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Development of a generic, model-based approach to optimize light distribution and productivity in strip-intercropping systems

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List of abbreviations and acronyms

%	Percent
° E	Degree east, longitude
° N	Degree north, latitude
°C	Degree centigrade
µmol	Micromole
a.s.l.	Above sea level
AIC	Akaike Information Criteria
ANOVA	Analysis of variance
APAR	Available photosynthetically active radiation
AX	Surface area of the largest leaf, IXIM model
CANH	Maximum maize canopy height, IXIM model
cm	Centimeter
cm^2	Square centimeter
DAS	Days after sowing
DFG	Deutsche Forschungs-gemeinschaft
DOY	Day of year
DSSAT	Decision Support System for Agrotechnology Transfer
e.g.	For example
FAO	Food and Agriculture Organization of the United Nations
Fig.	Figure

GRK	Graduiertenkolleg, DFG
ha	Hectare
HI	Harvest index
J	Joule
kg	Kilogram
km^2	Square kilometers
L.	Linné
LAI	Leaf area index
LFMAX	Maximum leaf photosynthesis rate, CROPGRO model
LSR	Leaf to stem ratio
mm	Millimeter
M	Million
m	Meter
m^2	Square meter
NCP	North China Plain
NPK	Nitrogen-phosphorus-potassium fertilizer
N	Nitrogen
N_{min}	Soil mineral nitrogen
PAR	Photosynthetically active radiation
PDM	Pod dry matter
RMSE	Root mean square error
RUE	Radiation use efficiency
R^2	Coefficient of determination
SIZLF	Maximum size of full leaf, CROPGRO model
SLA	Specific leaf area
SRAD	Solar radiation

ssp.	Subspecies
s	Second
TDM	Total dry matter
TKW	Thousand kernel weight
t	Ton
T_{max}	Maximum air temperature
T_{min}	Minimum air temperature
US/USA	United States of America
var.	Variety
WRB	World Reference Base for Soil Resources

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1 Introduction

1.1 Agriculture in China: Current status and future challenges

During the last five decades, Chinese cereal production increased remarkably by 3.7% per annum, which is considerably higher than the world average of 2%. The increases in cereal yields were mainly achieved by a higher productivity per arable land than an extension of the cultivated cereal area. For instance, the productivity of the three main cereals rice, wheat, and maize increased by 320, 850 and 460% from 1961 to 2009; whereas, the land devoted to cereal production only increased by 30% (Fan et al., 2012). Overall, the cereal production in China increased 4.5-fold since 1949 accompanied by a lower decrease of 2.5-fold of the population (Zhang et al., 2011). Nowadays, China feeds around 22% of the world population with utilizing only 7% of the world's arable land. Additionally, the number of undernourished people has decreased by almost 90%, from 250 million in 1978 to 29 million people in 2003 (Chen, 2007). Nevertheless, the Chinese population is growing and a peak is expected to be reached in 2033 at around 1.6 billion (Fan et al., 2012). In addition, a higher living standard and a larger proportion of the urban population changed the dietary behavior with a higher demand for meat, dairy and aquatic products (Wang et al., 2004). In order to meet the grain demand of the growing population along with an increasing living standard, the grain production has to further increase by at least 35% during the next 20 years (Zhang et al., 2011). However, the arable land per capita in China is among the lowest worldwide and a further expansion is limited. Furthermore, a loss of arable land is caused by the current agricultural practice and also, to a minor degree, by the ongoing urbanization and infrastructural development (Chen, 2007). Furthermore, the considerable increase of productivity in the past was mainly achieved by intensification with a large expansion of the irrigated arable land and an increase in consumption of chemical fertilizers with the largest share of nitrogen fertilizers (Fig. 1.1). Especially excessive and imbalanced inputs of nitrogen fertilizers led to severe environmental problems, such as groundwater pollution (Ju et al., 2006), eutrophication (Le et al., 2010) and high emissions of ammonia and nitrous oxides (Liu et al., 2006). Moreover, the extension of the arable land area under irrigation led to an alarming decline of groundwater tables (Sun et al., 2006). In order to diversify the crop production and generate higher income possibilities for the rural population, the arable land area dedicated to the production of high-value crops, such as vegetables and fruits, increased in China 4.2 and 4.5 times from 1978 to 2002 (Chen, 2007). Vegetable production is especially very intense, and the large amounts of water and fertilizer being applied have largely exceeded crop demands, which has aggravated the negative environmental impacts. Therefore, in order to feed the growing population in China, agricultural production is more challenged than ever before. The productivity per area has to be increased further; however, in contrast to the intensification in the past, this is to be done without increasing fertilizers and water inputs. Consequently, there is an urgent need to develop cropping systems that are both highly productive and sustainable.

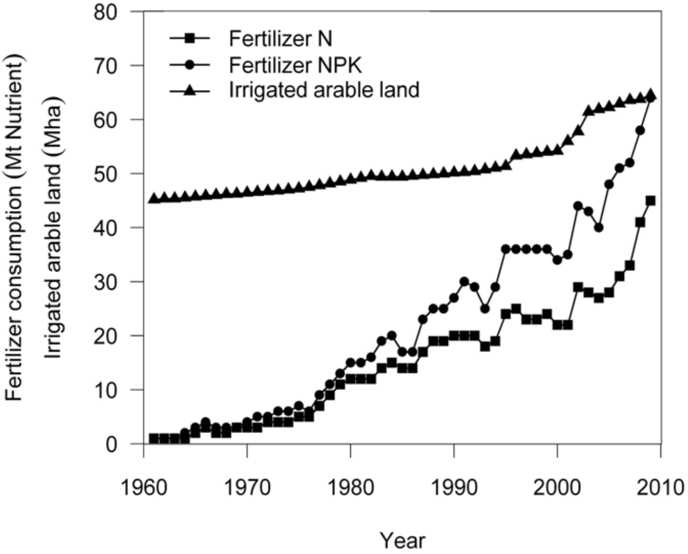

Fig. 1.1: Consumption of N and NPK fertilizers (Mt Nutrients) and irrigated arable land (Mha) in China from 1961 to 2009 (Source: FAO, 2013).

The above described environmental problems and the limited availability of land and water resources are particularly challenging for current and future agricultural production in the North China Plain (NCP). This region, also called the 'Granary of China', is the largest and most important agricultural area in China where on 18.6% of the national agricultural land, 75% and 35% of the national wheat and maize are produced (Changming et al., 2001; Meng et al., 2012; Wu et al., 2006). The NCP comprises in total one fifth of the national food production including other important crops like soybean, peanut as well as vegetable species (Chen et al., 2004; Wu et al., 2006; Zhang et al., 1999). This region includes five provinces (Anhui, Hebei, Henan, Jiangsu, Shandong) and two large cities (Beijing and Tianjin). It is east China's largest alluvial plain, and it is situated in the North-East between 100-120° E and 32-40° N covering an area of approximately 300.000 km^2 (Fig. 1.2).

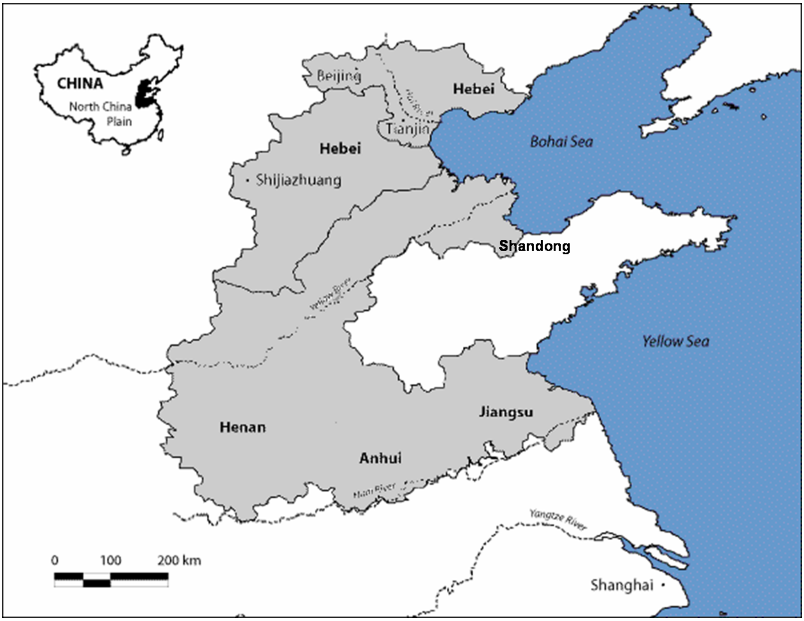

Fig. 1.2: Location of the study region 'North China Plain' within China. (modified from http://www.eoc.csiro.au/aciar/book/Overview.html; verified 11 Jan. 2014).

The weather in the NCP is characterized by a continental monsoon climate with hot, rainy summers, and cold, dry winters with an average precipitation between 500-800 mm and an average temperature of 10-14 °C. The amount of annual precipitation is highly variable, ranging between 300 to 1000 mm and mostly concentrated during the summer months (Changming et al., 2001; Meng et al., 2012). The agricultural production is very intense, with a large necessity of irrigation during spring for the abundant wheat production. In addition, fertilizer inputs are far above the crop requirements. For instance, for the region's typical double cropping system consisting of wheat and maize, inputs of N-fertilizers range between 500-600 kg ha^{-1} exceeding crop requirements almost twice (Cui et al., 2010). Additionally, groundwater tables are declining at an annual rate of 1 m in the NCP (Wang et al., 2002). Considering the importance of the NCP for the current and future Chinese food production and the severe environmental problems related to the current agricultural practice, the International Research Training Group (IRTG) entitled 'Modeling Material Flows and Production Systems for Sustainable Resource Use in Intensified Crop Production in the North China Plain' was established by the Deutsche Forschungs-gemeinschaft (DFG) and the Chinese Ministry of Education (MOE) at the University of Hohenheim and the China Agricultural University in June 2004 and lasted until 2013.

