dealing with simulating intercropping scenarios, as shown in chapter two within this dissertation (Knörzer et al., 2010).

Some models for interspecific competition only deal with a few aspects of intercropping, e.g. mortality of individual plants in a stand (Yokozawa and Hara, 1992) or radiation transmission (Tsubo and Walker, 2002; Tsubo et al., 2005), and not with the cropping system itself. In addition, modeling intercropping is often based upon the assumption that the competing plants have a common pool (soil water and nutrients and solar radiation) for their supply of growing factors, ignoring that most intercropping systems are not species mixtures within a given area, but separated and alternating strips of different crops. Leaf area index and plant height are the driving forces for simulated plant growth in intercropping model approaches with e.g. the ALMANAC (Kiniry and Williams, 1995) or APSIM (Carberry et al., 1996; Nelson et al., 1998) model. These approaches are limited with respect to intercropping systems where both species are planted at the same time and in an appropriate plant density that allows the understorey plant to gain sufficient light for growth. In relay intercropping systems, where one plant is far ahead in its development before the companion plant is sown, these models are of limited use.

Thus, a new approach is presented in chapter two and five as part of the topic design, model and evaluation of improved cropping strategies in intercropping systems. Therefore, the DSSAT model was chosen as the model capable of simulating various different crops, having proven to be robust in agriculture systems modeling, offering the possibility to test a new competition algorithm, and to broaden the view on intercropping in a spatial dimension.

OUTLINE AND HYPOTHESES

Ecology meets agronomy in patchy agricultural landscapes (Knörzer et al., 2010). Intercropping has not been analyzed from the point of view that fragmented agricultural landscapes with predominant smallholder farming correspond to intercropping at a larger scale, defining the sum of small fields next to each other as intercropping. Hence, the theory of borders or boundaries from ecology can be transferred to agronomy: The border and the two edges appear as a consequence of the interaction and constitute what is called a boundary (Fernández et al., 2002). Within each small field there is a yield distribution between border rows and centered rows comparable to intercropping and monocropping as intercropping depends upon field border effects. Thus, modeling intercropping could be or interpreted as modeling field boundaries.

To analyze, design, evaluate and in the end model intercropping within an agricultural landscape where smallholders are predominant, the following **elementary questions** have to be answered:

- What are the status quo and the potential of intercropping in China?
- Are common mixed models applicable for intercropping?
- Do we have to broaden our view on intercropping to a spatial dimension?
- How is competition for solar radiation modeled, and is it the driving force within intercropping systems?
- How shall interspecific competition effects be weighted?
- Can intercropping be modeled with DSSAT using simple algorithms?

To answer these questions the underlying **hypotheses** evoked: Crop growth models can be used to simulate intercropping systems by implementing site-specific modeling and by evaluating general competition algorithms. Phenological, morphological and physiological differences between different species handled as intercropping partners will increase beneficial and synergistic effects concerning yield and resource use efficiency.

Covering the full range of intercropping from intercropping distribution and intercropping practice in China (macro level) to site-specific simulation of a single intercropping system (micro-level), the dissertation is structured according a stepwise approximation from the macro to the micro level.

In the **first chapter**, a literature review about the status quo of intercropping of cereals in China was done. It was a first approach to identify and classify different agro-climatic regions in China according to their intercropping systems, their distribution, their frequency of occurrence, their species combination, and their degree of intensification. In addition, the overview over the long and successful history of intercropping combined with the actual research effort in Chinese intercropping systems led to an assessment of intercropping sustainability and its future potential within Chinese agriculture.

In the **second chapter**, crop growth models were reviewed which are already able to simulate interspecific competition or intercropping, or model approaches which have introduced basic and elementary competition algorithms. In that context, around 20 different models were presented. Most of these models simulated intercropping by using either the turbid layer medium analogy or the principle of reducing leaf area index of the understorey species as far as the dominant species reached a special height. As the CERES models within DSSAT do not model plant height a different approach for simulating changed solar radiation within intercropping systems has to be developed. Thus, a unique and contradicted model approach was used by evaluating a shading algorithm taking the neighboring plant height and its proportional shading potential to the target plant into account.

Chapter three deals with the problem how to analyze intercropping systems adequately. As intercropping is mostly practiced as row or strip intercropping – on the fields as well as in intercropping experiments –, there is a problem in statistical data analysis: Strip intercropping systems lack in a basic analytical principle, namely randomization. Thus, usually applied analysis of variance (ANOVA) with a baseline model might estimate significant differences too optimistically. Spatial models have to be applied helping to improve the model fit and to analyze intercropping as well as field boundary effects.

As China is the largest peanut producer in the world, and peanuts were included into the Chinese field trials, **chapter four** was added as some kind of excursus into the dissertation. Four major peanut producing provinces were chosen for a modeling study in order to simulate large area yield estimation and to evaluate potential yield with respect to average rainfall. Anhui, Henan, Hebei and Shandong are located in the North-Eastern part of China. In these regions, drought stress between germination and pod setting could be severe and yield declines because of uneven rainfall and climate variability.

In **chapter five**, the intercropping modeling approach with the DSSAT model, first presented in chapter two, was further tested. In more detail, the shading algorithm for the wheat and maize crops grown as inter- and monocrops was described and introduced into the DSSAT model as modified weather input. In addition, microclimate influence, such as solar radiation, wind speed and soil temperature, and its distribution over the growing season in intercropping in comparison to monocropping systems were studied more closely. Nitrogen dynamics based upon soil temperature differences as well as CO_2 dynamics based upon windbreak effects of a taller neighboring plant might often be small or subtle, but their spatial variability in conjunction with the heterogeneity of plant canopies can be considerable and constitute the starting point for modeling intercropping.

In **chapter six** there is a switch from the DDSAT to the APSIM crop growth model. Both models are process-oriented plant-soil-atmosphere models and operate similarly. Previous versions of APSIM were based upon the cereal models within DSSAT and thus, both models calculate crop phenology based upon thermal time unit requirements. In addition, the models have some bio-physical algorithms in common. Nevertheless, the DSSAT intercropping approach presented in this thesis differs substantially from that in APSIM (Carberry et al., 1996). Incoming solar radiation and photosynthetic active radiation (PAR) are modeled in different ways, especially with respect to competition for solar radiation in intercrops. The comparison between DSSAT and APSIM concerning their intercropping modeling approach was not intended to be especially related to accuracy or to test whether the one or the other has been more suitable for modeling intercropping. The comparison was done order to increase the understanding of modeling competition and to review the general modeling of competition for solar radiation and hence, further research emphases.

Intercropping is a good deal more than the survival of the fittest or a blind alley for overcoming modern high-tech agriculture. Each intercropping system is a system on its own, sensitive balanced between competition and facilitation out in the fields and between benefits and limitations for the farmers’ practice. Thus, generating the basic methodology for using a process-based simulation model for the design and strategic planning of intercropping systems under different agro-climatic conditions could contribute to a further understanding and improving of intercropping systems and, hence, to intercropping winning its due acceptance.

2 Field Experiments conducted for publications

To study intercropping effects in comparison to monocropping and to develop a suitable dataset for modeling intercropping in DSSAT, field experiments were conducted in China (experiment I) as well as in Germany (experiment II) during the years 2007 and 2009 (Table 1). The experimental design used at both locations was similar in order to apply similar statistical methods for analyzing and to study similar processes involved, but the intercropping components differed. In China, a maize/peanut intercropping system, especially widespread in northern parts of China, and in Germany, a maize/pea as well as a maize/wheat intercropping system was used.

To evaluate a basic dataset that can be used for introducing interspecific competition into the model, it was important to design a simple experiment allowing effects occurring in intercropping and monocropping during the growing season to be assigned to the relative cropping system. Thus, an experimental layout without different conventional treatments, e.g. fertilizer amount within plots, was chosen and arranged as a non-randomized complete block design with four replications. Randomization was not possible as intercropping experiments need alternating plots, strips or rows. In contrast, the distance to plot border where intraspecific competition turns more and more into interspecific competition was taken as treatment. As a result, one or each experimental plot within a block contained one species and was divided into several subplots or strips, each defined by their distance to the plot border and each containing several crop rows. Data was collected within subplots.

Table 1: Geographical situation, average air temperature, average precipitation and soils of the two experimental locations in China and Germany.

	Wuqiao (China)	**Ihinger Hof (Germany)**
Geographical situation	37.3°N and 116.3°E	48.46°N and 8.56°
Average air temperature	13.1°C	7.9°C
Average precipitation	562 mm	690 mm
Soils	Alluvial soils sandy clay	Keuper with loess layer silty clay loam

EXPERIMENT I: FIELD TRIALS IN CHINA 2008 TO 2009

Experiment 1 was conducted in northeast China (37.3°N and 116.3°E) at the China Agricultural University experimental station in Wuqiao, Hebei province, during the years 2008 and 2009. In Wuqiao, the average rainfall per year is 562 mm; the average temperature per year is 13.1°C. In this region, mainly alluvial soils occur with a disposition to salinization.

The experiment was designed in four non-randomized complete blocks with alternating plots of spring maize and peanut in each block (Figure 4). Maize and peanut were sown in May 2008 and 2009 with a row spacing of 60 cm and 30 cm, respectively, and a sowing depth of 5 cm. Plant density of spring maize was seven plants m^{-2}, plant density of peanut was 30 plants m^{-2}. No N fertilizer was applied. Pesticides were given once a week after emergency of maize until stem elongation. Spring maize and peanut were harvested between mid and end of September 2008/09. Both crops were sown in alternating plots 8 m wide and 20 m long. Each plot was divided into several subplots in dependency from the distance to the plot border. The plots were big enough to reflect monocropping within the central subplot. In the Chinese experiment, every row equaled a subplot. Thus, data collection was done row by row via square meter-cuts in order to detect differences within the positions of the plots.

During the growing season, three 0.6 m^2 cuts at different maize and peanut growth stages were taken in each subplot to determine dry matter accumulation. In addition LAI as well as plant height were measured over the growing season. At maturity, 1.2 m^2 cuts were done to determine final dry matter and grain yield of both crops. In addition, the number of kernels per ear and the thousand kernel weight (TKW) were measured for maize.

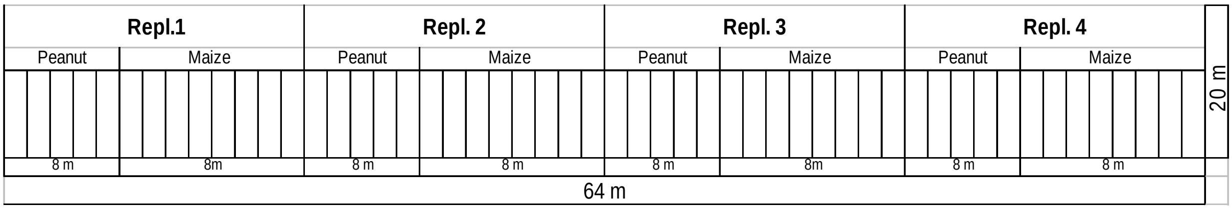

Figure 4: Field layout of the field trial in China for the years 2008 to 2009.

EXPERIMENT II: FIELD TRIALS IN GERMANY 2007 TO 2009

The second and similar experiment was conducted in southwest Germany, at the Universität Hohenheim experimental station ‘Ihinger Hof’ during the years 2007 to 2009. The station is located 48.46°N and 8.56°E and has an average temperature of 7.9°C per year and an average rainfall of about 690 mm per year. Dominant soils are keuper with loess layers.

The experiment comprised a maize/wheat intercropping system as well as a maize/fieldpea intercropping system, each within a not-randomized complete block design and four replications (Figure 5). Thus, each replication contained complete blocks of both systems and each system’s replication consisted of four plots. Two plots were used for time harvests and weekly measurements during the growing season and another two plots were used for the final harvest. The two species were planted in an alternate pattern. Each plot was 10 x 10 m² for wheat as well as for pea, and 12 x 10 m² for maize, respectively, and included five subplots (5 x 2 x 10 m²) for wheat and pea, and eight subplots (8 x 1.5 x 10 m²) for maize. Within those subplots, data was collected (Table 2) in order to detect crop performance differences between different distances from the plot border. The plots were big enough to reflect monocropping within the central subplot. Row orientation was from north to south.

In both years, the previous crop was sugar beet and soil preparation and sowing was done by a reduced tillage system. Plant protection was carried out according to ‘Good Agricultural Practice’.

The wheat variety ‘Cubus’ was sown in October 2007 and 2008 with a row spacing of 13 cm and a plant density of 300 plants per m^2. Maize (‘Companero’) was sown in May 2008 and 2009 with a row spacing of 75 cm and a plant density of 10 plants per m^2. The fieldpea variety ‘Hardy’ was sown between end of March and beginning of May 2008 and 2009 with a row spacing of 13 cm and a plant density of 70 plants per m². Harvest of wheat and pea was at the end of July. Maize was harvested in October.

Wheat was fertilized with 160 kg N ha^{-1}, split into three dispensations (60/60/40) of Nitro-chalk. Maize was fertilized once with 160 kg N ha^{-1} (ENTEC). Fieldpea as a leguminous plant was not fertilized at all.

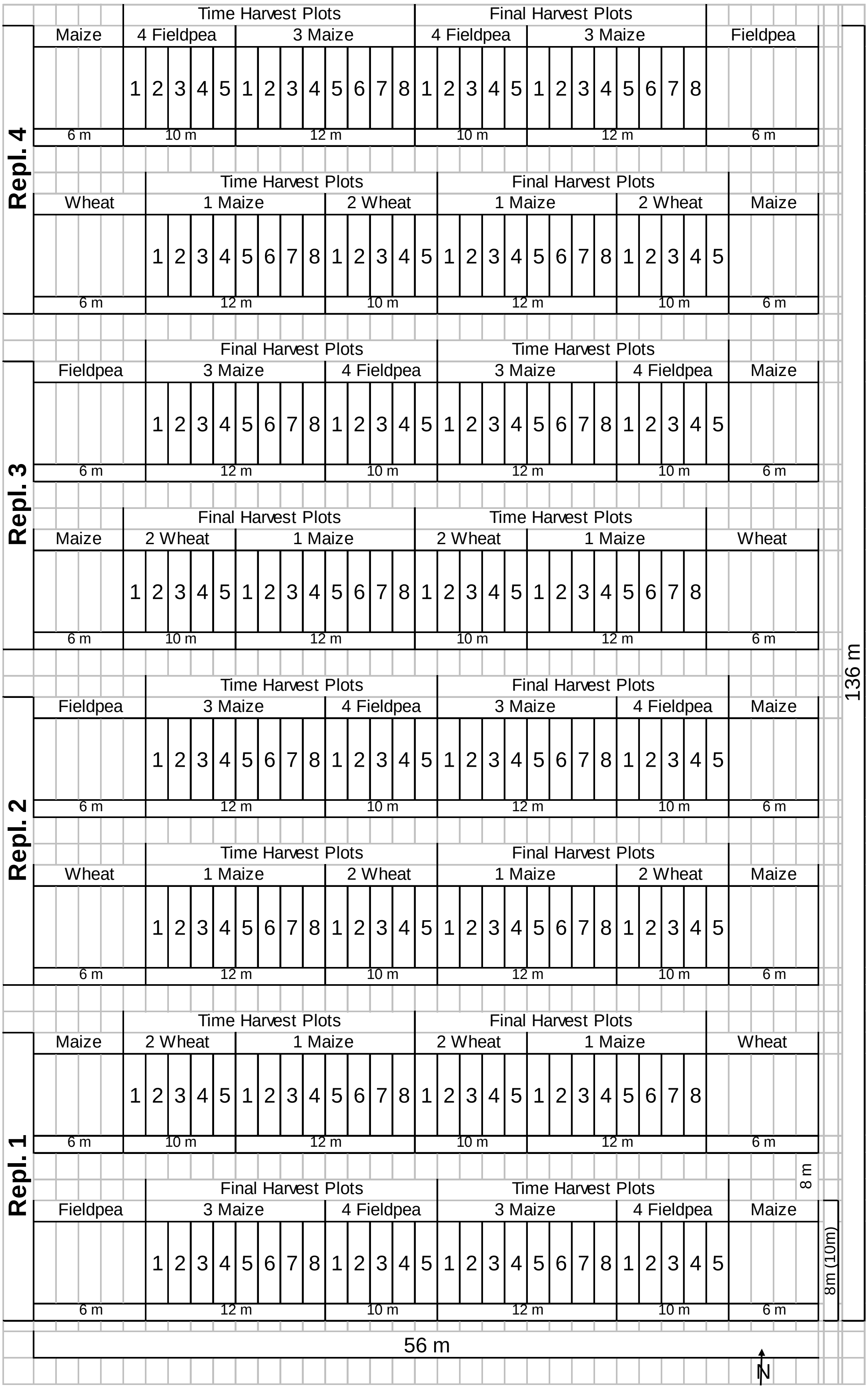

Figure 5: Field layout of the field trial in Germany for the years 2007 to 2009.