The main aims of the project were to develop high-yielding cropping systems and management practices that are more sustainable under environmental, economical, and social perspectives. In general, research focused on quantifying material flows and developing modeling approaches on different levels and scales (field, farm and regional levels). This was done to create linkages between disciplines and to assess the impact of new agricultural strategies. For this purpose, eleven subprojects from various disciplines, namely soil sciences, plant nutrition, plant ecology, physics, plant production, plant breeding, weed science, agricultural engineering, farm management, agricultural informatics and rural development policy, were involved. Further information is available at https://rtgchina.uni-hohenheim.de (verified 11 Jan. 2014). The present doctoral thesis was realized within the subproject 'plant production' entitled 'Design, modeling and evaluation of improved cropping strategies and multi-level interactions in mixed cropping systems in the North China Plain'. The focus of this subproject was to evaluate cropping system prototypes - with special regard to intercropping systems - based on: (i) the quantification of competitive relationships between crop species regarding yield, solar radiation, water and nitrogen; (ii) designing the necessary methods and basic approaches to identify the key parameters influencing plant growth and yield formation; (iii) transferring the gained knowledge into modeling approaches, which lead to a comprehensive understanding of the interactions between the crops and their growth environment; and, (iv) use the developed modeling approaches to suggest further improvements with the aim to maximize the overall productivity of intercropping systems.

1.2 Intercropping

Intercropping, the practice of growing two or more crops simultaneously on the same field is a common practice in developing countries, especially in low-input, smallholder farming systems (Vandermeer, 1989). Nevertheless, in recent years intercropping also received more attention in farming systems in developed countries, especially regarding the combination of trees with annual crops (Dufour et al., 2013) and several combinations of annual crops in organic farming systems (Hauggaard-Nielsen et al., 2013; Jannoura et al., 2014). In China, intercropping has a long history and a large number of different intercropping combinations are practiced, including for cereals (e.g. maize, wheat), legumes (e.g. soybean, faba bean), cotton, and also vegetable species (Feike et al., 2010; Knörzer et al., 2009; Li et al., 2001). In general, the interest in intercropping systems can be attributed to the often reported higher land use efficiency of intercropping systems (Dhima et al., 2007; Zhang et al., 2007) by a more efficient use of water (Morris and Garrity, 1993; Walker and Ogindo, 2003), of nutrients (Li et al., 2001) and of solar radiation (Awal et al., 2006; Gao et al., 2010b; Keating and Carberry, 1993; Tsubo et al., 2001). Furthermore, a higher yield stability in intercropping systems might decrease the vulnerability to climate change (Altieri and Nicholls, 2013; Lin et al., 2008).

The particular interest in intercropping systems in Chinese agriculture can be explained by the long history of this practice having been passed on to the next generations; and, especially by the very limited land resources with average farm sizes between 0.1-0.5 ha, but also by the large numbers of available labor as intercropping systems in China are very labor intense (Knörzer, 2010).

The decisive question is how to optimize intercropping systems over space and time. A large number of different cropping pattern exists which differ in their temporal (e.g. sowing date of each crop) and spatial arrangement (e.g. mixed, rows or strips). Therefore, in order to maximize the productivity, the temporal and spatial interactions between the crops and their environment have to be known. The interactions between the crops can basically be separated into two opposite effects: (i) competition, which describes the effect that the modification of the growth environment by one crop is causing a negative response in the other crop; and (ii) facilitation, which defines the situation that the growth environment modified by one crop results in a positive response in the other crop (Vandermeer, 1989). Competition and facilitation between the crops occur below-ground for water and nutrients and above-ground for light. In general, below-ground competition will play a major role between crops of similar canopy height; on the contrary, when the intercrops exhibit large differences in height, competition for light will strongly influence the total productivity. The degree of competition or facilitation depends on the temporal resource requirements of the crops, and their ability to adapt to the modified microclimate when grown in association with another crop. This explains why, in general, intercropping systems comprise crops that differ in morphology, physiology, and/or phenology to achieve a high complementary use of resources by the crops over space and time.

In north-eastern China, intercrops are most frequently grown in narrow alternating strips. The intercrops are not sown and harvested at the same time. This system, so called relay strip-intercropping, allows the first crop to develop earlier which leads to a competitive advantage over the second crop. However, the first crop is harvested earlier, thus, allowing the second crop to use more resources and compensate for the early competition. This temporal optimization was studied extensively in wheat-maize and wheat-soybean strip-intercropping systems (Li et al., 2001; Zhang and Li, 2003), and was described by the authors as the ‘competition-recovery-principle’. The studies mentioned showed that the competition was mainly below-ground with a considerably higher uptake of nitrogen, phosphorus and potassium in the border rows of wheat next to maize and soybean, resulting in increased wheat yields compared to wheat grown in monocropping. Even though, maize and soybean plant growth was reduced in the border rows by the strong nutrient-competition of wheat; after wheat harvest, border rows of both crops showed higher plant growth rates which resulted not only in equal (Knörzer et al., 2011), but in some cases, in even higher yields than their monocrop equivalents (Li et al., 2001; Zhang and Li, 2003).

In the case of maize-soybean strip-intercropping, where one or two rows of maize are alternated with three rows of soybean, and is also practiced in north-east China, the growing periods of both crops overlap most of the time and above-ground competition for light will strongly influence plant growth, and finally, total productivity. The overall productivity of the maize-soybean strip intercrops has been shown to be higher than growing both crops in monocropping due to increased yields of maize plants receiving more radiation, and a comparably smaller reduction of soybean yields as a result of shading (Gao et al., 2010b).

Despite the high productivity of these narrow strip intercropping systems, their future practice cannot be regarded without discussing socio-economic and technical changes in China. The rapid economic development in China, led to a large migration of rural laborers to urban areas, seeking higher income possibilities. Furthermore, the use of agricultural, mostly small-size machinery, is steadily increasing in China. Under these circumstances, it is likely that the frequency of labor-intensive intercropping systems will further decrease as reported recently from a county in Hebei province (NCP) by Feike et al. (2010).

For a future management of intercropping systems under a lower availability of manual labor, the cropping pattern has to be optimized spatially to facilitate mechanized management. An option more common in modernized agricultural systems with the desire to use machinery (Vandermeer, 1989), is growing the crops in wider strips as practiced, e.g., in US and Argentinean farming systems (Ghaffarzadeh, 1999; Lesoing and Francis, 1999; Verdelli et al., 2012). These kind of strip-intercropping systems were initiated in the USA due to an ongoing mechanization, which was not adapted to maize and soybean grown in alternating rows or pairs of rows (Pendleton, 1963). Numerous studies were conducted, mainly in the US, showing at least a productivity equivalent to monocropping (e.g. West and Griffith, 1992; Lesoing and Francis, 1999) or increased total yields of maize and soybean when intercropped in wider strips (Ghaffarzadeh et al., 1994). Even though most studies concluded that maize yields increase in border rows due to a higher radiation interception and soybean yields decreased due to shading, actual measurements of radiation availability are very rare (e.g. Jurik and Van, 2004, Verdelli et al., 2012). Furthermore, the reduced radiation induces functional and structural adaptations on the leaf- and canopy-level in many plant species (e.g. Gardiner and Craker, 1981; Smith and Whitelam, 1997; Tsubo and Walker, 2004). These shade adaptations aim at higher and more efficient use of radiation by increasing canopy height and width (Cox, 1978; Hang et al., 1984; Jurik and Van, 2004), and developing larger and thinner leaves (Björkman, 1981; Evans and Porter, 2001; Tsubo et al., 2001). Therefore, it is of primary importance to know the temporal and spatial distribution of radiation across the strip of each crop, particularly for the smaller shaded crop. Knowing the quantity of radiation available for the smaller crop enables the study of the quantitative response to shading on the leaf- and canopy-level, and finally total dry matter and yield. On the contrary, in maize rows next to a smaller crop, radiation availability is increased which results in a higher yield potential. The actual yield response of maize depends mainly on the cultivar-specific threshold for kernel set (Andrade et al., 1999) and the water availability (Francis et al., 1986). In a summary about strip intercropping systems in Iowa (USA), Ghaffarzadeh (1999) acknowledged the need for studies on the performance of different maize cultivars in strip intercropping systems; however, to the best knowledge of the author, no respective study has been published to date. Given the large number of possible combinations of crops and cultivars, their spatial and temporal arrangement, and the interactions between the crops and the local environment, the factors influencing plant growth and yield formation of the intercrops are too numerous to be studied in field experiments. Therefore, there is an urgent need for comprehensive modeling approaches to evaluate how soil, weather and management conditions modify the growing conditions and yield of the intercrops and their impact on the environment (Malézieux et al., 2009).

1.3 Modeling competition and crop growth

Simulation models are a highly valuable tool in understanding the relationships between plants and their growth environment, and are regarded as a crucial part of further improvement of cropping systems including more than one crop. In particular, process-oriented models are most suitable for intercropping systems as they bear the potential to make predictions outside the range of the data available for parameterization (Malézieux et al., 2009). Thus, simulations can be used to assess the effect of different intercropping combinations under different environments and management conditions leading to suggestions of locally optimized cropping designs. The identification of these promising cropping patterns limits the number of factors to an experimentally feasible extend.

In contrast to intercropping, modeling of plants grown in monoculture received considerably more attention, and several process-oriented plant-soil-atmosphere models have been developed (Brisson et al., 2003; Jones et al., 2003; Keating et al., 2003). The simulation of intercropping systems was addressed either by the extension of existing monocropping models (e.g. Baumann et al., 2002; Berntsen et al., 2004; Brisson et al., 2004) or by new simplified models developed for a particular cropping system (O'Callaghan et al., 1994; Tsubo et al., 2005).

In the present doctoral thesis, special emphasis was given on the simulation of the light availability for a smaller crop grown between maize strips. Light competition was more frequently investigated and as well simulated in row-intercropping systems, e.g. by Tsubo et al. (2005) in alternating rows of maize and bean. However, when the crops are grown in alternating strips, the light availability will be more heterogeneous across the strip of each crop as the shade intensity varies with distance from the neighboring crop and time of day (Munz et al., 2014). Knörzer et al. (2011) developed a shading algorithm to estimate the level of shading at the top of the canopies of wheat and maize in a relay strip intercropping system. The shading algorithm was based on the relationship between weekly measured canopy height and radiation. However, the need for empirical data to calibrate the algorithm does not allow for predicting the light distribution under conditions differing from the ones in the experiment. Furthermore, even though the differences of canopy height between the crops play an important role in the light distribution among crops, there are many other factors, such as strip width and orientation, leaf area index, leaf angle distribution and location that have to be considered.

For the simulation of plant growth under shade, the CROPGRO model integrated in the DSSAT (Decision Support System for Agrotechnology Transfer) software shell (Jones et al., 2003) was chosen in the present study. CROPGRO was developed for the simulation of grain legumes grown as monocrops. It has a process-oriented structure with an hourly simulation of leaf-level photosynthesis and algorithms that account for effects of reduced radiation on canopy dimensions (height and width) and specific leaf area (Boote et al., 1998). Furthermore, the generic nature of CROPGRO allowed for the integration of many grain legumes, but also non-legume crops, such as tomato, cabbage and cotton (Boote et al., 1998; Messina et al., 2004; Scholberg et al., 1997). Recently, the CROPGRO model was used to simulate cotton growth under shade in an alley-cropping system (Zamora et al., 2009). However, there is no published article about the ability of CROPGRO to simulate growth of an intercropped legume. Legume crops are a key component of many intercropping systems (Ofori and Stern, 1987). Most frequently a smaller legume is intercropped with a tall C4-species, in most cases maize (Seran and Brintha, 2010).

1.4 Outline and Objectives

The present doctoral thesis focused on strip-intercropping systems of maize with a smaller legume crop. Competition for light plays the major role in these systems due to the large height differences between the crops during their co-growing period. The major aim was to develop modeling approaches that account for: (i) the factors that influence the light distribution among the crops; and, (ii) the adaptations of the plants to the modified light regime and their influence on the productivity. Based on these modeling approaches, the processes driving the productivity can be explored and future research can be guided towards locally optimized strip intercropping systems.

The specific objectives of this thesis were:

- to investigate the light availability on high temporal and spatial resolutions,
- to develop and validate a model that simulates the light availability for the smaller crop grown between maize strips, and accounts for the major aspects of cropping design,
- to determine the effect of the modified light availability on growth of maize and the legume crop bush bean,
- to evaluate the CROPGRO plant growth model for its ability to simulate growth of bush bean strip intercropped with maize,
- to investigate the interactions between maize cultivar, strip width and the local environment,
- to identify promising cropping designs and detect future research needs to increase the productivity of strip intercropping systems.

For the accomplishment of the objectives described, field experiments were conducted during three years (2010-2012) at the experimental station 'Ihinger Hof' of the University of Hohenheim in southwestern Germany and during three years in China, namely at the experimental station of the Institute of Agricultural Sciences in Fangshan, Beijing in 2010 and 2011, and at the experimental station of the China Agricultural University in Shangzhuang, Beijing in 2012. The field experiments comprised of strip-intercropping maize (*Zea mays* L.) with a rotation of smaller vegetables, including Chinese cabbage (*Brassica rapa* L. ssp. *pekinensis*) and bush bean (*Phaseolus vulgaris* L. var. *nana*). Growing the crops in strips facilitates mechanized management, addressing the ongoing decrease of intercropping in China due to labor scarcity in rural areas. The crop combination of maize, a tall C4-crop with erectophile leaves, and smaller C3-crops with a more horizontal leaf orientation, was chosen due to the large potential for a complementary resource use. The legume crop bush bean, grown during summer, might further reduce the competition with maize for nitrogen by atmospheric N-fixation. Frequent measurements of dry matter accumulation of all plant organs were conducted in individual rows across the strip of each crop. Measurements of radiation were conducted in five-minute intervals during a two-months co-growing period of maize and bush bean (Fig. 1.3). The experimental design is described in detail in Chapter I, II and III of the present thesis.

Fig. 1.3: Measurements of the photosynthetically active radiation in individual rows across the strip of bush bean intercropped with maize shortly after emergence (left) and shortly before harvest (right) of bush bean.

The **first Chapter** presents the development of a light partitioning model that simulates the amount of photosynthetically active radiation (PAR) that is available across the strip of the smaller crop grown between maize strips. The model was evaluated for different rows across the strip of bush bean, under both clear and cloudy conditions, and a sensitivity analysis was performed to detect the influence of maize canopy architecture and crop arrangement on light availability for the smaller, neighboring crop.
In the **second Chapter**, the response of bush bean to different levels of shade as experienced when grown in alternating strips with maize was investigated, both on the leaf- and canopy-level. Furthermore, the derived field data and the light partitioning model developed (Chapter I) were used to evaluate the CROPGRO model for its ability to simulate growth and shade adaptations of the two most shaded rows of bush bean next to maize. The CROPGRO model was employed on the code-level, and data was transferred via text-files. This allowed the comparison between simulations based on the default daily input of radiation with an hourly

radiation. Limitations of the model and the most important key parameters were identified and discussed.

In **Chapter three**, the interactions between maize cultivar, growing conditions and yield formation across the maize strip were evaluated on the derived data from seven growing seasons, four in Germany and three in China. The differences between the two locations and across the years regarding weather, irrigation (rainfed or irrigated) and maize cultivars provided a large data set. Based on the derived data and the application of the developed light model (Chapter I), this study aimed at a global understanding on the influences of weather, location and management on maize yield and the light availability for the smaller crop in strip intercropping systems.

Chapters I-III present the results which have been submitted to peer-reviewed journals or have already been published. The details of each publication are given in the following chapter ‘Publications’. The three scientific articles provide the body of the present dissertation. Additional publications and presentations in the context of the dissertation are listed in Table A1 in the appendix.

2 Publications

The present cumulative thesis consists of three articles which have been published in peer-reviewed, international high standard referenced journals. For citation of the three articles, which correspond to the Chapters I-III of the present thesis, please use the references given below.

Chapter I

Munz, S., Graeff-Hönninger, S., Lizaso, J.I., Chen, Q., Claupein, W. (2014): Modeling light availability for a subordinate crop within a strip-intercropping system. Field Crops Research 115, pp. 77-89.

Chapter II

Munz, S., Claupein, W., Graeff-Hönninger, S. (2014): Growth of bean strip-intercropped with maize - Evaluation of the CROPGRO model. Agronomy Journal 106, pp. 2235–2247.

Chapter III

Munz, S., Feike, T., Chen, Q., Claupein, W., Graeff-Hönninger, S. (2014): Understanding interactions between cropping pattern, maize cultivar and the local environment in strip-intercropping systems. Agricultural and Forest Meteorology 195–196, pp. 152–164.

3 Chapter I: Modeling light availability for a subordinate crop within a strip-intercropping system

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Publication I:

Munz, S., Graeff-Hönninger, S., Lizaso, J.I., Chen, Q., Claupein, W. (2014): Modeling light availability for a subordinate crop within a strip-intercropping system. Field Crops Research 115, pp. 77-89.

Many studies about strip-intercropping of crops exhibiting large height differences attributed the largest influence on productivity to the modified light availability. In particular, shading by the taller crop reduced yields of the smaller, subordinate crop. However, actual light measurements are rare and a comprehensive approach to quantify the influence of crop arrangement, crop architecture, and location has not been developed. Facing this background, Chapter I focused on the light availability for a smaller crop grown between maize strips. Measurements were conducted on high temporal (five-minute interval) and spatial resolutions (individual rows across the strip) in a strip-intercropping system of maize and bush bean. A model simulating the light availability for the smaller crop was developed, including the major aspects for designing strip-intercropping systems, such as strip width, strip orientation, and canopy architecture (leaf area index, leaf angle distribution, canopy height and width). The model was evaluated on the derived data and a sensitivity study was performed to identify the parameters mostly influencing the light availability for the smaller, subordinate crop. Model simulations showed a high accuracy both under clear and cloudy sky conditions. Simulations indicated that canopy height and leaf area index of maize mostly influence the light availability for the smaller crop, in particular in the row adjacent to the maize strips. The developed light model enables: (i) to identify the most promising cropping arrangements of different crops and cultivars to guide further experimental research; and, (ii) to further investigate the influence of the modifed light availability on plant growth and yield formation in plant growth models.

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Modeling light availability for a subordinate crop within a strip–intercropping system

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ABSTRACT

The shift of rural laborers out of the agricultural sector led to a steady decrease of intercropping in the North China Plain (NCP). Strip intercropping facilitates mechanized management, and has the potential to out yield monocropping by an optimized resource use of the intercropped species. Therefore we developed a light partitioning model, that calculates the available amount of photosynthetically active radiation (*PAR*) at the top of the canopy for a given point within a strip of a smaller, subordinate crop. The model was described, evaluated on various simulation time steps and tested for the purpose of designing strip–intercropping systems. PAR reaching the top of the canopy of various rows of the strip subordinate bush bean (*Phaseolus vulgaris* L. var. *nana*) was measured continuously under different sky conditions. In the dominant strip, maize (*Zea mays* L.) was grown. Then the model was tested for its ability to account for the influence of different widths of the bush bean strip, strip orientations and maize canopy architecture (height, leaf area index, and leaf angle distributions). Comparison between hourly averaged simulated and observed values of PAR across the bush bean strip showed a high accuracy of the simulations, under both, clear and cloudy conditions. Overall, simulations of hourly values of PAR across the bean strip showed a root mean square error (RMSE) ranging between 47 and 87 μmol m^{-2} s^{-1} and a percent bias (PBIAS) ranging between −3.4 and 10.0%. A simulation time step of 20 min is recommended to preserve the accuracy of the model across the strip. The model captured reasonably the influence of strip design (width and orientation) and maize canopy architecture. Results suggested that the highest potential to increase PAR across the bush bean strip is by reducing height and leaf area index of maize, especially in the most shaded border row adjacent to the maize strip. The model proved to be a helpful tool for understanding the characteristics of light availability across the strip of the subordinate species and can be further used to examine a number of strip intercropping arrangements prior to labor and time consuming field trials.