During both growing seasons, neither water nor nitrogen (N) stress occurred so that differences in plant growth and yield performance could be attributed onto intra- and interspecific competition. Weekly measurements of soil water content between end of May and beginning of July with a Trime-TDR-system (time domain reflectometry) from IMKO GmbH (Ettlingen/Germany) indicated that no water shortage occurred during the two growing seasons.

Three temporal harvests according to the DSSAT guide were carried out as square meter cuts, and grain yield, dry matter, and nitrogen concentration of plants were analyzed 2007 - 2009. Nitrogen concentration was determined with the NIRSystems 5000 (ISI-Software, USA). In addition, N_{min} content of soil was determined at the beginning of the growing season and after harvest according to VDLUFA methods (VDLUFA, 1991). In addition, in the year 2009, five N_{min} samples were taken weekly between May and June in wheat, three in pea and two in maize, in order to detect differences between N budgets within different subplots. Soil temperature was determined in 2 cm soil depth with the testo 925 (Testo AG, Lenzkirch/Germany) on a weekly basis as well as solar radiation with the AccuPAR LP-80 (UMS, München/Germany) and the testo 545 (Testo AG, Lenzkirch/Germany) 2007 - 2009. Wind speed was measured in the year 2009 above the canopy with anemometer compact (Thies Clima, Göttingen/Germany). Growing stages according to the BBCH scale (Meier, 1997) and plant height were reported on a weekly basis. After the final harvest, yield and yield components like thousand kernel weight (TKW), tiller number, ears or pods per plant as well as N concentration and N uptake were determined for all crops.

Table 2: Description of data and parameters collected and evaluated during the experiments 2007 – 2009 in Germany.

Data / Parameter	Determination
Plant growth stage	2007 -2009: documented weekly from emergence to maturity using the BBCH scale (Meier, 1997)
Plant density	2007 – 2009: wheat/pea: 0.7 m² counted (2 rows x 2.75 m x .0,13 m) maize: 1 m² counted (2 rows x 0.66 m)
Plant height	2008 – 2009: measured weekly between May and July
N_{min}	2007 – 2009: determined at the beginning of the growing season and after harvest according the VDLUFA methods (VDLUFA, 1991) 2009: between May and June weekly samples (5 x wheat, 3 x pea, 2 x maize)
Soil moisture	2008 – 2009: between May and July weekly measurements with the Trime-TDR-system (IMKO GmbH, Ettlingen/Germany)
Solar radiation	2008 – 2009: measured weekly between April and July with the AccuPAR LP-80 (UMS, München/Germany) and the testo 545 (Testo AG, Lenzkirch/Germany)
Soil temperature	2008 – 2009: measured weekly between May and June with the testo 925 (Testo AG, Lenzkirch/Germany)
Wind speed	2009: measured above the canopy continuously during the growing season with anemometer compact (Thies Clima, Göttingen/Germany)
LAI	2008: between May and June weekly destructive LAI determination within wheat with the LI-3100 Area Meter (LI-COR, Lincoln/Nebraska USA) 2008 – 2009: between May and July weekly non-destructive LAI determination with the LAI-2000 Plant Canopy Analyzer (LI-COR, Lincoln/Nebraska USA)
N/C concentration	2008 – 2009: time and final plant harvest samples were analyzed with the NIRSystems 5000 (Foss, Rellingen/Germany; ISI-Software/USA)

Data / Parameter	Determination
Time harvests - dry matter -	2008 – 2009: three square meter cuts during the growing season maize: 1st at BBCH 16, 2nd at BBCH 63, 3rd at BBCH 85; wheat: 1st at BBCH 13, 2nd at BBCH 65, 3rd at BBCH 85; pea: 1st at BBCH 14, 2nd at BBCH 67, 3rd at BBCH 79
Time harvests - grain yield -	2008 – 2009: three samplings every second week after anthesis wheat: 10 ears/subplot cut, dried and weighted maize: 4 ears/subplot cut, dried and weighted
Final harvests	2008 – 2009: square meter cuts for determining dry matter; harvesting of subplots with Hege 180 for determining grain yield (15.5 m² of wheat and pea, 11 m² of maize)
Yield components	2008 – 2009: TKW ears/pods per plant kernels per pod number of tillers per m²

3 Publications

The thesis consists out of six chapters which have been published, accepted or submitted as papers to peer-reviewed and international high standard referenced journals or books. For citation of chapters I-VI, please use the references given below.

CHAPTER I:

Knörzer, H., Graeff-Hönninger, S., Guo, B., Wang, P., and Claupein, W. (2009): The rediscovery of intercropping in China: a traditional cropping system for future Chinese agriculture. Springer Series: Sustainable Agriculture Reviews 2: Climate Change, Intercropping, Pest Control and Beneficial Microorganisms, ed. by E. Lichtfouse. Springer Science+Business Media, Berlin, pp. 13-44.

CHAPTER II:

Knörzer, H., Graeff-Hönninger, S., Müller, B.U., Piepho, H.-P., and Claupein, W. (2010): A modeling approach to simulate effects of intercropping and interspecific competition in arable crops. International Journal of Information Systems and Social Change 1 (4), pp. 44-65.

CHAPTER III:

Knörzer, H., Müller, B.U., Guo, B., Graeff-Hönninger, S., Piepho, H.-P., Wang, P., and Claupein, W. (2010): Extension and evaluation of intercropping field trials using spatial models. Agronomy Journal 102 (3), pp. 1023-1031.

CHAPTER IV:

Knörzer, H., Graeff-Hönninger, S., and Claupein, W. (2010): Model-based approach to quantify and regionalize peanut production in the major peanut production provinces in the People’s Republic of China. GI-Edition - Lecture Notes in Informatics „Precision Agriculture Reloaded – Informationsgestützte Landwirtschaft”, pp. 101-104.

CHAPTER V:

Knörzer, H., Grözinger, H., Graeff-Hönninger, S., Hartung, K., Piepho, H.-P., and Claupein, W. (2010): Integrating a simple intercropping algorithm into CERES-wheat and CERES-maize with particular regard to a changing microclimate within a relay-intercropping system. Field Crops Research (in press).

CHAPTER VI:

Knörzer, H., Lawes, R., Robertson, M., Graeff-Hönninger, and Claupein, W. (2010): Evaluation and performance of the APSIM crop growth model for German winter wheat, maize and fieldpea varieties in monocropping and intercropping systems – a critical review. Journal of Agricultural Science and Technology (submitted).

4 Chapter I:

The rediscovery of intercropping in China: a traditional cropping system for future Chinese agriculture

PUBLICATION I:

Knörzer, H., Graeff-Hönninger, S., Guo, B., Wang, P., and Claupein, W. (2009): The rediscovery of intercropping in China: a traditional cropping system for future Chinese agriculture. Springer Series: Sustainable Agriculture Reviews 2: Climate Change, Intercropping, Pest Control and Beneficial Microorganisms, ed. by E. Lichtfouse. Springer Science+Business Media, Berlin, pp. 13-44.

The first chapter marks the status quo of intercropping practice and intercropping research in China as well as a starting point of future research within that topic. The term ‘rediscovery’ might be misleading as various multiple cropping systems, especially intercropping, are existing, practiced and developed in China, and the agricultural history of those systems is as long as diversified. Nevertheless, the term should acknowledge the vulnerability of a cropping system often considered as a typical cropping pattern for African and Asian smallholder farming, and stigmatized as old-fashioned and hand-labour dominated. Thus, the chapter should give a brief overview over the potential of intercropping regarding its tradition and distribution as well as its contributions for an increase in sustainability within existing cropping systems. In addition, integrating intercropping into modern scientific research methods led to several international scientific publications which increased the knowledge of species combination and interspecific competition in intercropping. Basically, the study was a literature review aiming to answer the question: ‘What were and what are the contributions and extent of intercropping of cereals for Chinese agriculture in past, present and future?’ The spectrum of intercropping is even broader than described here where the main emphasize was laid upon intercropping of cereals leaving aside vegetables and trees. There is obviously a vast amount of different intercropping systems in China. But in comparison to some African countries or India, the systems seem to be less documented and studied. Still, there are many black dots on the map of Chinese intercropping. The study is a first approach to comprehend basic definitions, tradition, provincial practice, and potential as well as international research efforts on intercropping of cereals in China.

The rediscovery of intercropping in China: A traditional cropping system for future Chinese agriculture – a review

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The story of intercropping in China is more than thousand years old, and intercropping is still widespread in modern and traditional Chinese agriculture. Nowadays, agricultural systems in China are stigmatized to exhaust high levels of input factors like mineral fertilizer, irrigation water or pesticides. This contributes severely to environmental problems like desertification, river eutrophication, soil degradation and greenhouse gas emissions. In this context, monocropping systems have to be revised and may not be the best performing systems any more with regard to sustainability, income security and nutritional diversity in rural areas. In contrast, intercropping systems offer alternatives for a more sustainable agriculture with reduced input and stabilised yield. Especially in the last decade intercropping is rediscovered by scientific research. Studies showed increased yield of cereals intercropped with legumes: Chickpea facilitates phosphorus uptake by associated wheat, maize intercropped with peanut improves iron nutrition and faba bean enhances nitrogen uptake when intercropped with maize. China's intercropping area is the largest in the world. Nevertheless, there are only few international studies dealing with intercropping distribution, patterns and crops. Most studies deal with nutrient use efficiency and availability. This study is a first approach to gain an overview over Chinese intercropping history, patterns and determinants of interspecific facilitation and competition. Finally, four intercropping regions could be distinguished and explicitly described with their intercropping intensity, potential and conditions.

Publication link:
http://www.springer.com/life+sciences/agriculture/book/978-90-481-2715-3

5 Chapter II:

A modeling approach to simulate effects of intercropping and interspecific competition in arable crops

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PUBLICATION II:

Knörzer, H., Graeff-Hönninger, S., Müller, B.U., Piepho, H.-P., and Claupein, W. (2010): A modeling approach to simulate effects of intercropping and interspecific competition in arable crops. International Journal of Information Systems and Social Change 1 (4), pp. 44-65.

Whereas chapter I was an overview on intercropping in China as such, the second chapter deals with the modeling and simulation of intercropping and interspecific competition. The chapter addresses the questions of: how was knowledge about competition effects used and transferred to crop growth models and simulations so far? Which models dealt already with intercropping and interspecific competition effects? What single or multiple effects were considered, modeled, and in which way? Within this modeling intercropping thesis at hand, chapter I is a literature review about the status quo of 'intercropping', and chapter II is a literature review on the status quo of 'modeling' of those systems. Both studies generated the basis on which further modeling within that thesis was done and assessed. On the one hand, the review showed what has been done and what has been possible to model or simulated intercropping so far. Yet, it showed its limitations as well as, as a result, a first approach to model intercropping of cereals with DSSAT and with a basically different procedure. Thus, it shows an alternative and for further researches a promising way to handle intercropping within modeling and simulation, wherefore the second part of chapter II could be considered as a theoretical framework or concept and a starting point for further intercropping studies with DSSAT as well as other crop growth models. The theoretical approach of integrating a shading algorithm into the model as well as considering microclimate differences within intercropping systems was shown and evaluated using own field data of a wheat-maize intercropping system.

A Modeling Approach to Simulate Effects of Intercropping and Interspecific Competition in Arable Crops

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Simone Graeff-Hönninger, Universität Hohenheim, Germany
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Intercropping, defined as the growing of two or more crops simultaneously on the same field, is widespread all over the world. Especially in smallholder farming like Africa (e.g. Malawi: 80 – 90 % of soybean cultivation), India (17 % of arable land) or China (25 % of arable land), intercropping is a common cropping system for past and future agriculture. In times of climate change, rising food prices and shortage of arable land and food in third world countries and countries with a rapidly increasing population, adjusted traditional cropping systems become more and more important. Farmers tend at least to utilize every centimetre of available arable land for production and for diversification of their families diet. Besides, there is a so called unconscious intercropping. Because fields and farm size are very small (< 0.1 – 0.5 ha), the sum of field borders can be considered as intercropping in a larger scale.

Intercropping is very interesting for modern research, as it is considered to be an embryonic form of sustainable and ecological farming (Gong et al., 2000). Improving and adjusting those cropping system is getting more and more important wherefore the simulation of intercropping or interspecific competition might be a useful tool to successfully adjust and optimize the combination of intercropped plants. However, most models simulate the effect of intercropping using a similar model approach for simulating e.g. competition for solar radiation. The development of a general competition algorithm to be introduced as a submodel in existing crop models might be a chance to promote the intercropping research turning from evaluating and validating to adjusting. Nevertheless research still strikes for finding and proving such a general algorithm. In addition, introducing a generalized submodel is not easy to handle all over the various models and needs sometimes a reprogramming of the model. After all, it would be a competition submodel for solar radiation and not for interspecific competition at all.

The paper mentions case studies in which various existing intercropping models have been successfully validated. It ranges from being applied in European organic farming systems to the simulation of maize and legumes growth and development in Africa as well as the prediction of performance of intercropped vegetables. Based on the evaluation of existing models research gaps were identified and a simple submodel for the simulation of intercopping was developed and introduced in the process-oriented crop growth model DSSAT 4.5. The model approach was developed and validated based on own field data and compared to other intercropping model approaches.

Literature about intercropping and intercropping behaviour was studied. In addition, literature about intercropping modeling approaches was reviewed in order to detect suitable models for simulation and application. Around 20 different models are described for modeling interspecific competition in a different way. In addition, a new model approach was developed and tested with own field data by introducing a simple algorithm for intercropping in the DSSAT crop growth model. Field trials were conducted in Germany with a wheat/maize and a pea/maize intercropping system within a non-randomized complete block design and four replications. In a first step, different behaviour of intercropped species was studied with special regard to borderline effects and final yield. In a second step, the DSSAT model was evaluated to simulate these intercropping systems. In comparison to other intercropping model approaches, a new algorithm was introduced into existing model files according to the measured field-data. Field trials showed that not only competition for water and solar radiation occurs, but also wind speed and soil temperature influenced crop performance. Aboveground interactions and therefore microclimate changes play an important role in intercropping systems with species behaving and reacting different to those impacts. E.g. reducing the effective LAI – as done in some model approaches - of the understorey species when shading occurs and the dominant species reaches a special height is a possible tool to simulate intercropping but does not reflect the real or basic biological status quo as LAI is not decreased indeed.

Results of this study identified two different starting points for a modelling approach of intercropping. The most common one is to extend a sole crop model with a submodel concerning an intercropping situation. Similarly, a usually crop-weed or a multispecies ecosystem model was extended to model the crop performance considering interspecific competition. The other approach is to draw near the competitive effects more theoretical with data from literature, mathematical and dimensional assumption. In most cases, the models have similar basic assumptions, especially when considering competition for solar radiation. In fact, light interception and solar radiative transfer are the most often considered competitive factors. In a lot of approaches the basic modeling assumption is that radiation fluxes within a canopy are according to an extended Beer’s law. As well as, for most intercropping models, the turbid layer medium analogy, dividing the competing species into different canopy layers and calculating light interception for each layer, have been proofed to be suitable. The various models draw near those components through different approaches, e.g. to reduce LAI, to model light interception individually in each canopy layer or to introduce a competition function. There are various approaches and those various approaches seem to be promising and prolific to each other, but there is still a gap between the modeling of case studies and the application of those models and the adjustment of existing cropping systems. To extent the point of view from competition parameters like solar radiation to a whole species view, e.g. to subdivide not only the canopy layers but also the within species effects and to model one species as the sum of subspecies behaviour under different intercropping related environmental circumstances, as done successfully with the DSSAT model, is a more generalized but therefore a more comprehensive and integrative approach. This model study is a first attempt to simulate strip intercropping with a complete different algorithm and approach than other intercropping models in order to allow different intercropping scenarios or designs with regard to adjust cropping systems.

<u>*Publication link:*</u>
http://www.igi-global.com/bookstore/Article.aspx?TitleId=47181

6 Chapter III:

Extension and evaluation of intercropping field trials using spatial models

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PUBLICATION III:

Knörzer, H., Müller, B.U., Guo, B., Graeff-Hönninger, S., Piepho, H.-P., Wang, P., and Claupein, W. (2010): Extension and evaluation of intercropping field trials using spatial models. Agronomy Journal 102 (3), pp. 1023-1031.