1. Introduction

Intercropping is widely practiced in the North China Plain (NCP), but socioeconomic changes over the last decades led to a steady decrease, mainly because of the high demand of manual labor (Feike et al., 2012). Facing the current challenges of labor scarcity and environmental problems related to overuse of groundwater for irrigation and excessive application of fertilizers (Meng et al., 2012), there is an urgent need in the NCP for highly productive, sustainable, and mechanizable agricultural systems. Strip intercropping might be an appropriate system, combining the potential of a higher resource-use-efficiency of intercropping with the facilitation of mechanized management.

In general, intercropping advantages have been related to a higher radiation interception of the dominant species, especially for C$_4$-species (Keating and Carberry, 1993). Radiation is the major factor that is changed by the system design, and cannot be kept at the optimum level (referring to monocropping) like fertilization and irrigation. Maize is the dominant annual crop most often used in intercropping systems, intercropped most frequently with a smaller legume (Seran and Brintha, 2010). According to studies by Ghaffarzadeh et al. (1994), Lesoing and Francis (1999), Jurik and Van (2004), Verdelli et al. (2012), strip–intercropping out yielded monocropping mainly due to an increased yield in the border rows of the dominant species having a higher radiation interception. This yield increase was comparably larger than the decrease of the

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yield in the border rows of the shaded, subordinate crop. Hence, an important key to further increase the overall productivity is to increase the radiation availability for the neighboring, subordinate crop. Ghaffarzadeh (1999) summarized the results from extensive studies on strip intercropping of corn and soybean in Iowa (USA). The author concluded that strips planted in a north-south orientation with a strip width of greater than six rows limit the shading to the first border row of soybean adjacent to the maize strip, which results in an overall yield advantage, compared to monocropping. Furthermore, the author acknowledged the lack of studies examining the influence of different maize cultivars on strip productivity, and pointed out the importance of the diurnal shading pattern that resulted in yield differences between eastern and western border rows. Nevertheless, actual measurements on light availability across the strip of a subordinate crop are rare (Jurik and Van, 2004; Zhang et al., 2008; Verdelli et al., 2012). The most detailed study was conducted by Jurik and Van (2004) who measured PAR received across a soybean strip in a narrow (four rows wide) intercrop system of maize, soybean, and oat. The authors showed the large variation which may occur during the growing period across the soybean strip. The soybean row farthest from the maize strip received 38 to 140% more PAR compared to the border row next to maize. However, the studies mentioned above vary in many aspects, such as cropping pattern (maize-soybean or maize-soybean-oat), row width (four to twelve rows wide), and strip orientation. Thus, it is not possible to extrapolate the results to other locations, nor is it feasible to conduct studies comprising numerous combinations of crops (and cultivars) and spatial arrangements at other locations (Knörzer et al., 2011).

For future improvements in strip intercropping systems there is a need for a comprehensive model, which provides a better understanding of the temporal and spatial availability of radiation across the strip of the subordinate crop. Based on such a model, the most suitable cropping pattern could then be identified and further tested in field trials.

A promising modeling approach of light distribution that involves the important aspects of strip intercropping systems was developed by Gijzen and Goudriaan (1989) for row crops. The model is based on architectural and geometrical relationships, accounting for spatial distances between crop rows, canopy height and width, row orientation, distribution of leaf area inside the row (considering row and path width), and the local position of the sun. This approach was further used by other authors to represent the geometric relationship between crops and weeds (Schnieders, 1999), in row-intercropping of bean and maize (Tsubo and Walker, 2002), and with a simplified approach after Pronk et al. (2003) in a relay strip–intercropping of wheat and cotton (Zhang et al., 2008). The study by Tsubo and Walker (2002) compared the performance of the geometrical with a statistical model to simulate the instantaneous light transmission and radiation use efficiency in an alternate canopy of maize and bean. Both models showed a high accuracy, but only the geometrical model is able to capture spatial differences of instantaneous light transmission within a row of bean or maize, respectively. Zhang et al. (2008) studied the light interception and utilization of relay intercrops of wheat and cotton planted in different numbers of rows per strips of wheat and cotton (3:1, 3:2, 4:2, 6:2). The simplified modeling approach was used to calculate the light interception on a daily basis. However, actual measurements of PAR were only conducted on a few days, and no model evaluation was shown.

Therefore, the objectives of this study were to: (i) obtain detailed measurements of PAR at the top of the canopy across the strip of a subordinate crop; (ii) develop and evaluate an instantaneous light partitioning model for strip intercropping systems that calculates the available amount of PAR at the top of the canopy of a given row within the strip of a subordinate crop; (iii) determine the adequate time step for the calculations; (iv) evaluate the models ability to design improved strips by combining such components as strip width, strip orientation, and maize canopy architecture.

2. Materials and methods

2.1. Model development

Briefly described, the model first calculates the position of the sun (elevation and azimuth angle) for a given location and time. Then it further calculates the amount of direct and diffuse PAR available at a given point across the strip of the subordinate species based on the geometric relationship of the strip–intercropping arrangement.

2.1.1. Solar position

The solar position is defined by the solar elevation β and the solar azimuth ϕ, and are calculated based on algorithms available at http://www.esrl.noaa.gov/gmd/grad/solcalc/calcdetails.html (verified 13 September 2013). The required inputs are latitude, longitude and the time zone of the location. The desired time step of the calculation was adapted. The solar position is further used as an input for the geometrical calculations in the model. The variables used as model input and calculated in the model are listed in Table 1.

2.1.2. Geometry of the strip–intercropping system

The implemented method to represent the geometric relationship of the strip–intercropping system was developed by Gijzen and Goudriaan (1989). Fig. 1 shows the coordinate system modified from the original row system to the strip arrangement. The width of the maize strip equals row width in the calculations, while the width of the bean strip equals the path width, respectively. The strips are represented as hedgerows with a rectangular cross-section in the xz-plane, and an infinite length in the dimension y along the row.

The incoming light beam is defined by its elevation angle β and its azimuth angle ϕ. With those two angles and the azimuth of the strips ϕ_r the other two angles α_c and β_c can be calculated as:

$$\sin\beta_c = \cos\alpha * \cos\beta \tag{1}$$

$$\cos\alpha_c = \sin\beta / \cos\beta_c \tag{2}$$

where α is the difference between strip azimuth ϕ_r and beam azimuth ϕ, α_c is the angle of the projection of the light beam within the xz-plane perpendicular to the strip orientation, and β_c is the angle of the light beam with the xz-plane. The height of both crops is integrated into the calculations as the effective height parameter (H_{eff}, m), which is calculated as, $H_{eff} = H_M - H_B$, where H_M (m) is the height of the dominant maize strip and H_B (m) the height of the subordinate bean strip, respectively. Strip width of maize (SW_M, m) is given by:

$$SW_M = (n_{t,row,M} - 1) * R_M + CW_M \tag{3}$$

where $n_{t,row,M}$ is the total number of maize rows of the strip, R_M is the row spacing of maize (m), and CW_M is the canopy width of maize (m). The total cross-section width SW_t (m) is the sum of SW_M and strip width of bean SW_B (m). SW_B (m) is calculated as equation (3) with the respective values for bean.

Based on the calculated angles and the dimensions of the maize strip, the length of the shadow cast by the maize strip (l_s, m) is equal to:

$$l_s = H_{eff} * \tan(\alpha_c) \tag{4}$$

An important aspect of strip intercropping contrary to monocropping or one-row intercropping systems is the

Table 1
Definition and units of variables used as model inputs and of variables calculated in the model.

Variable	Definition	Units
	Model input	
CW_M	Width of maize canopy	m
H_B	Height of bean canopy	m
H_M	Height of maize canopy	m
k_d	Extinction coefficient for diffuse radiation	–
LAI	Leaf area index	$m^2\,m^{-2}$
Latitude	Latitude of the location	decimal degrees
Longitude	Longitude of the location	decimal degrees
$n_{row,B}$	Number of bean rows	–
$n_{t,row,B}$	Total number of bean rows in the maize strip	–
$n_{row,M}$	Number of maize rows	–
$n_{t,row,M}$	Total number of maize rows in the bean strip	–
$N_{t,max}$	Maximum number of maize strips	–
PAR	Photosynthetically active radiation (above the maize canopy)	$\mu mol\,m^{-2}\,s^{-1}$
R_B	Row spacing of bean	m
R_M	Row spacing of maize	m
Solar radiation	Solar radiation	$MJ\,m^{-2}\,d^{-1}$
Time Step	Time step used in the calculations	min
Time zone	Time zone of the location in Universal Time Coordinated (UTC)	h
X	Ratio of average projected areas of canopy elements on horizontal and vertical surfaces	–
ϕ_r	Azimuth of the strip (due to south, counterclockwise)	degrees
σ	Scattering coefficient	–
	Model calculation	
$APAR$	Available photosynthetically radiation at canopy level of bean	$\mu mol\,m^{-2}\,s^{-1}$
$APAR_D$	Available direct photosynthetically radiation at canopy level of bean	$\mu mol\,m^{-2}\,s^{-1}$
$APAR_d$	Available diffuse photosynthetically radiation at canopy level of bean	$\mu mol\,m^{-2}\,s^{-1}$
$APAR_{d,fvd}$	Available diffuse photosynthetically radiation at canopy level of bean without traversing maize leaf area	$\mu mol\,m^{-2}\,s^{-1}$
$APAR_{d,t}$	Available diffuse photosynthetically radiation at canopy level of bean traversing maize leaf area	$\mu mol\,m^{-2}\,s^{-1}$
DL	Day length	min
fv_d	Diffuse view factor (for diffuse radiation)	–
fv_D	Solar view factor (for direct radiation)	–
H_{eff}	Difference between height of bean and maize canopy	m
K_D	Extinction coefficient for direct radiation	–
LAI_D	Maize leaf area index traversed by light beam	$m^2\,m^{-2}$
LAI_d	Average maize leaf area index traversed by diffuse radiation	$m^2\,m^{-2}$
LAD	Leaf area density	$m^2\,m^{-3}$
l_s	Length of shadow cast perpendicular to the maize strip	m
l_t	Path length of the light beam traversing the maize canopy	m
N_t	Integer number of total strip widths (SW_t) traversed by the light beam	–
SW_B	Width of bean strip	m
SW_M	Width of maize strip	m
SW_t	Total strip width (of bean and maize)	m
x	Distance between a given point within the bean strip and the maize strip	m
x_t	Length of the first unit strip traversed by the light beam	m
α	Difference between strip azimuth and solar azimuth	degrees
α_c	Angle of the projection of the light beam within the *xz*-plane perpendicular to the strip orientation	degrees
β	Solar elevation	degrees
β_c	Angle of the light beam with the *xz*-plane	degrees
τ	Transmittance of *PAR* through leaves	–
ϕ	Solar azimuth (due to south, counterclockwise)	degrees

asymmetry or different pattern of light that each row of the subordinate strip receives over the daytime. Asymmetry in this case relates to the different distances of a bush bean row to the adjacent maize on both sides of the strip. Therefore, in the model, each bean row was defined by x_1, the distance from the maize strip when the light beam originates from the east and x_2, the distance from the maize strip when the light beam originates from the west. Values of x (m) are calculated as:

$$x = R_B * n_{row,B} - \frac{R_B}{2} \qquad (5)$$

x_1 for $\alpha \geq 0$: $n_{row,B}$ counted from the west end of the bean strip

x_2 for $\alpha \geq 0$: $n_{row,B}$ counted from the east end of the bean strip, where R_B is the row spacing of bean (m), $n_{row,B}$ is the number of bush bean rows up to the respective row. Subtraction of $R_B/2$ places the given point in the center of the row to represent an average value for the respective row. In a next step, the length of the first unit strip traversed by the light beam (x_t, m) is calculated for x_1 as:

$$x_{t1} = [(l_s + x_1) - N_{t1} * SW_t] - SW_B \qquad (6)$$

where subtraction of the strip width of bean limits the traversed strip length only to the maize strip. x_{t2} is calculated with the respective values x_2 and N_{t2}. During early and late hours with a low solar elevation angle, the light beam travels through more than one maize and bean strip (SW_t) until it reaches the respective bush bean row. The integer number of SW_t traversed by the light beam (N_t) is given by:

$$\alpha < 0 : N_{t1} \leq \frac{l_s + x_1 - x_{t1}}{SW_t} \qquad (7)$$

$$\alpha \geq 0 : N_{t2} \leq \frac{l_s + x_2 - x_{t2}}{SW_t} \qquad (8)$$

The model assumes an infinite number of N_t, therefore in a first step N_t is reduced to the maximum number of strips $N_{t,\max}$ from the given row towards the direction of the light beam, $N_t \leq N_{t,\max}$. The path length of the light beam traversing the maize canopy, l_t (m) is given by:

$$\alpha < 0 : l_t = (x_{t1} + N_{t1} * SW_M)/(\sin\alpha_c * \cos\beta_c) \qquad (9)$$

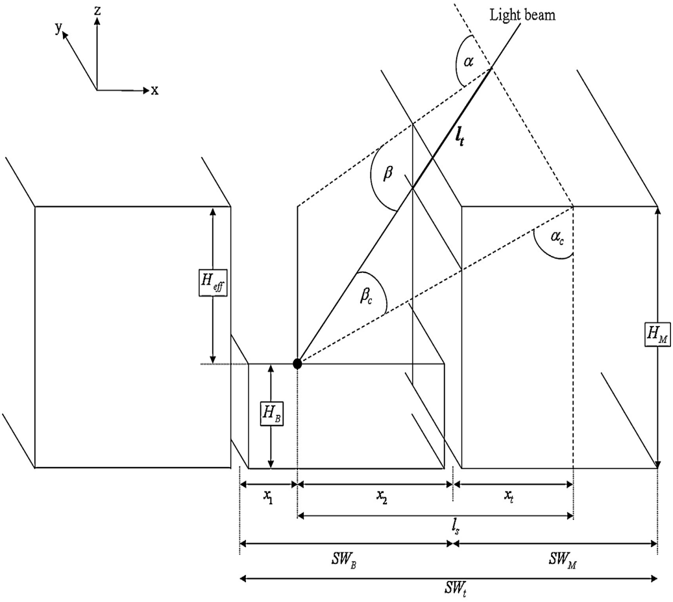

Fig. 1. Coordinate system of a strip–intercropping system of two crops. The dimensions are defined by height of the maize canopy (H_M), the bean canopy (H_B) and their difference H_{eff}; and width of the maize strip (SW_M), the bean strip (SW_B) and their sum (SW_t). The position of a given point within the bean strip is defined by the distances x_1 and x_2. x_t is the length of the first unit strip traversed by the light beam. l_s and l_t are the length of the shadow cast perpendicular to the strip, and the path length of the light beam traversing the maize canopy, respectively. α is the difference between strip azimuth ϕ_r and beam azimuth ϕ, α_c is the angle of the projection of the light beam within the *xz*-plane perpendicular to the strip orientation, β is the elevation angle and β_c is the angle of the light beam with the *xz*-plane. (Modified after Schnieders, 1999).

$$\alpha \geq 0 : l_t = (x_{t2} + N_{t2} * SW_M)/(\sin\alpha_c * \cos\beta_c) \tag{10}$$

where the division by $\sin\alpha_c$ and $\cos\beta_c$ corrects for the initial projection of the light beam. Then, leaf area index traversed by the light beam (LAI_D) is calculated as the product of the total path length (l_t) and the leaf area density (LAD):

$$LAI_D = l_t * LAD \tag{11}$$

where LAD is assumed homogenous over the entire maize strip and therefore equal to:

$$LAD = LAI/H_{eff} \tag{12}$$

2.1.3. View factors

We assume a uniform overcast sky (UOC), i.e. equal radiation quantities from all sky angles. Thus the proportion of diffuse radiation that reaches the given point unimpeded throughout the entire day only depends on distance and height relationships between the plants of the respective point within the bean strip and the adjacent maize strip. Based on these assumptions a view factor for diffuse radiation, called fv_d is calculated. The underlying relationship is illustrated in Fig. 2.

The calculation is performed as follows:

$$\sphericalangle fv_d = 180 - \arctan(H_{eff}/x_1) - \arctan(H_{eff}/x_2) \tag{13}$$

$$fv_d = \frac{\sphericalangle fv_d}{180} \tag{14}$$

Subsequently an explanatory parameter called solar view factor, fv_D is calculated. This parameter is the proportion of the day when direct radiation reaches the given point within the bean strip without traversing any maize foliage. fv_D not only depends on the geometry of the strips like fv_d, but as well incorporates solar position, day length and strip orientation. Initially, the period when LAI_D equals zero is summed up for the given point within the bean strip. Next, this sum ($\sum t_{LAI_{D=0}}$, min) is divided by day length (DL,

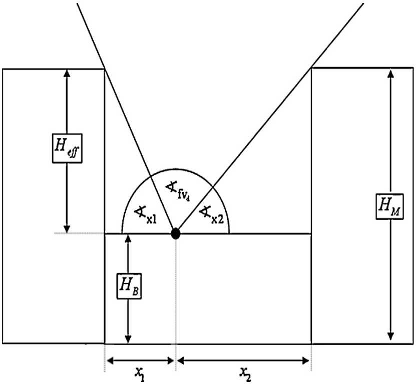

Fig. 2. Geometrical relationship for the calculation of the diffuse view factor (fv_d). *H* is canopy height of bean (*B*), maize (*M*) and their difference (*eff*), respectively. The position within the bean strip is defined by the distances x_1 and x_2 with their corresponding angles $\sphericalangle_{x1}$ and $\sphericalangle_{x2}$, respectively. $\sphericalangle_{fvd}$ is the angle of the diffuse view factor.

min; http://www.esrl.noaa.gov/gmd/grad/solcalc/calcdetails.html, verified 13 September. 2013), which leads to the equation:

$$fv_D = \frac{\sum t_{LAI_D=0}}{DL} \tag{15}$$

2.1.4. Incoming radiation

The amount of incoming direct PAR (PAR_D) and diffuse PAR (PAR_d) depends on the atmospheric transmission and the fraction of PAR in the incoming solar radiation. The atmospheric transmission depends on the extraterrestrial radiation and the locally measured solar radiation. The calculations are performed according to Spitters et al. (1986) with the modified equation for the separation of the solar radiation into direct and diffuse fractions (Lizaso et al., 2005). The amount of total diffuse radiation is further divided into two parts. One part reaches the given point within the bean strip directly, named $APAR_{d,fv}$ and is given by:

$$APAR_{d,fv_d} = PAR_d * fv_d \tag{16}$$

The second part is the remaining diffuse PAR traversing the maize strip, and is given by:

$$PAR_{d,t} = PAR_d - APAR_{d,fd} \tag{17}$$

$PAR_{d,t}$ is reaching the given point from all sky angles that traverses maize foliage throughout the entire day, hence the daily average of LAI_D is used in the calculation of the transmitted diffuse radiation, denoted as LAI_d.