After reviewing and studying a wide range of publications dealing with intercropping, a basic issue in designing and later on analyzing intercropping experiments was identified. At least row, strip, and relay intercropping experiments contravene one of the three fundamental statistical principles as there are blocking, replication, and randomization. The latter cannot be fulfilled as row and strip intercropping systems require alternating rows or strips. Thus, spatial variability has not been taken into consideration so far while analyzing row or strip intercropping systems with a common analysis of variance. As a result, detected significant differences between treatments or traits such as yield or yield components bear the potential of being estimated in a too optimistically manner. The application of spatial models for analyzing row and strip intercropping trials and for improving the model fit are suggested. In chapter III, several spatial models were presented, tested, and applied for the German and Chinese field experiments during 2007 and 2009. In addition, the question arose, if small fields within fragmented agricultural landscapes, like parts of China, are intercropping in a larger scale? Intercropping is based upon field border effects, and hence, the sum of field borders becomes important within those landscapes when analyzing crop performance. Again, the spatial dimension of intercropping has to be considered and is shown in the following chapter.

The publication of this chapter had been announced for the Research Highlight Program 2010 of the American Society of Agronomy, the Crop Science Society of America, and the Soil Science Society of America (ASA-CSSA-SSSA).

Extension and evaluation of intercropping field trials using spatial models

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Intercropping, defined as the cropping of two or more crops grown simultaneously on the same field is mainly practiced in Asia and Africa where smallholder tend to make the best use of their tiny fields in time and space. But analyzing intercropping experiments in the context of finding the most suitable combination of possible partners bears some constraints. Experimental arrangements lack in randomization as the cropping system imposes alternating strips. Thus, spatial variability and its effects have to be regarded differently. In addition, intercropping has often been considered as a secluded cropping system within one field. However, the more fragmented the agricultural landscape, the more relevant the borders can become: small fields alternate as strips with different crops grown on them turn the collection of fields into a kind of unplanned intercropping.

The study analyzed the effect of field boundaries on crop performance and the peculiarities of intercropping designs in order to broaden the view on intercropping to a spatial dimension. Considering crop yield in fragmented agricultural landscapes, it might not be sufficient to gauge the yield of a small field as a whole as there is a yield distribution in those fields. Cultivation practice or variety influence could be overestimated when neglecting competition effects. A spatial analysis could account for these factors.

Field trials were conducted in China and Germany over the years 2007-2009. Experiments were designed in four non-randomized complete blocks. Each block contained a maize/peanut system in China and a maize/pea and a maize/wheat system in Germany with crops grown in alternating plots. Each plot included different strips determined by the distance from plot border. Data of each strip within the plots were collected. To detect significance of response differences between strips with different distances from the field border, a mixed model with fixed position effects and a random effect modeling the spatial trend by covariance structures was fitted for different traits. Different spatial models were added on to the baseline model to account for the spatial trend within plots.

The results showed that for the German experiment the baseline model fitted well in the year 2008 and a common analysis of variance seemed to be well suited. However, for the Chinese experiments and the German experiment in the year 2009 the spatial models improved the model fit. Statistical analysis of intercropping experiments has been done by a simple analysis of variance without taking the impossibility of randomization into account. By using simple analysis of variance, significant differences could be estimated in a too optimistically way. Applying spatial models could help to improve the model fit and the precision of the estimates. As a general strategy, the authors propose to start the analysis of intercropping experiments by a baseline model and to extend by spatial add-on components.

Publication link:
https://www.crops.org/publications/aj/abstracts/102/3/1023

7 Chapter IV / Excursus:

Model-based approach to quantify and regionalize peanut production in the major peanut production provinces in the People's Republic of China

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PUBLICATION IV:

Knörzer, H., Graeff-Hönninger, S., and Claupein, W. (2010): Model-based approach to quantify and regionalize peanut production in the major peanut production provinces in the People's Republic of China. GI-Edition - Lecture Notes in Informatics „Precision Agriculture Reloaded – Informationsgestützte Landwirtschaft", pp. 101-104.

Chapter IV is a potential peanut yield study in four major peanut producing provinces in China without differentiating between intercropping and monocropping systems. Therefore, the study does not predominantly deal with intercropping and could be classified in this context as an excursus. As the peanut crop was part of the Chinese field experiments, the potential yield study was included into this thesis in order to gain an overview over yield and yield potential in the provinces Shandong, Anhui, Hebei, and Henan, the latter three being part of the study region 'North China Plain'. Like in chapter III, the DSSAT model was chosen. Peanut yield data for the different provinces was taken from the China Provincial Statistical Yearbooks, and collected soil as well as weather data from previous project members could be used to evaluate and validate the model, to account for provincial differences, and to analyze yield potential in a long-term point of view. Special regard was given to water supply and water shortage as precipitation is a major limiting factor of peanut production within the North China Plain.

Model-based approach to quantify and regionalize peanut production in the major peanut production provinces in the People's Republic of China

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China is the largest peanut producer in the world. Therefore, peanut is an essential economic product pulling in significant sales for Chinese farmers. The major provinces for peanut production are located in the middle and eastern provinces which partly belong to the North China Plain. In these regions, especially drought stress between germination and pod setting could be severe. As a result, yields decline because of uneven rainfall and climate variability. In the North China Plain, 50-75% of the total rainfall occurs between July and September. In most years, the amount of rainfall is enough to satisfy the demand. Water shortage may occur at the beginning of the growing season and may last until the critical phase of pod setting approximately 50 days after sowing.

Four provinces – Anhui, Hebei, Henan and Shandong - were selected for modeling and simulating large area yield estimation in order to evaluate potential production scenarios with regard to average rainfall in each particular region. Measured average yield during the regarded years ranged from 2918 kg ha^{-1} to 3969 kg ha^{-1} with a mean yield of 3420 kg ha^{-1} and a mean simulated yield of 3422 kg ha^{-1}. The model showed a good fit between observed and simulated data with a RMSE of 252 kg ha^{-1}. Model error was 7.4%.

The simulation showed furthermore that for Anhui and Henan, the long-term average rainfall met the demand of peanut. No supplement irrigation would be needed. In contrast, the average rainfall in Hebei and especially in Shandong was not enough to satisfy the demand. Without irrigation, peanut yield decreased notable in Shandong. The sandy soils predominant in Shandong were more likely to desiccate than the silty soils in the other provinces.

In conclusion, the CROPGRO-Peanut model as part of the DSSAT software shell was able to simulate and estimate large area yield for the four major peanut producing provinces in China. To study the potential yield of peanut with special regard to water demand, the approach was useful comparing possible lacks in demand with average rainfall.

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http://www.gi.de/service/publikationen/lni/gi-edition-proceedings-2010/gi-edition-lecture-notes-in-informatics-lni-p-158.html

8 Chapter V:

Integrating a simple intercropping algorithm into CERES-wheat and CERES-maize with particular regard to a changing microclimate within a relay-intercropping system

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PUBLICATION V:

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The modeling approach presented in chapter II was further developed and is presented in the following chapter. In comparison to the one year dataset used in chapter II, the complete dataset of the field experiments from 2007 to 2009 was taken. In addition, the influence of different or changing microclimates within two different intercropping systems were analyzed and considered in more detail. Two major aspects contributed to the outcome of chapter V. The first one was for sure that the first model run (chapter II) and the concept of introducing a shading algorithm to modify the weather input for the model instead of introducing an additional submodel routine into DSSAT seemed to be promising. Thus, an additional dataset was necessary to test the model performance further on. The second one was that there was some kind of development within the ongoing field trials between the first and the second experimental year. During and after data collection and analysis in 2008, different aspects, effects, and issues evolved. Competition within intercropping seemed not to be restricted to competition for solar radiation solely, but in contrast much more influenced by multiple factors of changing microclimate. Thus, spatial and temporal measurements like wind speed and soil temperature had to be extended in the second year in comparison to the first year. Additional N_{min} samples were needed, too. As a result, the shading algorithm as well as microclimate influences could be considered in the modeling approach and the simulation of strip intercropping and were the main objectives of the following chapter.

Integrating a simple shading algorithm into CERES-wheat and CERES-maize with particular regard to a changing microclimate within a relay-intercropping system

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Combined wheat and maize cropping systems are the dominant multi-cropping systems in the North China Plain. To improve and adjust those systems and to study interspecific competition effects, large scale field experiments are necessary. Because field experiments are time consuming, labour intensive and expensive, a feasible alternative is the use of crop growth models that can quantify effects of management practices such as fertilization and tillage on crop growth and productivity. Field experiments showed that intercropped maize had similar yields compared with monocropped maize, and grain yield of intercropped wheat increased by up to 32%. Based on a process-oriented modeling approach, this study focuses on analyzing and modeling competitive relationships in a wheat/maize relay intercropping system with special regard to yield, solar radiation and microclimatic effects. A simple shading algorithm was applied and integrated into the CERES models, which are part of the DSSAT software shell vs. 4.5. The algorithm developed estimates the proportion of shading as affected by neighboring plant height. The model was tested to investigate the applicability of the shading algorithm within the CERES models when simulating grain and dry matter yield of wheat and maize. Model error of grain and dry matter yield for both species was below 10%. There was a tendency for grain yield to be simulated adequately but for dry matter yield to be slightly underestimated. Increased top soil temperature in intercropped wheat increased the mineralization of nitrogen and improved nitrogen supply. The wheat/maize relay system was nitrogen efficient. Thus, nitrogen dynamics were taken into account as well as CO_2 dynamics based upon wind speed. Wheat border rows were exposed to a higher wind speed until mid-June and to reduced wind speed thereafter. As a result, solar radiation, soil temperature and wind speed were different between monocrops and intercrops. Those microclimatic effects could provide a starting point for simulating intercropping. Microclimate effects are often small, subtle or non-existent while, in contrast, spatial and climate variability and the heterogeneity of plant populations can be considerable. Quantifying those effects may prove difficult but should not be neglected when modeling intercropping systems.

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9 Chapter VI:

Evaluation and performance of the APSIM crop growth model for German winter wheat, maize and fieldpea varieties within monocropping and intercropping systems – a critical review

PUBLICATION VI:

Knörzer, H., Lawes, R., Robertson, M., Graeff-Hönninger, and Claupein, W. (2010): Evaluation and performance of the APSIM crop growth model for German winter wheat, maize and fieldpea varieties in monocropping and intercropping systems – a critical review. Journal of Agricultural Science and Technology (submitted).

The basic idea behind chapter VI was to use two different models concerning their intercropping simulation approach to test both approaches with the same dataset and to compare the outcome. The intention was less to determine an inferior or superior intercropping modeling approach, but to improve the knowledge how to model interspecific competition within strip intercropping and to study the contribution and extent of different competition algorithms on crop performance. Otherwise, without such a comparison or suggestion, the question is reliable, why evaluating another competition model instead of improving already existing ones (chapter II)? For that study or comparison, the APSIM crop growth model was chosen because of three reasons: 1) APSIM is based upon DSSAT in its development and previous version and thus, in both models monocropped species are modeled in a similar manner and with similar assumptions; 2) APSIM has been used in several multiple cropping studies instead of just one case study so far and seemed to be a useful and validated tool; 3) The APSIM competition algorithm and approach is based upon Beer’s law, often used in other models studies (chapter II). As APSIM has been used predominantly for Australian crop growing conditions, the model had to be calibrated for temperate European zones conditions in a first step. Results from the previous chapter were taken then to compare the differences between the DSSAT and the APSIM intercropping modeling approach.

Evaluation and performance of the APSIM crop growth model for German winter wheat, maize and fieldpea varieties within monocropping and intercropping systems – a critical review

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Competition for solar radiation between plants grown in multi-species cropping systems can severely limit crop production of individual species within that system. There are various approaches for modeling light interception within mixed-cropping and row or strip intercropping systems. To extend the knowledge about model behavior and different model approaches under interspecific competition conditions, the APSIM model was evaluated and calibrated for field experiments previously described and simulated by DSSAT. Initially the APSIM plant model was successfully modified to simulate wheat, maize and fieldpea monocultures in the European agro-ecological zone. Once calibrated, the APSIM model was then used to simulate a strip relay intercropping maize/wheat and maize/fieldpea system. In DSSAT, a shading algorithm was introduced to modify the daily weather input in order to take competition for solar radiation into account. In addition microclimate influences were modified for the relay intercropping system. In contrast, APSIM simulates interspecific competition using the canopy module, which is based on a modified Beer's law for multi-component or mixed canopy conditions, and a routine that defines soil water and nutrient supply for each species component in a daily alternating manner. After a re-evaluation of the model regarding a minimum change of crop coefficients and variables, APSIM was able to simulate dry matter and grain yield of German maize, winter wheat and fieldpea varieties adequately. However, APSIM is a point-based model, and many of the processes that influence strip cropping cannot be accommodated by adjusting Beer's Law alone. So far none of the tested frameworks successfully modeled strip or relay intercropping. The processes governing growth in the numerous and very diversifying intercropping systems are complex and at this point in time have not been captured in sufficient detail. Further modifications to DSSAT and APSIM are required to successfully simulate strip or relay intercropping. We discuss some of the key changes that need to be made to these models to simulate strip intercropping systems.

Introduction

Adjusting cropping systems in order to increase their efficiency is a global issue. High yield and sustainability are the catchphrases of production in the 21st century, and agricultural production has to solve the balancing act between ecology and economy. Therefore, the demands on farmers, consultants and researchers are rising and production modes are changing. Nevertheless, solutions need to be found, accepted and implemented locally in order to be successful. The use of modeling and simulation tools supports the acceleration of research attainments and the understanding of cropping systems. The application of crop growth models has increasingly become a scientific tool for the analysis of cropping systems. Those models have mostly been evaluated for monocrops. With the paradigm of sustainability in mind, the modeling of mixed cropping and intercropping systems is of increasing interest. In the intercropping research context the following benefits appear repeatedly [14]: maximized land use, several harvests per year, yield stability, increased resource use efficiency, reduced soil erosion and leaching, reduced pests and diseases. The simulation of both systems, intercropping and monocropping, requires robust and carefully evaluated and validated models. There are various approaches to modeling intercropping and interspecific competition [5][15]. Most of these approaches deal with the modeling of competition for solar radiation in mixed species canopies [12]. In this paper, two issues of modeling are addressed.

1.) A brief methodology of calibrating a crop growth model for monocropping and intercropping scenarios is shown. For this, the APSIM model (Agricultural Production Systems Simulator) [17][18] was chosen.

2.) A comparison between two different modeling intercropping approaches was carried out to gain further insight into the methodology models used to capture the competitive processes that govern plant growth and development in these systems. This is combined with a critical review of persisting shortcomings concerning the modeling of strip and relay intercropping systems. DSSAT (Decision Support System for Agrotechnology Transfer) [11] was chosen for comparison with APSIM.

The process-oriented APSIM Vs 7.1 (www.apsim.info/Wiki/APSIM-Documentation.ashx) crop growth model was used to model monocropping and intercropping experiments. APSIM is a dynamic soil-plant-atmosphere model, similar to the DSSAT Vs 4.5 crop growth model, which allows modeling and simulation of crop and pasture production, residue decomposition, soil water and nutrient flow and management influences.

Previous versions of the cereal models – e.g. APSIM-Nwheat [2] -, included into APSIM were mainly based upon the DSSAT CERES models. In addition, the evaporation algorithm developed by Ritchie [25] is used in both models. Thus, DSSAT and APSIM share a common set of modeling features. Nevertheless, APSIM was revised [1][8][23] and the version 7.1, used in this study, differed from earlier versions. For example, changes were made to the number of plant stages in the wheat module.

In contrast to DSSAT, APSIM includes a competition model that allows the simultaneous simulation of two crops competing for solar radiation, soil water and nutrients to a limited extend. Additionally, APSIM and DSSAT differ in modeling incoming solar radiation and photosynthetic active radiation (PAR). DSSAT uses the approach described by Spitters et al. [30]; APSIM uses the Beer’s law approach described by Monsi and Saeki, [21]. In addition, the simulation of relay intercropping with the DSSAT model [16] pursues a different approach than with the APSIM model [6]. In DSSAT, a shading algorithm as well as modified microclimate influences were taken into account in this study by modifying the daily weather input with particular regard to solar radiation and the initial conditions within the relay intercropping system. In contrast, APSIM simulates interspecific competition using the canopy module based on a modified Beer’s law for multi-component or mixed canopy conditions and a routine that defines soil water and nutrient supply for each species component in a daily alternating manner. Various canopy layers are defined starting at the top of the tallest canopy which is equal to the plant height of the dominant species in the system. The fraction of light transmitted out of the top layer can be calculated, and this in turn is the fraction entering the next layer below [4].

In this paper, we demonstrate a methodology for calibrating the APSIM model for a monocropping system in temperate European zones , a region where it had not previously been used. We then compare and contrast the two different modeling intercropping approaches employed in APSIM and DSSAT [16] to gain further insight into the methodology the models use to capture the competitive processes that govern plant growth and development in these systems. Finally we critically review the shortcomings concerning the modeling of intercropping systems.

Material and methods

Field experiments 2007 to 2009

Experiments were conducted in southwest Germany at the University of Hohenheim experimental station ‘Ihinger Hof’ during the years 2007 to 2009. The station is located 48.46°N and 8.56°E and has an average temperature of 7.9°C per year, an average rainfall of 690 mm per year and 1674 average sunshine hours per year. Dominant soils are silty loamy medium-deep para-brown colored soils over loess, classified as *Orthic Luvisols* [10].

The experiment comprised a maize/wheat relay intercropping system as well as a maize/fieldpea intercropping system, each within a complete block design with four replications. Thus, each replication contained complete blocks of both systems and each system’s replication consisted of four plots (Figure 1). Two plots were used for sequential harvests and weekly measurements during the growing season and another two plots were used for the final harvest. The two species were planted in an alternate pattern. Each plot was 10 x 10 m² for wheat and for pea, and 12 x 10 m² for maize, and included five subplots (5 x 2 x 10 m²) for wheat and pea, and eight subplots (8 x 1.5 x 10 m²) for maize. Within those subplots, data was collected to detect crop performance differences between different distances from the plot border. The plots were large enough for the central subplot to effectively represent a monocropping system. Row orientation was from north to south.

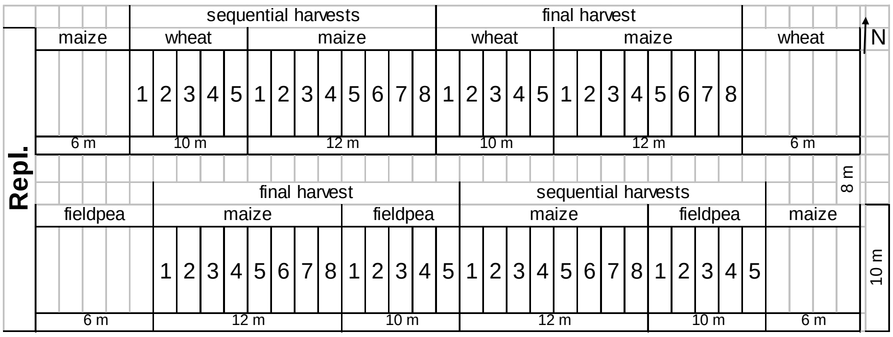

Figure 1: Experimental design of the strip/relay intercropping systems maize/winter wheat and maize/fieldpea during the years 2007 to 2009. Field trials were conducted in southwest Germany

In both years, the previous crop was sugar beet and soil preparation and sowing was done by a reduced tillage system. Plant protection was carried out according to ‘Good Agricultural Practice’.

The wheat variety ‘Cubus’ was sown in October 2007 and 2008 with a row spacing of 13 cm and a plant density of 300 plants per m^2. Maize (‘Companero’) was sown in May 2008 and 2009 with a row spacing of 75 cm and a plant density of 10 plants per m^2. The fieldpea variety ‘Hardy’ was sown between the end of March and the beginning of May in the years 2008 and 2009 with a row spacing of 13 cm and a plant density of 70 plants per m². Harvest time of wheat and pea was at the end of July. Maize was harvested in October.

Wheat was fertilized with 160 kg N ha^{-1}, split into three applications (60/60/40) of Nitro-chalk. Maize was fertilized once with 160 kg N ha^{-1} (ENTEC). Fieldpea, being a leguminous plant, was not fertilized.

Three sequential harvests were carried out as square meter cuts, and grain yield, dry matter and nitrogen (N) concentration of plants were analyzed for the years 2007 - 2009. Nitrogen concentration was determined with the NIRSystems 5000 (ISI-Software, USA). Growing stages according to the German BBCH [19] scale and plant height were reported on a weekly basis. After the final harvest, yield and yield components such as thousand kernel weight (TKW), tiller number, ears or pods per plant as well as N concentration and N uptake were determined for all crops.

Model set-up

For the monocropping model approach, the APSIM crop growth model version 7.1 was applied. Datasets for soil characteristics and daily weather (©<Hohenheimer Klimadaten>) for the years 2007 to 2009 were identical to those used for the DSSAT modeling approach [16]. Initial nitrogen content for the soil model was set according to mineralized nitrogen content (N_{min}) measurements taken for each crop at the beginning of the growing season. Management input variables such as sowing date, sowing density, sowing depth, fertilizer application as well as fertilizer amount were set according to field experiment management and documentation. Each crop and each year was simulated with separate model runs. Thus, the initial soil variables varied from one year to the next.

For the intercropping simulation, the evaluated plant variety specific coefficients within the monocropping system were used. The companion crop sown later was added to the component sown earlier and linked through the canopy module [4] without changing soil, weather or management input.

Evaluation of the winter wheat variety model

Within the APSIM model, differences in performance of various wheat varieties are based on differences in overall accumulated thermal time units for maturity, photoperiodic sensitivity and vernalization requirements taking thermal time units for the individual and different growing stage durations as a fixed setup. So far, the APSIM model has mainly been used for Australian and African temperate, semi-arid, tropical and subtropical simulation studies and has proved to be a robust model for simulating crop growth with particular regard to water shortage and drought [1][9][13][27]. Nevertheless, Asseng et al. [2] showed that the APSIM Nwheat model, a previous version of the APSIM model used in this study, can also be used to model crops grown in a European environment. Thus the variables in the APSIM Vs 7.1 wheat module were modified to simulate German high-yielding wheat varieties. This was achieved by modifying the three variables (thermal time unit requirements, photoperiodic and vernalization sensibility) used to simulate different wheat varieties within the model. No fundamental processes were modified.

The main problem within the modeling of German wheat varieties in comparison to Australian varieties was that dry matter was overestimated for the German varieties and, by contrast, grain yield was underestimated. The performance of total biomass could be adequately simulated, but the allocations to stem and leaf dry matter on the one hand and grain yield on the other hand seemed to be inappropriate. In addition, the simulated duration of floral initiation was longer than that observed and the beginning of flowering and grain filling was later than that observed. As a result, to improve the model fit, further evaluations of crop coefficients and variables had to be performed with special regard to biomass partitioning, dry matter allocation and the duration and beginning of individual crop growth stages.

The model was evaluated stepwise, using data from German field experiments from the years 2007 to 2009 and the wheat variety ‘Cubus’ grown under monocropping conditions [16]. The variety was evaluated using the data from the years 2007 – 2008, and the modified coefficients and variables were tested with the data from 2008 – 2009. Changes within the wheat model were partly made by using coefficients similar to those used in the DSSAT crop growth model for the wheat variety ‘Cubus’ and are shown in Table 1.

Table 1: Results of the stepwise model evaluation of APSIM, coefficient and variable modifications for the German wheat variety 'Cubus'

Phenology	Coefficient / variable	Default			Calibrated		
Maturity type	maturity type		580			610	
Thermal time calculation	x_temp_units	0	26	34	0	16	35
Phylochron interval	y_node_app_rate		95			130	
Biomass partitioning	Biomass Partitioning	6	6.9	7	4	4	3
Dry matter allocation	Fraction of remaining dm allocated to leaves	0.6	0.6	0.42	0.5	0.5	0.52
	Fraction of dm allocated to pod	0.33	0.33	0.33	0.1	0.3	0.3
Senescence	x_dm_sen_frac_leaf		1			2	
	y_dm_sen_frac_leaf		1			0.5	
	node_sen_rate units		60			58	
	fr_lf_sen_rate		0.035			0.033	

The first step was to test the model using the given variables for the individual varieties, especially maturity type. Thermal time units for maturity were changed from 580 to 610, thus elongating the growing season and increasing the overall dry matter yield. The next step was testing the model performance after changing the base temperature for grain filling in the thermal time calculation from 26°C to 16°C [7]. This is accomodat the fact that European winter wheat varieties are much more adapted to cool temperatures not only during the winter months, but also in spring and early summer. Accordingly to the calculated thermal time units from field data collected in 2008 (120) and the DSSAT cultivar coefficients (130), values concerning phylochron intervals were changed from the standard 95 to 130 [16]. Biomass partitioning coefficients as well as coefficients for the dry matter allocation to leaves and pods were modified to reduce stem and leaf dry matter and to increase grain yield. Only those partitioning coefficients were changed which determine allocations during the flowering and grain filling period to postpone the allocation and prolong the life cycle of the crop. This change allows the crop to develop more photosynthetically active tissue, increases the total amount of carbohydrates and finally increases grain yield. Observed data from separated stem, leaf and ear dry matter during the growing season were taken as basic assumptions. In a last step, senescence coefficients were evaluated to ensure that the shift of dry matter allocation was eventually used for increased grain yield instead of increased leaf dry matter. Earlier senescence of leaves can lead to a reallocation of assimilates from leaves to grains and hence increase grain yield.

After each evaluation step, the model was run and the following variables were compared to detect the differences in model behavior and the impact of the modifications made on wheat phenology: dry matter (biomass), actual above-ground dry matter (dlt_dm), potential change in live plant LAI (dlt_lai_pot), potential change in LAI allowing for stress (dlt_lai_stressed), change in number of leaves (dlt_leaf_no), potential leaf number (dlt_leaf_no_pot), extractable soil water in different soil layers (esw_layr(1), esw_layr(2), esw_layr(3)), plant water uptake (ep), N in grain (grain_n), grain number (grain_no), weight of grain (grain_wt), size of each grain (grain_size), LAI (lai), N demand of plant (n_demand), N uptake (n_uptake), demand for NO_3 (no3_demand), NO_3 available to plants (no3_tot), root depth (root_depth), growing stage (stage), soil water supply (sw_supply), soil water demand (sw_demand), soil water deficit in different layers (sw_deficit(1), sw_deficit(2)) and grain yield (yield). Starting point was an appropriate Australian wheat variety ('tennantstart') for comparison, adding step by step the modified maturity type ('maturity'), thermal time calculation ('thermtime'), phylochron interval ('PHINT'), biomass partitioning ('biomasspart'), dry matter allocation to leaves ('dmleaves'), dry matter allocation to pods ('dmpod') and lastly senescence ('cubusend').

Evaluation of the maize variety model

To introduce a new variety into the APSIM maize model, several variables had to be defined or calibrated. Most of those variables define the accumulation of thermal time units within the individual growing stages, plant development and the switching from the vegetative to generative phase. Maize varieties differ in these traits, especially when adapted to and bred for different purposes and climatic zones. Thus, thermal time units evaluated for Australian and African maize varieties within the APSIM model have to be modified in order to model maize varieties bred and grown in temperate zones. Main differences are increased water supply, decreased incoming solar radiation, adaptation to lower average temperatures and adaptation to the duration of the growing season of maize grown in temperate zones in comparison to maize grown in semi-arid, tropical or subtropical zones. Again, as in the wheat model, the main challenge for the simulation of maize growth in temperate zones is to model the possibility of high yielding varieties in those areas with yields exceeding those in major Australian crop production regions. Simulation runs with default maize varieties within the APSIM model showed that these were not able to cope with German soil, weather and input variables and, as a result, crop growing stages were not simulated adequately. In particular flowering and grain filling had to occur earlier for the German variety 'Companero', grown under monocropping conditions. In most cases, the given default maize varieties did not even ripen. Thus, the coefficients and variables for growth stage appearance, development and duration had to be modified.

Similar to the wheat model evaluation, the maize model evaluation was done stepwise, using data from German field experiments from the years 2008 and 2009. The variety 'Companero' was evaluated with the data from the year 2008, and the changed coefficients and variables were tested with the data from 2009. Changes within the maize model were partly made by using coefficients similar to those used in the DSSAT crop growth model for the same variety and are shown in Table 2.

Table 2: Results of the stepwise model evaluation of APSIM; coefficient and variable modifications for the German maize variety 'Companero'

Phenology	Coefficient / variable	Default	Calibrated
Phylochron interval	leaf_app_rate1	65	25
Thermal time units	tt_emerg_to_endjuv	250	300
	tt_flower_to_maturity	550	750
	tt_flag_to_flower	50	70
	tt_maturity_to_ripe	1	5
Grain number	head_grain_no_max	850	580
Grain growth	grain_gth_rate units	11	7.7

First, the phylochron interval was changed from 65 to 25 according to DSSAT (25) and to calculated thermal units in the year 2008 (38). Once the crop was established, leaf appearance rate occurred rather fast and flowering as well as grain filling started earlier allowing the crop to develop fast within a shorter growing season in temperate zones and in addition, allowing the maize plant to have an adequate duration of grain filling in order to achieve high dry matter and grain yield. The decreased time for the plant to develop in the vegetative phase led to a decreased number of kernels per ear and a decreased grain growth rate unit later on. Thus, those variables were modified from 850 to 580 (DSSAT = 550) and 11 to 7.7 (DSSAT = 7.7), respectively. In addition, thermal time units for the individual plant stages were adjusted in order to simulate growth stage durations and maize phenology adequately.

After each evaluation step, the model was run and the following variables were compared in order to detect the differences in model behavior and the impact of the modifications done on maize phenology: biomass, dlt_dm, dlt_lai_pot, dlt_lai_stressed, dlt_leaf_no, ep, grain_n, grain_no, grain_wt, grain_size, lai, n_demand, n_supply_soil, no3_demand, no3_tot, no3_uptake(1), no3_uptake(2), stage, sw_supply, sw_demand, sw_deficit(1), sw_deficit(2) and yield. Starting point was an appropriate Chinese maize variety (‘zhongdan2start’) for comparison, adding step by step the modified phylochron interval (‘PHINT’), thermal time units (‘thermtime’), potential grain number (‘grainno’) and grain growth units (‘companeroend’).

Evaluation of the fieldpea variety model

In comparison to the wheat and the maize model within APSIM, the German fieldpea variety ‘Hardy’ within a monocropping system was simulated appropriately using a default Australian variety. The legume model seemed to be more robust with regard to plant-soil-atmosphere interferences than the cereal model. Moreover, there is a much wider range of plant varieties than with legumes due to more extensive breeding efforts. In Germany there are fewer than ten different varieties of fieldpea. Nevertheless, an Australian variety could be used to simulate yield of a German fieldpea crop. The timing of the progression through the various plant stages was adequately simulated by the default variety, but final grain yield was overestimated. Total biomass production was also adequately simulated, but the final partitioning between biomass and grain yield needed revision as ‘Hardy’ accumulated more biomass in an early stage than simulated, and observed grain yield was lower than simulated (Table 3). Both experimental years reflected a typical fieldpea performance and growth for German conditions with pea growing fast up to a height of 90 cm until flowering, but breaking down rapidly afterwards to a plant height of 20 to 30 cm, mainly due to the widespread occurrence of near wilt (*Fusarium oxysporum f. sp. Pisi*) followed by leaf and stem necrosis. As APSIM is not able to simulate plant pests and diseases, dry matter yield at flowering stage was taken for the model testing instead of final dry matter. Thus, dry matter accumulation was taken as a reference value before the disease occurred.

Table 3: Results of the stepwise model evaluation of APSIM, coefficient and variable modifications for the German fieldpea variety ‘Hardy’

Phenology	Coefficient / variable	Default	Calibrated
Leaf number and area senescence	node_sen_rate units	46.6	20
Biomass Partitioning	frac_leaf_units	0.43 0.4	0.35 0.33

After the two evaluation steps, the model was run and the following variables were compared in order to detect the differences in model behavior and the impact of the modifications made on pea phenology: biomass, yield, dlt_dm, change in retranslocation cohort 1 dry matter (cohort1retranslocationwt), dlt_lai_stressed, dlt_leaf_no, dlt_leaf_no_pot, ep, esw_layr(1), grain_wt, lai, leaf_no, number of senesced leaves per square meter (leaf_no_sen), N demand of plant (n_demanded(1), n_demanded(2)), N supply (n_supply_soil), N uptake (n_uptake), senesced dry matter (senescedwt), stage, sw_demand, sw_deficit(1) and sw_supply. Starting point was an appropriate Australian fieldpea variety (‘parviestart’) for comparison, adding the modified senescence (‘senescence’) and biomass partitioning (‘hardyend’) step by step.

Results

Simulation of the winter wheat experiment

The stepwise model evaluation showed a steady improvement and lastly a good fit between observed and simulated wheat dry matter and grain yield (Table 4, Figure 2). In both years model derivation for those traits was below 10%.

Table 4: Results of the observed and simulated grain and dry matter yield of the winter wheat variety 'Cubus' in the years 2007 – 2009 after the modification of the APSIM wheat model

	Simulated (kg ha^{-1})	Observed (kg ha^{-1})	Δ Difference (kg ha^{-1})
Year 2007/08			
Grain yield	9067	9054	13
Dry matter harvest	17488	16854	634
Year 2008/09			
Grain yield	8677	9070	393
Dry matter harvest	17522	17114	408
Ø Years 2007 - 209			
Grain yield	8872	9062	190
Dry matter harvest	17505	16984	521

To increase dry matter and grain yield in order to reflect yield potential in temperate European zones, the modification of the maturity type in combination with the thermal time calculation was necessary. Both variables showed a similar result in increasing yield potential, especially grain yield potential, by modeling an extended growing season which was in accordance with the documented growing stages through the growing season.