2.1.5. Extinction coefficients

The extinction coefficient for direct radiation, k_D is calculated after Campbell and Norman (1998):

$$k_D(\beta) = \frac{\sqrt{X^2 + \frac{1}{\tan^2 \beta}}}{X + 1.774(X + 1.182)^{-0.733}} \tag{18}$$

where X describes the ratio of average projected areas of canopy elements on horizontal and vertical surfaces. If no measurements are available the spherical leaf angle distribution is recommended, which is described by an X - value of 1. For a more vertical distribution $1 > X \geq 0$, for a horizontal distribution $X > 1$ and approaches infinity (Campbell & Norman, 1998). The extinction coefficient for diffuse radiation k_d was calibrated for each row with measured data during a cloudy day.

2.1.6. Scattering of radiation

Scattering is the sum of transmission and reflection (ρ) of PAR radiation reaching the plant canopy, and is defined by the scattering coefficient (Goudriaan, 1977). Based on the scattering coefficient σ transmittance and reflectance are calculated as follows:

$$\text{Transmittance}: \quad \tau = \sqrt{1 - \sigma} \tag{19}$$

$$\text{Reflection of diffuse radiation}: \rho_d = \frac{1 - \tau}{1 + \tau} \tag{20}$$

(after Goudriaan, 1977)

$$\text{Reflection of direct radiation}: \rho_D = \rho_d \frac{2k_D(\beta)}{1 + k_D(\beta)} \tag{21}$$

(after Goudriaan, 1988)

In the model, a value of 0.2 is used for σ (Goudriaan, 1977; Campbell and Norman, 1998).

2.1.7. Available radiation

The total amount of available PAR at the top of the canopy of the given row within the bean strip ($APAR$) is the sum of the available direct PAR, $APAR_D$ and the available diffuse PAR, $APAR_d$. The attenuation of direct and diffuse PAR traversing the maize foliage is assumed to follow the Beer–Lambert law. Thus the equation for $APAR$ is given by:

$$APAR = APAR_D + APAR_d \tag{22}$$

where

$$APAR_D = (1 - \rho_D) * PAR_D * \exp(-k_D * LAI_D * \tau) \tag{23}$$

and

$$APAR_d = APAR_{d,fv_d} + (1 - \rho_d) * PAR_{d,t} * \exp(-k_d * LAI_d * \tau) \tag{24}$$

2.2. Data collection for model evaluation

A field experiment was conducted at the experimental station "Ihinger Hof" of the University of Hohenheim in southwestern Germany (48° 44′ N, 8° 55′ E; 477 m a. s. l.) on a Vertic Luvisol (IUSS Working Group WRB, 2007). The long-term average precipitation per year is 690 mm with an average air temperature of 8.1 °C. The early-maturing dent-type maize cultivar 'NK-Ravello' (Syngenta Seeds GmbH, Bad Salzuflen, Germany) was sown on 27 April 2012 in strips consisting of six rows with a density of 8.5 plants m^{-2} and a row spacing of 0.75 m. Between the four strips of maize nine rows of the green bean, early-maturing bush-type cultivar 'Marona' (Hild-Samen, Marbach a.N., Germany), were sown on 14 June 2012 in rows spaced by 50 cm with a density of 28 plants m^{-2}. Orientation of the strips was measured with an AgGPS 332 GPS Receiver with RTK correction (Trimble Navigation Limited, Sunnyvale, USA). The experimental design is illustrated in Fig. 3.

In the two border rows (west side of maize strip, east side of bush bean strip) and the central row of each crop and strip, plant height, plant width and leaf number of 10 plants were measured weekly. Maximum leaf area of three maize plants per row and strip was determined destructively at silking with a LI-3100 Area Meter

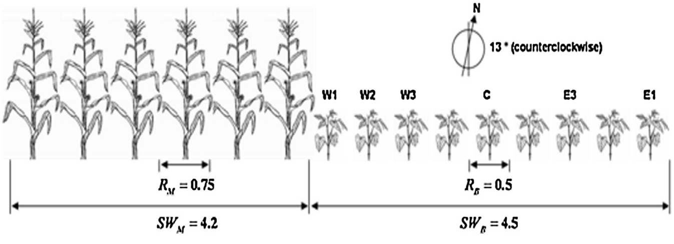

Fig. 3. Representation of the experimental strip–intercropping system of maize (M) and bush bean (B) with the dimensions (m) (R = row spacing, SW = strip width) and the experimental strip orientation used as inputs for the model evaluation. Designation of the investigated bush bean rows from west to east W1, W2, W3, C, E3 and E1 (for clarity reasons, maize strip only illustrated on the west side).

Table 2
Date, position of sensors[a] indicated as bush bean row, replicated rows, sensor height and maize height.

Date	Bush bean rows	Replicated rows	Sensor height (m)	Maize height (m)
01.07.–25.07.12	W1, W2, W3, C	W1, W3, C	0.20	1.45–2.50
28.07.–29.07.12	W1, C	–	0.40	2.50
30.07.–07.08.12	W1, C	–	0.50	2.50
08.08.–14.08.12	W1, C	–	0.60	2.50
16.08.–30.08.12	W1, W3, C, E3, E1	W1, C, E1	0.60	2.50
01.09.–09.09.12	W1, W2, W3, C, E3, E1	–	0.60	2.50

[a] PAR/LE line sensors (SOLEMS S.A., Palaiseau, France).

(LI-COR, Lincoln, USA). Photosynthetically active radiation (PAR) was measured with PAR/LE line sensors (SOLEMS S.A., Palaiseau, France), and a LI-190 SL quantum sensor (LI-COR, Lincoln, USA) as reference. The data was recorded continuously in five-minute intervals with a CR23X Micrologger (Campbell Scientific, Logan, USA). During the entire experiment one PAR/LE sensor and the reference sensor were installed at three meters height located 5 meters away from the border of the experimental field to monitor total incoming PAR. Solar radiation was derived from sunshine hours (Allen et al., 1998) measured at the local weather station. Available PAR was measured at the center of certain rows across the bush bean strip parallel to the row, adjusted at canopy height, and leveled with a bubble eye. The various programmed measurements (sensor positions across the strip) are listed in Table 2.

2.3. Calculation of input parameters

A sigmoidal function was fitted to the weekly measured values of maize canopy height according to Knörzer et al. (2011). Instead of days after sowing, growing degree-days with a base temperature of 8 °C were used. Based on the derived function, daily values of maize canopy height were calculated. Daily *LAI* values were obtained with the maize simulation model IXIM (Lizaso et al., 2011). IXIM was run with the experimental data (soil, weather and management data) and the cultivar coefficients were calibrated to simulate accurately silking date, the weekly measured leaf number per plant and the maximum *LAI* measured at silking. Based on daily averages of the measured total PAR and solar radiation, the local fraction of PAR as part of solar radiation was 43.8%. This is in good agreement to the average value of 43% determined by Lizaso et al. (2003) and 45% of Monteith (1965). To convert solar radiation ($\mathrm{J\,m^{-2}\,s^{-1}}$) to PAR ($\mathrm{\mu mol\,m^{-2}\,s^{-1}}$) the conversion factor 4.6 $\mathrm{\mu mol\,J^{-1}}$ (McCree, 1981) was used. The diffuse extinction coefficient k_d was fitted in 0.01 intervals on a root mean square error basis to the observed values of *APAR* on an overcast day (94% of diffuse radiation) for each investigated row. The fitted values of k_d were 0.15 in Row W1, 0.11 in Row W2, 0.05 in the Rows W3, C, E3 and 0.11 in Row E1, respectively.

2.4. Statistical analysis and model evaluation

To identify significant differences between observed daily values of APAR of each bean row, a mixed model was fitted using the mixed procedure of SAS 9.2 (SAS Institute, 2009), which can be described by: $y = \mu + \beta + \varepsilon$, where y is the observed APAR in each bean row, μ the mean value of overall APAR, β the fixed effect for the bean row, and ε the error effect. A spatial model that accounts for the lack of randomization of rows within the bean strip (Knörzer et al., 2010) did not increase the model fit (evaluated on the Akaike Information Criteria (Wolfinger, 1996)). Hence, the firstly described model was further used for an analysis of variance (ANOVA) based on the adjusted means of each bean row with a significance level of 5%. A letter display of all pairwise comparisons was derived with the algorithm of Piepho et al. (2004).

The model was evaluated by the comparison of the hourly observed and simulated values using the statistical indices root mean square error (RMSE), the RMSE-observations standard deviation ratio (RSR) and percent bias (PBIAS). These indices have the following expressions:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2} \tag{25}$$

$$RSR = \frac{RMSE}{STDEV_O} = \frac{RMSE}{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - \bar{O})^2}} \tag{26}$$

$$PBIAS = 100\,\frac{\sum_{i=1}^{n}(S_i - O_i)}{\sum_{i=1}^{n}O_i} \tag{27}$$

where S_i, O_i and $\bar{O}$ are the simulated, observed and the mean of the observed values, respectively. The number of data pairs is denoted as n and the standard deviation of the observed values as $STDEV_O$. All indices indicate a perfect fit at a value of zero. RMSE is expressed in the units of the analyzed variable. RSR is recommended to standardize the RMSE on a standard deviation basis (Moriasi et al., 2007). PBIAS indicates the average tendency of the simulated values to be over- or underestimated (Gupta et al., 1999). Positive values express an overestimation and negative values an underestimation, respectively.

3. Results and discussion

3.1. Observed radiation data

The light regime in an intercrop canopy is highly heterogeneous in space and time. In our study, we conducted a number of measurement protocols to obtain a large number of observations

Table 3
Average of PAR at the top of the canopy at different positions across the strip, from west to east (W1-W2-W3-C-E3-E1) and PAR (open area) averaged over two measurement periods. Means in one column sharing the same letter are not significantly different from each other (α = 0.05).