The observed length of time between wheat sowing and harvest was 300 to 310 days. The default Australian variety simulated around 290 cropping days, the modification in maturity type and thermal time calculation increased this to 310 cropping days. Whereas simulated daily dry matter accumulation was not influenced by the stepwise variation of all variables and coefficients, potential change in live plant leaf area index (LAI), potential change in LAI allowing stress and potential leaf number were influenced. Maturity type as well as thermal time calculation reduced those traits compared to the default simulation. Moreover, all modifications combined had no impact on the simulation of overall LAI development. Changes in thermal time units and biomass partitioning during flowering and grain filling resulted in similar LAI development with a reduced green leaf area potential and leaf area being less susceptible to stress. With fewer but vital green leaves, the same LAI was achieved by reducing leaf biomass production and instead increasing grain yield. The reduction of biomass partitioning and dry matter allocation coefficients on behalf of grain yield can be verified by measured stem-, leaf-, ear-ratio during flowering and grain filling. The ratio from stem+leaf:ear changed from 1.6:1 to 0.3:1 within one month, and ears showed to be a strong sink. Measured harvest index was rather high at approximately 0.55. Stem and leaf production as well as remaining dry matter allocation to stem and leaf were significantly reduced in favor of ear growth and development. Additionally, modified coefficients for earlier senescence of leaves may lead to a reallocation of assimilates from leaves to grains and hence increase grain yield.

Phylochron interval, biomass partitioning and senescence were the important factors for different simulation scenarios with regard to grain number, grain weight and grain protein content. There were no differences however for grain size. As dry matter allocation to leaves and stems was reduced and senescence started earlier, assimilated nitrogen and reallocated assimilates were shifted into grains, increasing not only grain yield per se, but also grain number, protein content and grain weight. With an observed 30000-31000 kernels per ha, the model still underestimated the grain number, but improved after modification simulating 22000-25000 instead of the previous 14000-17000 kernels per ha. In addition, observed protein content was between 13-14%. Without model modification, APSIM simulated 12-13%; after modification, APSIM simulated 14% grain protein content. Hence, the re-evaluation of the APSIM wheat model for simulating German wheat varieties showed that the model was able to simulate phenology effects and connected physiology effects adequately.

Finally, stress factors such as limitations in water and nitrogen supply and their impact on the default as well as the modified variety were compared. Soil water supply, soil water deficit and soil water demand within different soil layers as well as soil nitrate demand and content, for example, did not differ between the default and the stepwise modified varieties. The model modifications had no influence on those variables.

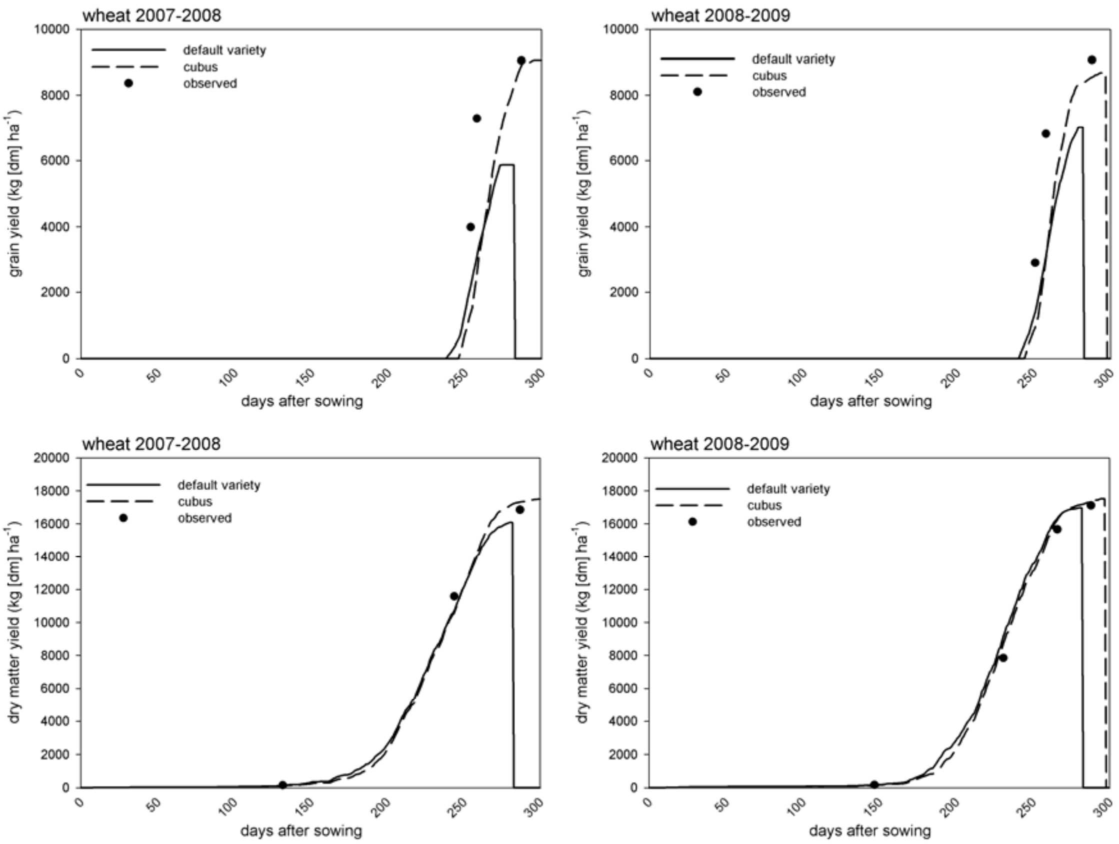

Figure 2: Measured and simulated dry matter and grain yield of the winter wheat variety ‚Cubus' during the growing seasons 2007/08 and 208/09 before (default variety) and after (cubus) the modification of the APSIM wheat model

Simulation of the maize experiment

Simulation results after the re-evaluation of the APSIM maize model showed a good fit between simulated and observed dry matter and grain yield (Table 5, Figure 3). The difference between observed and simulated average grain yield for both experimental years was 152 kg ha^{-1} and 55 kg ha^{-1} for average dry matter yield.

Table 5: Results of the observed and simulated grain and dry matter yield of the maize variety 'Companero' in the years 2008 – 2009 after the modification of the APSIM maize model

	Simulated (kg ha^{-1})	Observed (kg ha^{-1})	Δ Difference (kg ha^{-1})
Year 2008			
Grain yield	8944	8988	44
Dry matter harvest	23685	24375	690
Year 2009			
Grain yield	10216	10476	260
Dry matter harvest	27888	27089	799
Ø Years 2008/09			
Grain yield	9580	9732	152
Dry matter harvest	25787	25732	55

Modifications were needed to simulate yield height adequately. Most of the model modifications were made within the variety range and opportunities offered by APSIM. This means the determination of the crop remaining in the individual plant stages is based upon thermal time accumulation units. Once the maize plant was established, leaf tip occurrence happened rather fast as German maize varieties are adapted and bred in order to ripen within less than 200 growing days, can cope with a reduced amount of incoming solar radiation compared with tropical and subtropical regions and to achieve high yields. Thus, reduced thermal units for the phylochron interval boosted the amount of biomass and especially grain yield, but reduced the duration of the growing season, particularly the duration of the grain filling to harvest phase, drastically. As a result, grain yield was overestimated by the model after the first modification step. On the other hand, the occurrence of growing stages was modeled more adequately in comparison to the default variety except grain filling duration. Hence, a subsequent evaluation of thermal time units for flowering date and grain filling duration was necessary. With the modified thermal time units, not the duration of the whole growing season per se, but only the flowering and grain filling phase could be adjusted. Changes within the phylochron interval and the thermal time unit variables led to an increased production of daily biomass earlier in season due to an increase in daily leaf number development, daily leaf area potential and final leaf area. As a result, the vegetative phase was accelerated and the plant changed from vegetative to generative phase earlier in the season without the expense of biomass production. Nonetheless, the shortening of the vegetative phase reduced the ability of the plant to develop a high grain number potential. Modifying that coefficient led to a better model fit for the trait grain yield as it had been overestimated by the model before this evaluation step. The model still overestimated the thousand kernel weight (TKW) and assumed a higher proportion of nitrogen allocated to grain due to the increased stem and leaf biomass early in the season. The observed TKW was between 250 and 300 g. The simulated TKW ranged between 400 and 500 g. A reduction in grain growth rate simulated a final grain weight of about 350 g.

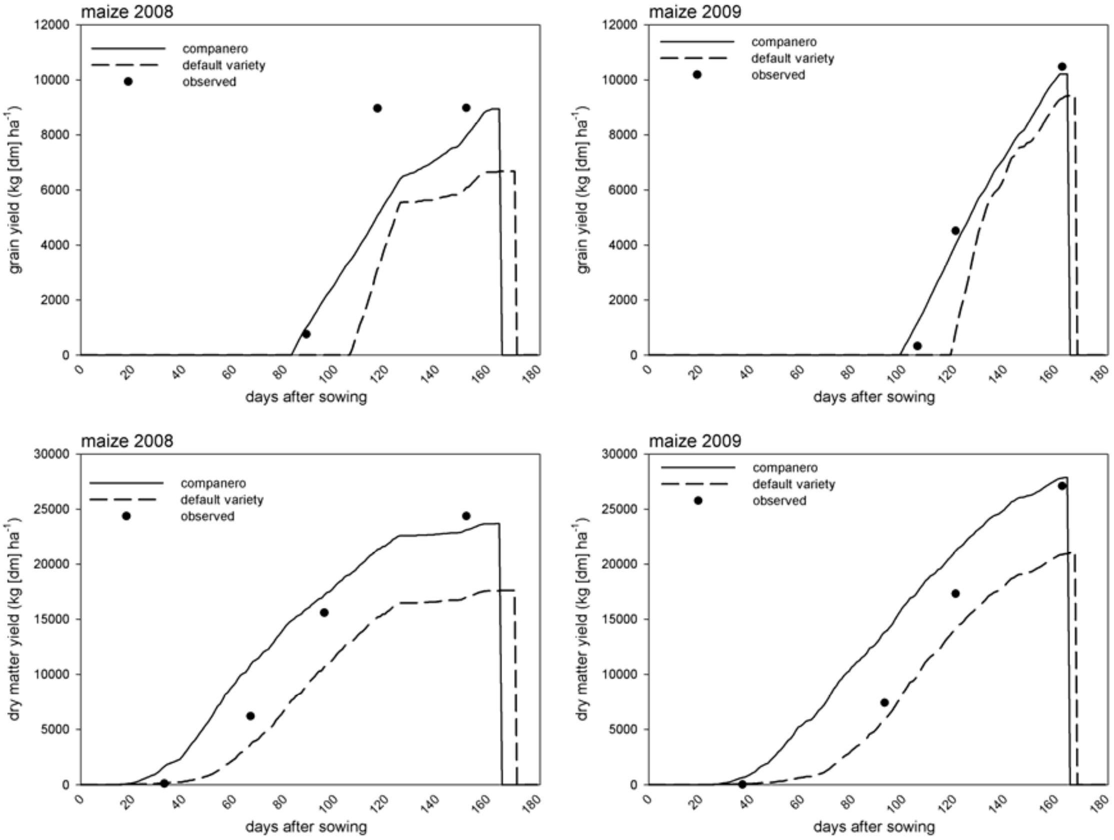

Figure 3: Measured and simulated dry matter and grain yield of the maize variety ‚Companero' during the growing seasons 2008 and 209 before (default variety) and after (companero) the modification of the APSIM maize model

In accordance with the accelerated vegetative phase of the adjusted in comparison to the default variety, the model simulated soil water and nitrogen demand earlier in the growing season with the tendency for the adjusted variety to have an increased demand for soil water and nitrogen. Water shortage is a less limiting factor for maize grown in Germany than in major Australian crop production zones.

Simulation of the pea experiment

Only a few modifications were necessary to adjust the APSIM fieldpea model to German fieldpea performance and growing conditions. Fieldpea is susceptible to waterlogging and to fungal diseases under muggy conditions, both likely to occur during the growing season in Germany. As a result, the pea leaf biomass declines rapidly after pod setting and within pod filling. Otherwise the APSIM was not able to fill the gap between dry matter accumulation and grain yield under those specific German pea growing conditions. The observed biomass accumulation was accelerated within ‘Hardy’ compared with the simulation, but observed grain yield was lower than simulated. After modifying biomass partitioning and senescence coefficients for the default APSIM variety, the model was able to cope with those conditions and to simulate dry matter accumulation until flowering and grain yield after harvest adequately (Table 6). The difference between simulated and observed results was under 400 kg ha^{-1} for each year and trait.

Table 6: Results of the observed and simulated grain and dry matter yield of the fieldpea variety ‘Hardy’ in the years 2008 – 2009 after the modification of the APSIM fieldpea model

	Simulated (kg ha^{-1})	**Observed (kg ha^{-1})**	**Δ Difference (kg ha^{-1})**
Year 2008			
Grain yield	4408	4738	330
Dry matter yield flowering	2224	2619	395
Year 2009			
Grain yield	5462	5187	275
Dry matter yield flowering	2758	3033	275
Ø Years 2008/09			
Grain yield	4935	4963	28
Dry matter yield flowering	2491	2826	335

The main priority was to set up the model in that way that until flowering sufficient biomass was simulated without simulating increased final grain yield by inducing earlier senescence. The final amount of senesced dry matter did not differ between the default and the modified variety, but the slope of the curve differed, as it rose earlier and less steep as the default. As a result, the nitrogen demand for the modified variety was reduced at the end of the growing season. The model reduced daily dry matter production as well as leaf area once the senescence coefficients had been changed, especially at the end of the growing season, whereas the default variety simulated a final peak in those traits. Both traits were further reduced by decreasing the fraction of remaining dry matter allocated to leaves, thus ensuring that leaf biomass was reduced and grain production increased. Both modifications had no influence on daily leaf number development, daily leaf number potential and final leaf number as well as daily stress potential for leaf area. In addition, growth stages were equal for the default and the modified variety, and there were no differences in modeled water demand or supply.

Simulation of the intercropping experiment

Linking the relative intercropping system’s components with the CANOPY module showed that APSIM was not able to simulate crop performance adequately. Those plants within the intercropping system – wheat and fieldpea – which were sown earlier than the companion species, maize, behaved according to the motto “the winner takes all” and were simulated adequately (fieldpea) or at least with a satisfactory bias (wheat) (Figure 4).

In the year 2008, the observed fieldpea dry matter yield at flowering was 3121 kg ha^{-1}, the simulated value 3145 kg ha^{-1}. Observed grain yield at harvest was 4121 kg ha^{-1}, 4731 kg ha^{-1} was simulated. At maturity 2008, wheat had 24506 kg ha^{-1} dry matter and 12400 kg ha^{-1} grain yield. The model simulated 21593 kg ha^{-1} and 10311 kg ha^{-1} respectively. In both intercropping systems, maize growing was not simulated or only implied. Maize was unable to develop grain in the wheat-maize system or fieldpea-maize system. In conformity with the competition module properties the simulation partitioned to the intercropped maize only 0.2% of the radiation fraction during the growing season on average. This drastically reduced radiation fraction disables maize to grow and develop.