Position	APAR (01.07.–25.07.12) in $\mathrm{\mu mol\,m^{-2}\,s^{-1}}$	APAR (16.08.–30.08.12) in $\mathrm{\mu mol\,m^{-2}\,s^{-1}}$
Open area	416.39^{e}	416.46^{d}
Row W1	217.99^{a}	211.89^{a}
Row W2	283.34^{b}	–
Row W3	324.65^{c}	327.13^{bc}
Row C	360.83^{d}	356.75^{c}
Row E3	–	355.46^{cd}
Row E1	–	288.39^{b}

across rows and to have repeated measurements of various rows at the beginning and the end of the experiment to evaluate the homogeneity of APAR across the repetitions. The results of the statistical analysis are presented in Table 3. In general, APAR was significantly lower above all investigated rows of the bean strip than above the maize canopy, i.e. different from a monocrop situation. The lowest values were observed in the border rows on both sides of the strip (Row E1 > Row W1) and the highest value in the center of the strip (Row C). Because there were no significant differences between the repetitions (not shown), APAR was regarded homogenously across the repetitions for each bean row, and measurements conducted without repetition were assumed representative.

3.2. Model validation

To substantiate the validity of a model, it is crucial to include both an evaluation comparing observed and simulated values, and a sensitivity analysis for the relevant issues the model is meant to be applied to (Plentinger and Penning de Vries, 1996). Hence, an evaluation of the model is first presented on observed and simulated results under different sky conditions using an initial time step of five minutes. Later, we examined the time step required by the model to maintain high level of accuracy. The sensitivity of the model is finally checked by comparing simulations obtained when substantial changes in strip width, strip orientation, and maize canopy architecture were introduced.

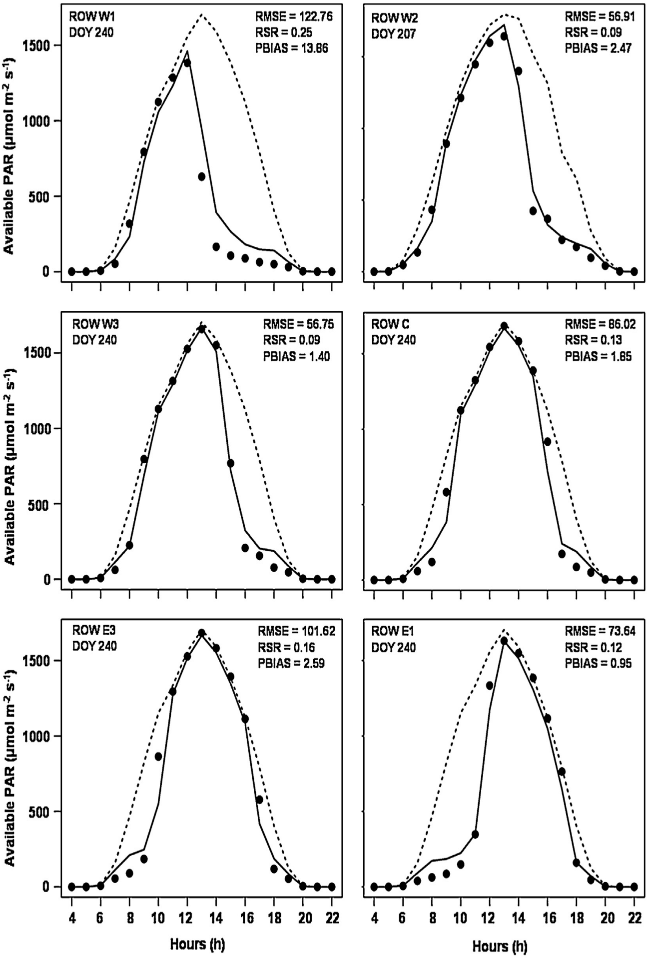

Fig. 4. Hourly observed (symbols) and simulated (solid line) values of the available photosynthetically active radiation (Available PAR) at the top of the canopy of the specified row across the bean strip from west to east (W1-W2-W3-C-E3-E1) and incoming PAR above the maize canopy (dotted line).

3.2.1. Model evaluation

Model performance was evaluated for all measured rows comparing hourly simulated and observed values of APAR. The hourly observed numbers are the average of twelve measurements in an interval of five minutes. In Fig. 4 the model performance is illustrated for a clear day (i.e. predominantly direct radiation) in several rows across the bean strip. The diurnal trend of PAR, resulting from shading by the neighboring maize strips, was simulated close to field measurements. Early in the morning, the row on the west side of the bean strip (Row W1) was outside the maize shadow boundary, thus it received most of the incoming PAR. More toward the east of the bean strip (Rows W2 to E1), the effect of the maize shadow becomes evident in morning hours. After solar noon, the situation changed and the maize shadow reached first the western rows of the bean strip. Even before solar noon, due to the strips azimuth (13° departure from N–S direction), row W1 already showed decreased PAR and maintained reduced light during the afternoon hours. Interestingly, the steep slope at the end or the beginning of a shading period was captured well by the model in all rows. Only Row W1 showed a slight overestimation of APAR shortly after solar noon. This overestimation of around 16% was detected by a high RSR value. The high sun elevation when Row W1 falls under shade might lead to inaccuracies if maize architecture differs between the border row and the other rows of the maize strip, because the model inputs define the maize architecture across the entire strip. This issue will be addressed later in detail for the leaf angle distribution.

The model behavior for various combinations of direct and diffuse radiation was tested with observed and simulated hourly values on a day with variable sky conditions, as illustrated in Fig. 5 for Row W1 and Row C. The model captured well the influence of the diurnal change of the fraction of diffuse and direct radiation. Overestimations mainly occurred in Row W1 shortly after solar noon and when a large share of direct radiation could be expected, as already discussed in the previous figure. The simulation in the central row fitted very accurately the diurnal course of the hourly measured values as indicated by a low RSR of 0.11 and an average overestimation of 2.9%. The other rows exhibited a level of accuracy comparable to the central row (not shown). The fitted values of k_d proved to work properly in the simulation of $APAR_d$. To the best of our knowledge, there are no published k_d -values for strip–intercropping systems. As an alternative, diffuse transmitted irradiance can be calculated after Campbell and Norman (1998) by integrating direct beam transmittance over a hemisphere (e.g., Tsubo and Walker, 2002; Colaizzi et al., 2012); however, these studies were conducted at semiarid locations, resulting in much greater influence of direct beam radiation compared with the diffuse components. Lindquist and Mortensen (1999) measured light extinction on two cloudy days for different maize hybrids resulting in k_d -values between 0.51 and 1.04. The discrepancy between the fitted values of k_d in this study, the procedure after Campbell and Norman (1998), and literature values most likely results from a low comparability between strip–intercropping and row–cropping systems. Further research will focus on directly measuring the diurnal course of diffuse radiation in order to identify parameters to estimate k_d for each row of the subordinate crop.

The overall model performance was tested by pooling all daytime hourly values of observed and simulated *APAR* for each row. The regression analysis of daytime hourly values was performed with an intercept of zero (through the origin) as the regression analysis of nighttime hourly values (i.e. hourly observed *APAR* is zero) showed an intercept of less than 0.004 μmol m^{-2} s^{-1} for all bean rows (not shown). The results for Row W1 and Row C – based on almost 900 daytime hourly values of *APAR* – are shown in Fig. 6. Especially in the central row (Row C), the model showed a very high accuracy indicated by a low RSR of 0.1 and an average underestimation of *APAR* less than 1%. In Row W1 *APAR* was overestimated by 10%, which most likely arose from the periods at high solar elevation at the beginning of the shading cycle in the afternoon (Fig. 4).

The other rows were evaluated as well (Table 4). Light simulated for the other rows was also highly accurate with an RSR between 0.1 and 0.14, and an overestimation of less than 4%. The regression analysis across all bean rows indicated that the slopes in all cases were significantly different ($p < 0.001$), although very close to 1.0, within a range of 0.955 (Row E1) to 1.042 (Row W1). This significance, in our view, was more related to the large number of data points than a relevant indication of substantial errors in our simulations.

The initial simulation time step of five minutes is too detailed compared to the hourly time step on which detailed crop growth models run. Therefore, we examined the effect of time steps of ten, twenty, thirty and sixty minutes. *APAR* of observed five-minute values and of simulated values based on the respective time step, were averaged hourly and compared (Table 5). The results indicated that a time step of twenty minutes yielded the most accurate results. Longer time steps reduced rapidly model accuracy as indicated by statistical indices. Simulating on hourly steps however, produced

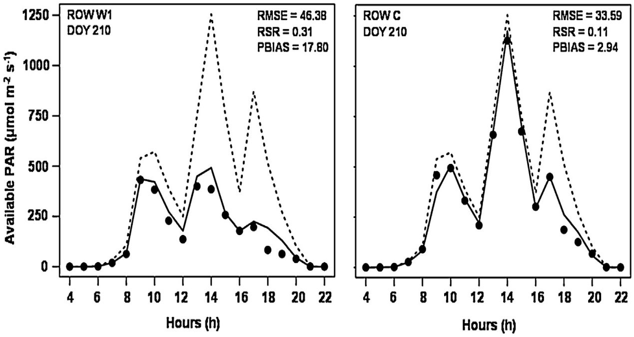

Fig. 5. Hourly observed (symbols) and simulated (solid line) values of the available photosynthetically active radiation (Available PAR) at the top of the canopy of the specified row on the west side (Row W1) and the central row (Row C) of the bean strip, and incoming PAR above the maize canopy (dotted line). Notice the change in vertical scale compared to Fig. 4.

Table 4
Model evaluation of the hourly simulated and observed available photosynthetically active radiation (APAR) at the top of the canopy across the bean strip from west to east (W2-W3-E3-E1), number of observations (*n*), average of the daytime hourly incoming PAR above the maize canopy (PAR), average of the daytime hourly simulated (APAR_Sim) and hourly observed PAR (APAR_Obs), Slope of regression line through the origin, RMSE, RSR and PBIAS (%).