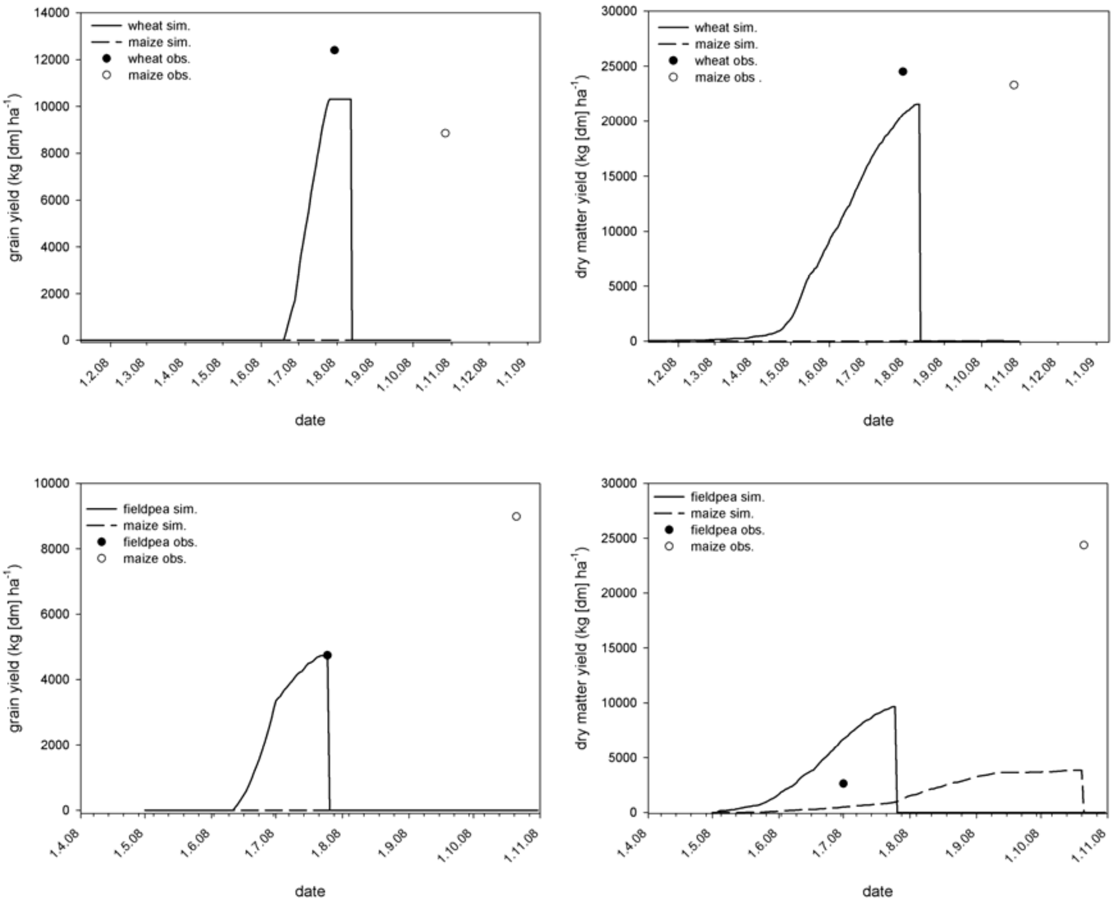

Figure 4: Simulated and measured dry matter (right) and grain yield (left) for maize/wheat (above) and maize/fieldpea (below) intercropping systems in the year 2008

This underestimation of maize growth occurs because the canopy module within the model was built to simulate mixed cropping and mixed canopy systems where competing species share a common soil water and nutrient pool and each plant species or crop row is located next to a different plant species or crop row. In addition, most mixed cropping systems are assumed to have a similar sowing date and a comparable plant height when development starts. The model could not deal with the development advance of one crop occurring in the relay intercropping of wheat and maize. By dividing the canopies into canopy layers, the understorey species gets scarcely any light because in the second layer (both canopies present), incoming light is reduced through the first layer (only taller plant canopy present) and, in addition, the species have to compete with each other. However, that approach does not reflect the reality of relay intercropping. The approach adopted in APSIM bares little resemblance to a relay intercropping system and its inadequacy in modeling the system is not surprising. In these systems where the competition effects occur in a few rows and the development of crops are staggered, plant growth cannot be modeled and simulated with the competition approach focused around the philosophy of Beer's law and represented in the APSIM CANOPY module. Point based models partition light, nutrients and water into pools which always ensure that the mass balance of the total system remains constant, and cannot model a system where this assumption is violated. If beneficial effects such as possible increases in light interception and possible changes in evaporation occur over multiple rows, then the total amount of light increases, and this cannot be represented in the current framework.

Increasing the yield of one species within intercropping systems without taking account of the performance of the companion species could not be realized with the modified Beer's law as competition algorithm.

Modeling competition for solar radiation and intercepted light is strongly based on simulated plant height as height defines the layers and the layers in turn define the fraction of light transmitted and entering the next layer below. In addition, LAI is distributed with height in the canopy. Total radiation intercepted in each layer is calculated according to the radiation transmission coefficient multiplied by LAI. If one species is much taller then the other, e.g. wheat in relay intercropping systems with maize, the maize canopy is assumed to be the lowest and intercepts barely enough light for plant growth. Modeled and observed plant height is shown in Figure 5 and shows the difficulties of taking simulated plant height as a basic premise. At maize sowing date, the wheat already has a height of about 50 cm and maize finds itself in the bottom layer. The module assumes that each maize row is surrounded by a wheat row and has to compete directly for light ignoring the fact that in strip intercropping there could be several rows of maize with row distances of 70 cm. Competition for solar radiation in those systems is reduced in comparison to mixed or row intercropping.

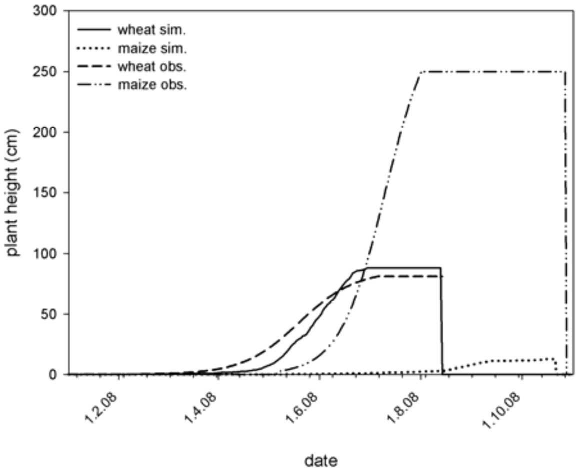

Figure 5: Simulated and observed maize and wheat height in the year 2008

Discussion

After a re-evaluation of the APSIM model through minimal modifications of crop coefficients and variables such as biomass partitioning, senescence and/or thermal time calculation or thermal time unit requirements, APSIM was able to simulate dry matter and grain yield of German maize, winter wheat and fieldpea varieties grown under monocropping conditions adequately. The ability of APSIM - predominantly used and applied for simulating crop productivity in Africa and Australia - to simulate wheat performance in temperate European agro-ecological zones has already been shown by

Asseng et al. [2] for the Netherlands. However, the APSIM Nwheat model used by Asseng et al. differed from the APSIM Vs 7.1 used in this study. The similarities between APSIM and DSSAT supported model adjustment as similar data requirements for both models were needed and the collected data for the evaluation of the DSSAT model could be used as well as DSSAT coefficients per se.

So far, the APSIM canopy module has been used for multiple cropping systems assuming that competing canopies were well mixed in the horizontal dimension. That may be the case for mixed cropping as well as row intercropping systems. Indeed, studies on wheat/lucerne and canola/lucerne companion farming [28], maize/cowpea intercropping [6][26] and maize/legume pasture and sorghum/legume pasture [6] intercropping indicated a good model fit between measured and observed yields and showed the current overall ability to simulate interspecific competition. Additionally, the APSIM model approach has proved to be a useful tool to address competition between crops and weed and the resulting yield loss [29]. The model was tested over a range of locations, seasons, sowing times, cultivars, plant densities, water regimes and N fertilizer rates.

Nevertheless, there has to be a clear definition and demarcation within multiple cropping systems, because each of those cropping systems is a system in its own rights with its own competition effects and characteristics. Models simulating strip intercropping might not be able to simulate mixtures and vice versa. It is important to give a brief definition of the outlook of the cropping system or the experiment, without becoming indistinct. Mixed cropping and intercropping are often used as synonyms, but when modeling mixed or intercropped systems, the design and sowing pattern becomes important. The (row) distance between competing species is essential when scaling competition or choosing competition factors. In mixed cropping, roots intermingle and interact. Plants assimilate nutrients from the same soil or nutrient pool, and the impact of neighboring plant height might be significant on the target plant. Not only plant height or LAI, but also individual species’ compensation mechanisms, morphology or the appropriate timing of crop establishment of companion plants, govern competition.

So far, APSIM has been used to simulate mixed cropping or eventually row intercropping systems. Carberry et al. [6] suggested that the issue of spatially heterogeneous cropping systems also needs to be considered and that requires a different approach to the one currently implemented in APSIM. APSIM does not have the ability to model strip intercropping. Unless there is an issue of trade-off between the loss of crop yield in the intercrop relative to the sole crop [26], APSIM is able to address those losses due to competition for solar radiation. As soon as there is a winner, meaning a yield increase of the dominant intercropped species, without a loser, meaning an equivalent yield of the intercropped understorey species in comparison to the monocropped species, the modeling of competition for solar radiation using Beer’s law is insufficient or not applicable. This approach does not allow for compensation growth of the understorey crop nor for yield increase of the dominant crop, as occurs in the relay intercropping of wheat and maize and the strip intercropping of fieldpea and maize. Competition for solar radiation in those systems is an important factor for crop productivity but neither the most dominant nor the one and only. In fact, to limit competition effects to competition for solar radiation only fails to accommodate the fact that other competition effects – such as changed nutrient availability or supply, soil chemistry or microclimate - occur and are of major importance [20][24].

In contrast to the APSIM model approach, the competition approach presented within the DSSAT model seemed to be a promising way to address more than one competition effect and showed that increasing solar radiation within the wheat strips explained or reflected only half of the yield increase [15]. The evaluated shading algorithm [16] allows for compensation growth of maize after wheat harvest as well as for increased wheat productivity. Introducing shade into modeling intercropping and relating its intensity or proportion to monocropping is a promising way to overcome the problem of different distribution of incoming sunlight within different distances from strip borders. In addition, increased sunlight for border rows in comparison to centered rows can be taken into account. Shade length can be calculated at each point of time during the day as well as each location in the world by means of longitude, altitude and sun azimuth; 100 % or near 100 % shading cannot occur because plant porosity and the distances between two competing plant rows will always allow some light to penetrate. In a similar context, the degree or proportion of shading was already calculated and used successfully. Stilma et al. [31] developed a minimal reference model for the population dynamics of annual weeds underneath a shading crop canopy by including treatment-specific shade functions. The questions are: Does the modeling of interspecific competition need 3D model frameworks or individual-based neighborhood models? And is each intercropping system too individual and are competition factors too diverse to be captured within one model?

As an example, there is a black box 'soil' to be considered. Microclimate in intercropping in comparison to monocropping could change and differ leading to an increasing air humidity or soil moisture [22][32]. Shading could lead to decreased soil temperature and vice versa [16]. Those microclimatic effects and differences could contribute to different soil properties or microclimate for soil microbes within intercropping in comparison to monocropping. Those effects are difficult to handle in modeling approaches. In their review Berger et al. [3] identified three major shortcomings in the modeling of competition among plants, which were the effects of plants on their local environment, adaptive behavior and below-ground competition. Neither of those could be addressed fully in current modeling approaches as local interactions and adaptational behavior to biotic and abiotic environment and stress can hardly be captured at plant population level [3].

In conclusion, modeling of intercropping with DSSAT offers a promising and completely different alternative to customary model approaches. However it requires considerable further improvements and in particular further validation. Modeling of intercropping with APSIM also needs to be significantly revised before it can be used for simulating strip or relay intercropping scenarios.

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10 General Discussion

In the present thesis, the chapters I, II, III, V and VI are related, with chapter IV being an excursus into peanut production in China. The chapters deal either with intercropping or modeling intercropping or combine both aspects as shown in chapter II. Each chapter can be read independently and is discussed independently at its end. Thus, the aim of this general discussion is not to discuss the chapters in succession, but as an overall perspective of designing, modeling and evaluating intercropping systems with special regard to the North China Plain. Aspects and features introduced in the beginning of this thesis will be re-iterated, and the subtleties between intercropping and modeling intercropping issues will be studied critically.

Intercropping systems are the epicenter between traditional farming systems and modern production modes, and will be evaluated according to their performance, their contribution to sustainability and production, and to their potential for future agriculture. Modeling intercropping is a challenge. Although it is studied across a wide range of situations only a few issues have so far been investigated. Competition effects like solar radiation are difficult to handle system spanning. If there are black dots on the landscape of intercropping, there is a black box ‘soil’ for modeling competition.

THE FUTURE OF INTERCROPPING?

Without doubt intercropping is a cropping system of research interest. According to the keyword request ‘intercropping’ within the Scopus database, more than 2 800 topic related papers and articles can be found. Across many disciplines, e.g. plant nutrition (Inal et al., 2007; Zhang et al., 2004), crop production (Chen et al., 2004; Ghaffarzadeh et al., 1994; Ayisi et al., 1997; Lesoing and Francis, 1999; Pridham and Entz, 2008), agroecology (Jolliffe, 1997; Ren, 2005; Sanders, 2000), entomology (Ma et al., 2007), modeling (Caldwell, 1995; Keating and Carberry, 1993; Knörzer et al., 2010) as well as cropping systems studies, various studies dealt with issues related to intercropping in order to investigate competition effects, species interaction, optimal species combination, optimization of cropping systems, intercropping benefits, sustainability, agricultural practice and soil and plant properties changes and exchanges. Various intercropping systems are widespread all over the world, especially in Asian and African countries, but also in Latin America, Europe and the United States of America. Multiple cropping systems seem to be as old as the history of agriculture. The question is does intercropping have the potential for next generation agriculture in countries where **traditional farming systems** and structures will turn into **modern production modes** with mass production, high yield, mechanization, and high inputs being on headlines?

During the last couple of decades, China's agriculture has turned more and more from subsistence farming to a nation's self supplier, and an exporter of agricultural goods. The export value of food and live animals used chiefly for food (in million US dollars) tripled from 1999 to 2009 (China Yearly Macro-Economics, 2010). The fast development of the structural agricultural sector, mechanization and production growth is still ongoing. Within ten years, from 1999 to 2009, the gross output value of farming in Henan province rose from 14 106 to 30 611 million Yuan (China Yearly Macro-Economics, 2010). China belongs to those countries where intercropping is widespread on the one hand and modern production modes are developing on the other. Chapter I within this thesis deals with the distribution, characteristics and benefits of Chinese cereal intercropping systems in detail.

According to Li (2001) and Li et al. (2007), 20 to 25 % of China's arable land is under intercropping. Thus, intercropping seems to be a big issue in China. Having a closer look at major cereal production provinces like Hebei, a trend can be detected. Whereas in former times a relay intercropping of wheat and maize was predominant, nowadays plant breeding and mechanization contributed to a decline of that system that is being replaced by a double cropping system without overlapping growing season of both species (Wang et al., 2009). Fast maturing maize varieties and, in addition, the use of machines for wheat harvest instead of labor and time intensive cutting by hand were the reasons for replacing the traditional relay intercropping by a double cropping system. Within the last few decades, the degree of mechanization and the numbers of machines has increased steadily. Since 1980 the use and the application rate of chemical fertilizer and pesticides have been increased explicitly. The total power of agricultural machinery doubled and the consumption of fertilizers increased 2.5 fold between 1998 and 2008 (China Yearly Macro-Economics, 2010). China's cropping systems turned from low input systems to high input systems. Intercropping is known as an adjusted cropping system for low input but to lose ground when applying high input. The apparent unlimited host of labor force in rural China is declining too, as more and more rural workers move into cities in order to increase their income. In addition, rural household income is increasingly derived from non-farming work (internal IRTG presentations). As a result and as a future trend scenario, it is expected that through increasing mechanization, agriculture will be more efficient in terms of labor demand, full-time farmers will enlarge their farm size, and crop production will be intensified. Intercropping is known as labor and time intensive, feasible on small-scale farming, and profitable when low input driven. Hence, does the agricultural development oppose the traditional persistence of intercropping systems?

The disappearing wheat-maize relay intercropping system in the North China Plain is an example of the decline of intercropping practice. It could be opposed that new intercropping systems evolved in China too. In the 1980's the wheat-peanut relay intercropping was established and promoted, especially through the Shandong Peanut Research Institute (SPRI) (Gowda et al., 1996). This might be ideal as intercropping per se might not be replaced by monocropping or double cropping systems but could change, alter or diversify in the course of time. It is not static, in contrast, within intercropping's variability, adaptability and flexibility lies its potential for future persistence. To be provocative: intercropping has not only the status quo of being still alive in fast developing countries, but it emerges also in industrialized countries. As chapter I is entitled, intercropping is experiencing some kind of rediscovery. There is an increasing awareness deduced from organic farming, agroecology, and the debate around sustainability. To maintain or further improve intercropping systems, they have to be accepted by the farmer, because any agricultural practice must provide advantages over other available options in the eyes of the practitioner (Sullivan, 2003).

For Tom Frantzen, a farmer in Iowa (USA), the advantages of strip intercropping are that the strips can be considered as a crop rotation within one big field (Sullivan, 2003) as well as its economical benefits which are about $19 per acre higher for the strip intercropping than for the monocropped equivalent. Increased pest suppression, soil building advantages, and yield increase are the reasons for agronomist R. Cruse from the Iowa State University (Cruse, 1996) to encourage farmer taking intercropping into consideration (Sullivan, 2003). In comparison to scientific research, farmers have to be much more pragmatic concerning what sustainable agriculture means. Paul Mugge, a 320 acre farmer in Sutherland (USA), is practicing strip intercropping, because he and his wife want to obtain the most net profit from each acre and each hog (Kendall, 1996/1997). His long term vision is to be profitable, to be efficient in the terms of resources, to understand more about ecology and to use that understanding. He says (Kendall, 1996/1997): "I want my farm to contribute more than its share to feeding the world while contributing much less that its share to environmental degradation." Marvin J. Williams Jr. from Michigan (2003) possesses a United States Patent of an intercropping system. While explaining his invention’s aims, he emphasizes the production of commercial plants for commercial machine-driven agricultural methods. Avoidance of pesticides and herbicides, effective ground cover, soil enrichment, and increased drought resistance were the decision making reasons for him to practice intercropping.

Strip intercropping is often named as ‘**ecologically innovative agriculture**’ in the USA, this coupled with the above American farmer examples indicates that intercropping is not limited to traditional and old-fashioned smallholder farming, remote areas, or developing countries. Even if intercropping systems tend to disappear or decline when there is development from small scale and subsistence farming to farming on bigger scales, mostly connected to monocropped fields and where the arable land area is feasible for large, plain fields like in the North China Plain, there is a potential for intercropping that should not be neglected. The future of intercropping, viewed globally, might be that two doors will close, but one will open. Modern agricultural practices and especially the agro-industrialized cultivation have to be reflected in some critical way, as the claims and demands upon agricultural production raise and change. Besides food security, sustainability, ecological and environmental friendly production modes, healthy food, and conservation will be issues agriculture and agricultural politics have to deal with. For example, the Büro für Technikfolgen-Abschätzung beim Deutschen Bundestag (TAB) in its TAB letter no. 29 (2006) designated mixed intercropping as an ecological and economical potentially suitable ‘modern agricultural engineering and production method’. The TAB advises the German parliament on changes in technical and social matters.

While achieving high yields, increasing labor efficiency or increasing mechanization remain major objectives there is no way there will be a back-to-the roots development. Agro-romantic visions are inappropriate when dealing with global food safety or income security for peasants in developing countries, remote areas, or facing social disadvantages.

Reproaches generated against polycultures, multiple cropping systems, or intercropping were that they lack the potential of producing meaningful marketable surplus, that indigenous knowledge will not yield panaceas for agricultural problems in the world (Altieri, 2000), that **intensification of production** is essential for the transition from subsistence to commercial production (Blauert and Zadek, 1998), and that intercropping relies on hand tools and draft animals and cannot be mechanized in a large scale. US farmers like Tom Frantzen, Paul Mugge or Marvin J. Williams Jr. (Sullivan, 2003) showed that indeed, intercropping could be an economical as well as ecological alternative way of crop production. To handle intercropping as an option for production, as a production branch, and not as the one and only way offers the possibility of turning a cropping system to account for averting risks, saving inputs, increasing biodiversity, decreasing soil erosion, and simultaneously, stabilize and secure income. Innis (1997) showed in his overview over studies calculated the LER of inter- in comparison to monocropping systems that proportional yields or the output per unit are higher in intercropping systems than in monocropping. In addition, Altieri (2000) stated for the 1980s that in Latin America peasant polycultures' overall contribution to the general food supply reached approximately 41 % of the agricultural output for domestic consumption. Monocropping does not at all guarantee high yields. Besides, the focusing on partial aspects of single crops rather than total system yields of multiple crops as well as the focusing on quantity per acre rather than nutrition per acre neglects the fact that multiple cropping systems generally enhance total farm productivity rather than the yield of specific components (Altieri, 2003). Maybe intercropping has a need of a different rating of criteria than monocropping to evaluate its contribution to global agriculture and food supply.

At least, the claim that intercropping could not be **mechanized** and thus, it would be rather difficult to integrate it into modern monocropping systems is questionable. Exemplary, the US farmers are to be mentioned again. To apply regular herbicide treatments, Tod Intermill from South Dakota just uses a ground sprayer of strip width (Sullivan, 2003). Sullivan (2003) also reports from a US farmer who uses a 12-row planter for a maize-soybean intercropping system consisting out of six rows of maize and six rows of soybean. To establish the six-row strips he fills the middle six hoppers with maize and the outer three hoppers with soybean. Lloyd Younger (1978, [57]) from Illinois owns an United States patent for an apparatus for sowing a second crop in a standing crop in order to mechanize relay intercropping (Figure 6): Seeding of the crop is performed using a self-driven, preferably three-wheel vehicle carrying a grain drill box having flexible tubes which fit between the rows of grain and each of which discharges the seed into a gap between two downward-inward slanted discs which first cut a slit in the ground, then deposit the seed and finally cover the slit. Obviously, there are ways and methods to mechanize strip or

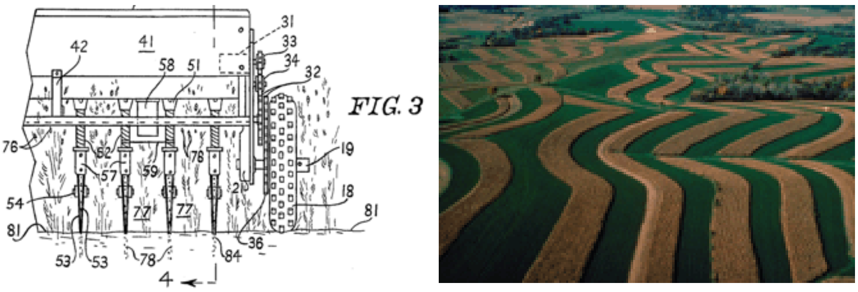

Figure 6: Fragmentary rear elevational view of a portion of an apparatus for sowing a second crop in a standing crop (left) (Younger, 1978). Strip intercropping appearance and practice in the USA (right) (http://www.thisland.illinois.edu/60ways/60ways_17.html).

relay intercropping. So far, there is no commercial production of those machines, which might be related to the fact that there is no big demand. In countries where intercropping is the most widespread, farmers do not have the capital to invest into machines. Nevertheless, the mechanization and productivity of intercropping is not impossible but it appears like the causes are rather social than technical (Altieri, 2003).

To intensify or to preserve the various intercropping systems in China and all over the world will be a challenge worth taking and a task for further research. Every system seems to be a system on its own and worth to be documented and/or analyzed. Although there have been a lot of studies about intercropping so far, there are still uncertainties, **black spots** and open questions. To study competition effects more closely and to test new species combinations, to optimize input amounts and applications, and to evaluate or breed suitable intercropping varieties in order to improve or adjust existing intercropping systems might be a more consistent approach for stimulating agricultural production than approaches undertaken in the first Green Revolution.

THE FUTURE OF MODELING INTERCROPPING?

A possibility to improve and adjust intercropping systems, and to pick up on questions which arose in the introduction of this thesis, is to model and simulate cropping systems. In chapter II, an overview was given over various models which already dealt with intercropping or interspecific competition. Whereas competition about solar radiation was the most common and advanced competition factor studied and detected, other factors were regarded, too, or at least seem to be of great influence. Examples are: plant density, self-thinning, and mortality in a plant population (Yokozawa and Hara, 1992), belowground competition or competition for water (O'Callaghan et al., 1994; Ozier-Lafontaine et al., 1995, 1998; Raynaud and Leadley, 2005), and competition for soil nutrients (Corre-Hellou et al., 2009; Hauggaard-Nielsen et al., 2006; Ibeawuchi, 2007; Jensen, 1996).

Competition for solar radiation, shading, and light interception are one of the key factors within multiple cropping systems, but not the one and only or of such importance that other factors could be neglected. Explicitly, the term 'multiple cropping' instead of 'intercropping systems' was used here, as multiple cropping systems like sequential cropping, mixed cropping, row or strip intercropping, and relay intercropping (Federer, 1993) differ greatly considering competition factors, competition impact and the ability to compensate competition. Models simulating strip intercropping might not be able to simulate mixtures as well and vice versa. In this case, it is important to give a brief definition about the outlook of the cropping system or the experiments, without becoming indistinct. Otherwise, the studies are entitled to analyze or simulate intercropping, but the cropping system is a mixture (Carberry et al., 1996; Hauggaard-Nielsen et al., 2006). Mixed cropping or intercropping are often used as synonyms, but when modeling mixed or intercropped systems, the design and sowing pattern becomes important.

Models have to reach the point from evaluation and validation to application. As reviewed in chapter II, a lot of studies about intercropping and interspecific competition exist and are published, but the question is, to which extent they are applicable for the use in the field or for making recommendations for farmers to improve there cropping strategies? Otherwise, are the models more applicative for modeling mixed cropping, row intercropping or the modeling of weed-cereal interactions than for strip or relay intercropping? Are the models over parameterized or is each system too individual and the competition factors too diverse to be captured within one model?

Some or most of the models used for modeling competition about solar radiation within intercropping or mixed cropping are based upon **Beer’s law** or a modification of Beer’s law (Carberry et al., 1996; Corre-Hellou et al., 2009; Debaeke et al., 1997; Sonohat et al., 2002; Tsubo et al., 2005). Beer’s law is defined as the linear relationship between absorbance and the concentration of an absorber of solar radiation, whereas absorber concentration equals canopy layers when Beer’s law is assigned to plant growth models. Light transmission is then computed as a negative exponential function of the downward cumulated leaf area index (LAI) and the plant extinction coefficient of each canopy. This approach has proven to be sufficient and successful in simulating mixed cropping, weed-cereal interactions, row intercropping, and additive intercropping systems. Nevertheless, in chapter VI it was shown, that for modeling strip or relay intercropping or a replacement intercropping system, the approach is not suitable. Within those cropping systems and according to that approach, the dominant species behave like the winner takes all. Point based models partition light, nutrients and water into pools that always ensure that the mass balance of the total system remains constant, and cannot model a system where this assumption is violated. If beneficial effects, like possible increases in light interception and possible changes in evaporation occur over multiple rows then the total amount of light increases and this cannot be represented.

The (row) distance between competing species is essential when scaling competition or choosing competition factors. In mixed cropping, roots intermingle and interact. Plants assimilate nutrients from the same soil or nutrient pool, and the impact of neighboring plant height might be significant on the target plant. The Beer’s law approach ignores the possibility of different LAI distributions within a layer (CANOPY, 2010) (uniform distribution), and instead distributes LAI with height in the canopy. Thus, it is assumed that 47 % of the leaf area is located in the top 10 % of plant height, 27 % in the next 10 %, 15 % in the next 10 %, and so on. This assumption might be appropriate for monocropping or mixed cropping, but within strip intercropping or relay intercropping, where neighboring species hold increased individual space at the strip borders because of development advance (relay intercropping) or row distance (replacement intercropping systems, strip intercropping), circumstances change. As a result, the understorey species, located in the second layer according to the Beer’s law approach, might receive more light than assumed or can compensate for the decreased incoming solar radiation after the dominant species is harvested. Compensation growth or mechanisms cannot be respected. Then, neighboring plant height and LAI are less determining for competition. Russell et al. (1989) confirmed that a non-uniform distribution of leaf area increases both the amount of PAR absorbed by the canopy and the amount of photosynthesis by comparison with a uniform distribution of leaf area.

Not only plant height or LAI govern competition, but individual species compensation mechanisms, morphology or the appropriate timing of crop establishing of companion plants (Tsubo and Walker, 2004), too. In fact, the restriction for competition for solar radiation neglects the fact that other competition effects - like changed nutrient availability or supply, soil chemistry, or microclimate - occur and are of major importance (Meinke et al., 2002; Raynaud and Leadley, 2005).

There is a **black box ‘soil’** to be considered. Two aspects influence soil related processes which in turn influences intercropping systems performance. First, a changing microclimate in intercropping in comparison to monocropping could increase air humidity or soil moisture (Njoku et al., 2007; Williams and Gordon, 1995), as well as shading could lead to decreased soil temperature and vice versa (Knörzer et al., 2010) (chapter V). Those effects could contribute to different soil properties or microclimate for soil microbes within intercropping in comparison to monocropping. Those effects are difficult to handle in modeling approaches if climate features are taken from standard weather stations without taking microclimate within the field into consideration. Mass balance of the total system remains still constant, but some focuses shifted and have to be re-estimated. Taking microclimate into consideration while modeling intercropping, as performed in a first modeling approach in chapter V, could improve the simulation excellence.

Secondly, initial soil properties as well as species combination could induce processes different to those within monocropping. Raynaud and Leadley (2005) found that nutrient uptake which is not proportional to size differences could occur in soils with higher water content when plants differ in nutrient uptake kinetics, and the mechanisms leading to size-asymmetry are very different from light competition since they arise from physiological differences in resource uptake capacity. In addition, Jensen (1996) stated that within a pea-barley intercropping system, the proportion of total N derived from fixation in the intercrop was significantly increased compared to the total N derived from fixation in monocropped pea. However, a rule or standard algorithm defining that N fixation is increased if legumes and cereals are combined, cannot be determined or found simplistic. Hauggaard-Nielsen et al. (2006) showed for their pea-barley intercropping experiments with different plant densities, that only at low cropping densities intercropped pea increased its reliance on N_2 fixation relative to sole cropping.

Thus, modeling intercropping by setting the initial soil conditions equal to those of equivalent monocropping situations or setting one combined nutrient pool for companion crops assuming a daily alternating nutrient and water supply is not adequate even if yield or dry matter accumulation might be simulated appropriately. With this approach, competition cannot be simulated and the modeling is restricted to fit the plant growth curve only without having a knowledge gain throughout modeling. Berger et al. (2008) identified three major gaps within their review about modeling competition among plants, which were the effects of plants on their local environment, adaptive behavior, and below-ground competition. Neither of those could be addressed fully in current modeling approaches as local interactions and adaptational behavior to biotic and abiotic environment and stress can hardly be captured on plant population level (Berger et al., 2008).

The modeling approach in the present thesis (chapters II and V) differed from those discussed above. Microclimate influence was taken into consideration as well as a more empirical than mechanistic modeling was chosen by introducing a **shading** algorithm. Nevertheless, this approach can be converted into a mechanistic one by further studying attributes of shade (distribution and proportion of PAR, porosity of species for neighboring species, shading intensities etc.), which is needed for further model improvement. Introducing shade into modeling intercropping and relating its intensity or proportion to monocropping is a promising way to overcome the problem of different distribution of incoming sunlight within different distances from strip borders. In addition, increased sunlight for border rows in comparison to centered rows can be taken into account. Modeling intercropping with the evaluated shading algorithm within DSSAT is still an approach, but could be regarded as a model testing for the potential hidden in ‘shadow’. It showed that competition for solar radiation is a major factor in modeling intercropping, but not the one and only. For the relay intercropping experiment with wheat and maize, the shading algorithm explained half of the yield increase in wheat (chapters II and V), but showed, too, that other competition effects are important to consider which lead away from the accentuation of modeling competition for light solely.

In addition, it has the advantages that it could be introduced into other existing models rather easy; shade length can be calculated at each point of time during the day as well as each location of the world by means of longitude, altitude, and sun azimuth; shading of approximately 100 % cannot occur because of plant porosity and distances from two competing plant rows, where light could penetrate, in comparison to Beer’s law and the division of canopies into different layers where the later established understorey species gets hardly any light and thus, could not assimilate sufficient light for growing within simulation. The shading approach might be more cropping system spanning and global.

In other coherencies, the degree or proportion of shading was calculated and used successfully. Stilma et al. (2009) developed a minimal reference model for the population dynamics of annual weeds underneath a shading crop canopy by including treatment-specific shade functions. In addition, the SOMBRERO model from Niewienda and Heidt (1996) was used to simulate complex shadow sceneries and to estimate the influence of shadows on passive solar systems by calculating the quantities and time dependency of geometrical shadow coefficients (Yezioro and Shaviv, 1994) and the proportion of a shaded area as a function of time and location. They stated that the shading depends in many ways on the orientation of the collecting surface (which is an understorey canopy in the case of competing plant growth modeling), its surroundings (neighboring dominant plants), on the season and the time of day. The question is, if modeling of interspecific competition needs 3D model frameworks comparable to the SOMBRERO tool or individual-based neighborhood models like Berger et al. (2008) indicated?

It is obvious that there is a need for further analysis of shade, the introducing of shading algorithms and the testing whether it is necessary to link different modeling frameworks with existing ones. Nevertheless, to enable process-oriented plant growth models to simulate various intercropping scenarios, the shading approach seems to be promising.

11 Summary

Intercropping is a good deal more than the survival of the fittest. Defined as the cropping of two or more crops within the same or an overlapping growing season and within the same field, **intercropping** offers a great variation of species combination, benefits as well as challenges for cropping systems design and farmers. Carefully balanced between facilitation and competition, intercropping bears the potential of increased yield and yield stability, income security, resource use efficiency and biodiversity. The contribution of intercropping systems, mainly practiced in Asian and African countries, should not be underestimated or neglected when considering rural income with smallholder farming predominant. In less developed countries, remote areas and on degradated soils, intercropping contributes substantially to local marked supply, diet diversification and sustainability. Under certain circumstances, intercropping is a concept with substance.

Taking China as an example where intercropping is widespread and approximately one third of the arable land is under intercropping, the system has a 3 000 year old tradition, is as diversified as the Chinese history, reduces pesticides and fertilizer consumption while performing even better under low than high input, reduces nitrate leaching and soil erosion, reduces pests and diseases and produces more output in a more sustainable way than monocropping systems in agro-industrialized monocropping systems. Intercropping gives evidence about traditional cropping systems with the potential for future production systems under the paradigm of sustainability. Wherefore North-American and European farmers rediscover those systems as an option to fulfill issues of modern agricultural production modes.

High yield and sustainability are the catchphrases of production in the 21st century – and agronomy research has to provide solutions in increasingly briefer terms. Thus, **improved cropping strategies** have to be developed. Taking modeling and simulation tools into account could help both to accelerate research attainments and to give a better understanding of cropping systems. How intercropping systems have to be designed and what problems arose, how datasets have to be evaluated for modeling and what kind of multi-level interactions has to be taken into account are the basic topics within the present thesis. The thesis has been carried out within the Sino-German International Research Training Group “Modeling Material Flows and Production Systems for Sustainable Resource Use in intensified Crop Production in the North China Plain”, and was financed by the German Research Foundation and the Chinese Ministry of Education. In this context, field experiments were conducted with a maize/peanut strip intercropping system in China and a maize/wheat as well as a maize/fieldpea strip intercropping system in Germany between the years 2007 and 2009.

The results indicated that border effects are the key component of intercropping performance, and modeling strip intercropping could be termed as modeling field borders. Nevertheless, analyzing strip intercropping has peculiarities as they lack in randomization as the cropping system imposes alternating strips. Thus, **spatial variability** and its effect on yield were regarded differently. For statistical analysis of the trials, different spatial models were applied to account for the spatial trend and to check whether or not standard models are suitable for analyzing strip intercropping experiments.

Throughout a review and evaluation of available data of cereal intercropping systems in China, four **intercropping regions** could be classified and distinguished. The four intercropping regions are the Northeast and North, the Northwest, the Yellow-Huai River Valley and the Southwest. Going from north to south, the cropping systems change from one crop a year with a great potential for intercropping to relay intercropping of especially maize and wheat and double cropping systems and at least three cropping seasons per year with different kinds of rotations and rotations replacing intercropping. The species spectrum within those systems is rather wide and includes wheat, maize, cotton, green manure, soybean, sweet potato, rape, peanut, broomcorn millet, bean, buck wheat, millet, tobacco, sorghum, rice, cassava, garlic and a great variety of vegetables.

In comparison to other countries, like India or Africa, intercropping systems in China seemed to be less documented and studied with the point of view to adjust or improve production patterns or to select for varieties specifically suitable for intercropping. Nevertheless, there is a vast amount of intercropping studies all over the world. In addition, there are a lot of studies about **modeling intercropping** or interspecific competition. The various approaches seem to be promising as the validation of the divers models showed. Nevertheless, most of the model studies restricted the competition effects to competition for solar radiation, not taking microclimate or soil effects into account. Although a lot of crop growth and weed models have been used to simulate intercropping and interspecific competition, only a few show completely different approaches or ideas how to simulate competition in general. Most often, a modified Beer’s law approach was used.

An example for a process-oriented model that has been used for simulating mixed intercropping scenarios by linking sole crop models with a Beer’s law implemented subroutine is the APSIM model. It was used as an example for a **model comparison** between a model already able to simulate interspecific competition and the DSSAT model, which was used predominately in this thesis to model the conducted strip intercropping experiments. So far, DSSAT was not able to model intercropping. Thus, a shading algorithm was evaluated and tested for DSSAT. In addition, the impact of changing microclimate within strip intercropping was analyzed. The Beer’s law approach was not capable to model strip intercropping. Unless there is an issue of trade-off between the loss of crop yield in the intercrop relative to the sole crop, those model approaches are able to address to those loss due to competition for solar radiation. As soon as there is a winner, meaning a yield increase of the dominant intercropped species, without a loser, meaning an equivalent yield of the intercropped understorey species in comparison to the monocropped species, the modeling of competition for solar radiation using Beer’s law is insufficient or not applicable. This approach does not allow for compensation growth of the understorey crop neither for yield increase of the dominant crop. Competition for solar radiation in those system is a driving force for crop productivity but neither the most dominant nor the one and only.

In contrast, the model approach with DSSAT showed, when applying a simple **shading algorithm** that estimated the proportion of shading in comparison to the monocropping situation and in dependency from neighboring plant height both systems performance could be simulated adequately. No submodel was needed to be introduced into the model, but instead, the standard weather file was modified. The advantage of that method is that it could be adapted for all species combination, and a simpler approach could be an adequate surrogate for a complex coherence.

Besides shading or competition for solar radiation, changing **microclimate**, e.g. soil temperature and wind speed, as well as its influence over time has to be taken into regard when modeling intercropping. Resource distribution and allocation in space and time seems to be more important than the total amount of resources. The linear shading algorithm modeling approach showed, that modifying only the incoming solar radiation did not explain fully the yield increase. Foremost the changing of initial conditions taking the higher amount of N cycling in the system, because of the increased soil temperature and N mineralization into account could explain the increase. Increased or decreased wind speed in border rows compared to centered rows might change the transpiration rate as well as the amount of CO_2 assimilation. Those effects have to be taken into account when simulating interspecific competition.

11 Zusammenfassung

Intercropping ist mehr als nur ein „survival of the fittest". Definiert als der Anbau von zwei oder mehr Feldfrüchten auf der gleichen Fläche und innerhalb der gleichen oder einer sich überlappenden Vegetationsperiode, bietet **Intercropping** eine große Bandbreite an Kombinationsmöglichkeiten von Feldfrüchten, verbunden mit vorteilhaften und nachhaltigen Effekten für die jeweiligen Kulturarten. Intercropping ist aber gleichzeitig eine Herausforderung für jeden Landwirt und stellt hohe Ansprüche an die Gestaltung des jeweiligen Produktions- oder Anbausystems. Letztendlich ist Intercropping ein Balanceakt von mindestens zwei Kulturarten, die sich wechselseitig begünstigen oder um Wasser, Nährstoffe oder Sonnenlicht konkurrieren. Gelingt dem Landwirt mit der Wahl geeigneter Kulturarten und Anbausystemen dieser Balanceakt, hat Intercropping das Potential zum erfolgreichen System. Dessen Vorteile sind unter anderem höhere Erträge, Ertrags- und Einkommenssicherheit, effizientere Ressourcennutzung und höhere Biodiversität. Den Beitrag, den Intercropping vor allem in Afrika und Asien hinsichtlich Produktionsvolumen, Belieferung örtlicher Märkte und Nahrungsmittel Diversifizierung liefert, ist nicht zu unterschätzen oder zu vernachlässigen. Intercropping wird hauptsächlich in kleinparzellierten Agrarlandschaften, in kleinbäuerlich strukturierten Ländern Asiens und Afrikas und in benachteiligten Gebieten betrieben, wo es beträchtlich zum Einkommen der ländlichen Bevölkerung und zu einer nachhaltigen Produktion beiträgt. Somit ist Intercropping ein Anbausystem das einerseits ein hohes Potenzial bietet, andererseits aber auch sehr große Herausforderungen an den Landwirt stellt.

Ein Beispiel für ein Land, in dem Intercropping weit verbreitet ist und auf eine 3 000 Jahre alte Geschichte zurückblicken kann, ist China. Schätzungen zufolge wird Intercropping auf rund einem Drittel der gesamten Anbaufläche Chinas praktiziert. Dortige Anbauspektren und Produktionssysteme sind so vielfältig und abwechslungsreich wie die Geschichte des Landes selbst. Der Einsatz von Pestiziden und chemischen Düngemitteln kann reduziert, Krankheits- und Schädlingsbefall eingedämmt und Nitrat-Auswaschung und Bodenerosion vermindert werden. Intercropping gilt als ein Anbausystem, welches bei geringerem Betriebsmitteleinsatz höhere Erträge oder Gewinne erzielt, verglichen mit den ausgedehnten Monocropping Systemen moderner Agrar-Industriebetriebe. Damit belegt Intercropping, dass in traditionellen Anbausystemen ein Potential für zukünftige und nachhaltige Produktionssysteme schlummert. Nicht ohne Grund haben auch Landwirte in

Nord-Amerika und Europa Intercropping wieder- oder neu für sich entdeckt, denn die Paradigmen für eine landwirtschaftliche Produktion haben sich im 21sten Jahrhundert geändert. Neben höheren Erträgen spielt die Art und Weise der Produktion, sprich deren Nachhaltigkeit und Ressourcenschonung, eine zunehmende Rolle.

Um diesen Paradigmen und um politischen, sozialen und ökonomischen Prämissen gerecht zu werden, muss die Agrarforschung Lösungen und **Strategien für angepasste Produktionssysteme** bereitstellen – und das in immer kürzeren Zeitspannen. Der Einsatz von computergestützten Pflanzenwachstumsmodellen, mit deren Hilfe komplexe Anbausysteme regional und überregional, sowie über längere Zeiträume hinweg simuliert und analysierte werden können, hat sich dabei als wertvoll erwiesen. Modellierung und Simulation tragen somit dazu bei Forschung voranzutreiben und gewährleisten, dass Anbausysteme vielschichtiger und intensiver untersucht werden können. Wie Intercropping Systeme gestaltet werden müssen und welche Probleme dabei auftauchen, welche Datengrundlage für eine Modellierung benötigt wird und welche systemimmanenten Interaktionen berücksichtig werden müssen, sind Gegenstand der vorliegenden Dissertation. Die Dissertation war eingebunden in das Deutsch-Chinesische Graduiertenkolleg „Modellierung von Stoffflüssen und Produktionssystemen für eine nachhaltige Ressourcennutzung in intensiven Acker- und Gemüsebausystemen in der nordchinesischen Tiefebene“ und wurde von der Deutschen Forschungsgemeinschaft und dem Chinese Ministry of Education finanziert. Die Datengrundlage basierte auf Feldversuchen, die in China in Form eines Mais/Erdnuss Strip Intercropping, und in Deutschland in Form eines Mais/Weizen und eines Mais/Erbsen Strip Intercropping in den Jahren 2007 bis 2009 durchgeführt wurden.

Die Auswertung der Daten belegte, dass Strip Intercropping auf einem Feldrand-Effekt basiert, Intercropping Modellierung somit auch als Feldrand-Modellierung bezeichnet werden kann. Allerdings gestaltet sich die statistische Auswertung von speziell Strip Intercropping als schwierig, da Intercropping-Versuche aufgrund der zwangsläufig streifenförmigen Anordnung nicht randomisiert werden können. Intercropping bedarf also einer räumlichen Betrachtungsweise, um ertragsrelevante Effekte adäquat abzuschätzen und statistisch abzusichern. Deshalb wurden die Versuche **geostatistisch** ausgewertet und mehrere räumliche Modelle evaluiert und getestet, um die Modellgüte zu verbessern.

Nicht nur die statistische Auswertung von Intercropping ist diffizil, auch die Datengrundlage von Intercropping in China ist lückenhaft. Im Vergleich zu anderen Ländern wie beispielsweise Indien oder Teilen Afrikas, wo Intercropping gängige Praxis ist, scheint die Dokumentation und Erforschung von Intercropping Systemen in China Nachholbedarf zu haben. In einer Literaturstudie (Kapitel 4) wurde deshalb ein erster Versuch unternommen, China in **agro-klimatische Regionen** hinsichtlich ihres Potentials und ihrer Verbreitung von Getreide betonten Intercropping Systemen einzuteilen. Vier unterschiedliche Regionen konnten detektiert werden: der Nordosten, der Norden, der Nordwesten, das Yellow-Huai River Valley und der Südwesten. Die Anbausysteme wechseln von Nord nach Süd von einer Ernte pro Jahr mit einem großen Potential für Intercropping, zu einem Relay Intercropping oder Double Cropping von hauptsächlich Mais und Weizen bis hin zu drei Ernten pro Jahr mit unterschiedlichen Fruchtfolgen, in denen Intercropping entweder integriert ist oder durch eine solche ersetzt wird. Das Kulturarten-Spektrum reicht von Weizen, Mais, Baumwolle, Gründüngung, Soja, Süßkartoffel, Raps, Erdnuss, Millet, Ackerbohne, Buchweizen, Tabak, Sorghum, Reis, Cassava, bis hin zu Knoblauch und einer Vielzahl von verschiedenen Gemüsearten.

In einer zweiten Literaturstudie (Kapitel 5) wurde dargestellt, welche Modelle für Intercropping bereits evaluiert, kalibriert und validiert wurden. Rund 20 verschiedene Modelle in diversen Studien wurden rezensiert, wobei auffiel, dass die **Modellierung von interspezifischer Konkurrenz** in Pflanzengesellschaften wie Mixed Cropping oder Intercropping oftmals auf Konkurrenz um solare Einstrahlung beschränkt wurde. Veränderte mikroklimatische Einflüsse oder Konkurrenz um Bodennährstoffe und –wasser wurden seltener oder gar nicht berücksichtigt. Obwohl die Bandbreite der Modelle relativ groß scheint, verfolgen doch viele Modelle ähnliche oder gleiche Ansätze, wenn es darum geht, Konkurrenz um solare Einstrahlung zu modellieren. Meist bildet ein modifiziertes Beer-Lambert’sches Gesetz die Grundlage.

Exemplarisch für ein prozess-orientiertes Pflanzenwachstumsmodell, welches multiple Anbausysteme und deren Konkurrenz um Sonnenlicht mithilfe des Beer-Lambert’schen Gesetzes simuliert, wurde in Kapitel 9 **APSIM** gewählt. Dieser in der Forschung recht gängige Ansatz wurde mit dem in der vorliegenden Dissertation evaluierten, getesteten und in DSSAT implementierten Beschattungs-Algorithmus verglichen. Mit dem DSSAT Modell war es bislang nicht möglich, Intercropping zu simulieren. Zusätzlich zur Evaluierung des Beschattungs-Algorithmus wurde im Modellierungsansatz mit **DSSAT** ein verändertes Mikroklima in Intercropping verglichen mit Monocropping untersucht.

Es zeigte sich, dass es mit einem modifizierten Beer-Lambert’schen Gesetz nicht möglich war, Strip Intercropping adäquat zu simulieren. Unter der Voraussetzung, dass es im Strip Intercropping einen Gewinner und einen Verlierer gibt, das heißt, dass eine Kulturart mehr

Sonnenlicht erhält als im Monocropping und eine andere dafür weniger, ist der Beer-Lambert'sche Ansatz viel versprechend und verwendbar. Die Kompensationsfähigkeit einer Fruchtart kann jedoch nicht simuliert werden, ebenso keine Ertragssteigerung der im System dominanten Fruchtart. Eine Ressourcenteilung kann simuliert werden, allerdings nicht der Umstand, dass Ressourcenverteilung in Strip Intercropping anderen Gesetzen zu unterliegen scheint. Außerdem ist Konkurrenz um solare Einstrahlung zwar ein wichtiger Einflussfaktor in Intercropping, allerdings nicht der einzige – und möglicherweise auch nicht der dominierende.

Im Gegensatz dazu zeigte sich, dass der **Beschattungs-Algorithmus**, der in DSSAT integriert wurde, beide Systeme – Intercropping und Monocropping – simulieren konnte. Der Grad der Beschattung wurde in Prozent berechnet, indem die Einstrahlung im Intercropping proportional zur Einstrahlung im Monocropping erfasst und in Relation zur benachbarten Pflanzenhöhe gesetzt wurde. Statt ein Konkurrenz-Modul in DSSAT zu integrieren, wurde stattdessen der Weather-Input-File gemäß dem Beschattungsgrad modifiziert. Der Beschattungs-Algorithmus kann relativ leicht auf andere Modelle und auf eine Vielzahl von Kulturart-Kombinationen übertragen werden.

Allerdings wurde in diesem Ansatz zusätzlich berücksichtig und getestet, dass Konkurrenz um solare Einstrahlung nicht die einzig bestimmende ist. Der Beschattungs-Algorithmus konnte zwar einen Teil des Ertragszuwachses im Intercropping erklären beziehungsweise simulieren, allerdings erst die Modifizierung des Boden-Stickstoffgehaltes im Intercropping basierend auf der höheren Bodentemperatur und der damit verbundenen höheren Mineralisierungsrate führte zu einer adäquaten Simulation der erzielten Erträge. **Mikroklimatische Einflüsse,** wie eine veränderte Bodentemperatur und eine veränderte Windgeschwindigkeit in Intercropping verglichen mit Monocropping, wirken sich auf Stickstoff-Verfügbarkeit und Stickstoff-Kreislauf im Boden und auf Transpiration und CO_2-Assimilation aus. Der Allokation von Pflanzenwachstumsfaktoren in Raum und Zeit kommt in Intercropping Systemen eine größere Rolle zu als deren absolute Höhe oder Menge. Solche Effekte müssen berücksichtig werden, um die Modellierung von Strip Intercropping weiterhin zu verbessern und Strip Intercropping Systeme zu optimieren.

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