Row	*n*	PAR	APAR_Sim	APAR_Obs	Slope	RMSE	RSR	PBIAS (%)
W2	424	597.36	415.52	406.31	1.005^{***}	54.23	0.12	2.27
W3	590	599.70	480.85	472.58	1.004^{***}	47.04	0.10	1.75
E3	360	631.88	523.69	541.90	0.964^{***}	75.33	0.14	−3.36
E1	360	631.88	431.22	440.83	0.955^{***}	61.61	0.12	−2.18

*** Slope significantly different from 1 ($p < 0.001$).

APAR values close to measurements. This accuracy has to be further evaluated for its influence on other processes, such as canopy photosynthesis.

3.2.2. Model sensitivity

The sensitivity of the model was investigated for selected rows by changing the following inputs: strip width, strip orientation, and parameters of maize canopy architecture (height, LAI and leaf angle distribution). Model was run with 20-minute time step.

3.2.2.1. Strip width. The experimental bean strip width of nine rows (4.5 m) was extended to twelve (6 m) and fifteen rows (7.5 m). The chosen strip widths were considered practically relevant referring to the predominantly small size machinery in the NCP (Feike et al., 2012) and to maintain a large number of maize strips on the field. Simulations on a clear day indicated negligible (<3%) increases of APAR in the border rows of the bean strip (Fig. 7A). The largest light gain (10%) was in the central row. The different behavior among rows can be explained by an increased solar view factor in Row C (Fig. 7B) resulting in a higher amount of directly available PAR_D (Fig. 7C), which is the share of PAR_D reaching the top of the bean canopy during the unshaded period. It is interesting that there is a very small effect of the increased solar view factor on directly available PAR_D in the border rows, which can be explained by the extension of the solar view factor to early hours on the west side of the bean strip and late hours on the east side of the strip with a low amount of PAR_D. In contrast, in Row C the solar view factor was extended to hours with a higher amount of PAR_D.

Even on a clear day, especially during the early and late hours, a proportion of around 20% has to be considered as diffuse radiation, which is the reason that the amount of *APAR* will realistically never reach 100% at any strip width and row across the strip. The amount of diffuse *APAR* is increasing by the extension of strip width, which can be well explained by the diffuse view factor, fv_d. For a high level of comparability between the previous clear day and cloudy day, the solar calculations of the same day were applied to a sinusoidal course of PAR (derived by calculations of Spitters et al., 1986) with a maximum *PAR* at noon of 500 μmol m^{-2} s^{-1} to investigate in detail the influence of increasing strip width on *APAR* on a cloudy day. Across all rows the simulated increase in *APAR* indicated minor differences between the rows than on a clear day, with a slightly higher increase in Row C compared to the other examined bean rows (Fig. 8A). The increase resulted from a higher diffuse view factor with increasing bean strip width (Fig. 8B). The increase of the diffuse view factor is more pronounced towards the center of the strip, especially in Row C, because the diffuse view factor is

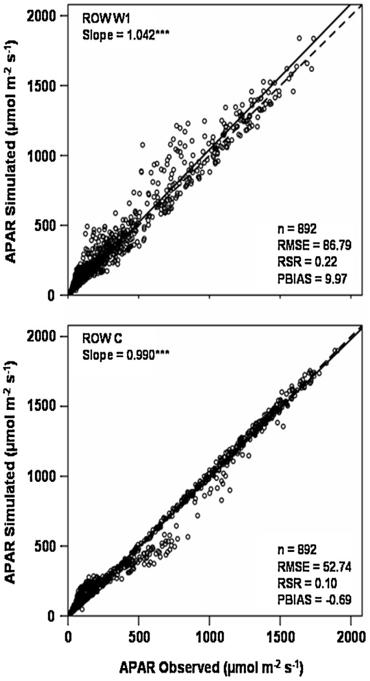

Fig. 6. Comparison between daytime hourly observed and simulated values of the available photosynthetically active radiation (APAR) at the top of the canopy of the first row on the west side (Row W1) and the central row (Row C) of the bean strip. Regression line through the origin (solid line) and 1:1 line (dashed line). *** Slope significantly different from 1 ($p < 0.001$).

Table 5
Model evaluation of simulated available photosynthetically active radiation (APAR_Sim) at the top of the canopy of the first and third row on the east side (Row W1, Row W3), and the central row (Row C) of the bush bean strip, respectively. Simulations were obtained with various time steps. Number of observations (*n*), observed APAR at the top of the respective bush bean row (APAR_Obs). RMSE, RSR and PBIAS (%).

Time Step (min)	APAR_Sim (μmol m^{-2} s^{-1})	RMSE	RSR	PBIAS (%)
Row W1 ($n = 892$, APAR_Obs = 339.40 μmol m^{-2} s^{-1})				
5	373.27	86.79	0.22	9.97
10	358.14	75.08	0.19	5.53
20	365.34	72.45	0.18	7.76
30	371.94	109.31	0.28	9.72
60	363.62	109.87	0.28	7.06
Row W3 ($n = 590$, APAR_Obs = 472.58 μmol m^{-2} s^{-1})				
5	480.85	47.04	0.10	1.75
10	473.35	44.82	0.09	0.16
20	477.96	44.43	0.09	1.14
30	480.47	77.50	0.16	1.67
60	472.67	95.99	0.20	0.02
Row C ($n = 892$, APAR_Obs = 549.41 μmol m^{-2} s^{-1})				
5	545.63	52.74	0.10	−0.69
10	540.48	53.18	0.10	−1.63
20	545.88	53.63	0.10	−0.53
30	541.91	61.05	0.11	−1.26
60	539.21	84.06	0.16	−1.96

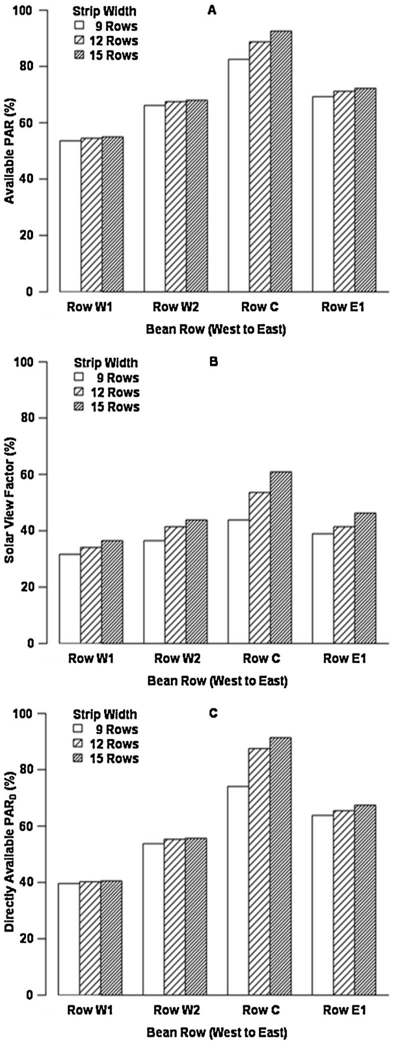

Fig. 7. Influence of bean strip width on a clear day. Available photosynthetically active radiation (available PAR) in percentage of total incoming PAR above the maize canopy (A), solar view factor (B) and directly available PAR_D in percentage of total PAR_D above the maize canopy (C). Bean rows W1-W2-C-E1 (from west to east) inside a bean strip consisting of nine, twelve and fifteen bean rows, respectively.

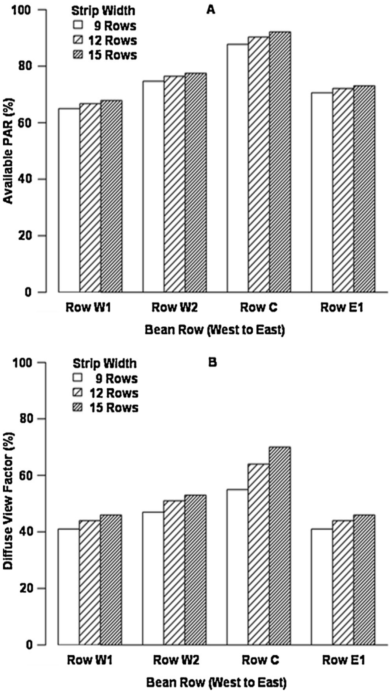

Fig. 8. Influence of bean strip width on a cloudy day. Available photosynthetically active radiation (available PAR) in percentage of incoming PAR (A) and diffuse view factor (B). Bean rows W1-W2-C-E1 (from west to east) inside a bean strip consisting of nine, twelve and fifteen bean rows, respectively.

extended towards east and west, whereas in the border rows only towards east (Row W1) and west (Row E1), respectively.

In general, on clear and cloudy days, simulations indicated that extending bean strip width, from nine to fifteen bean rows, will have a small effect on *APAR*.

3.2.2.2. Strip orientation. Assuming a uniform, diurnal distribution of radiation, a strip north–south oriented receives equal amounts of radiation in the corresponding rows (same distance to the adjacent strip of the dominant species) on both sides of the strip. Yet strips may deviate from north–south for a number of reasons. Under these circumstances, the orientation of the field has to be taken into account (e.g. when adjusting the strip width). It is assumed that the change of the strip orientation does not influence the diffuse radiation as it originates from all sky angles. Instead, it has a major influence on the direct radiation as the daily course of shading varies. Based on these assumptions, simulations were run on a clear day changing strip orientations between 0° and 90° for the two border rows on the west side (Rows W1, W2), the central row (Row C) and the border row on the east side (Row E1) of the bean strip. The simulations reflected a clear opposite effect on the east and west side when the strip orientation was changed (Fig. 9). The orientation was changed counterclockwise, which resulted in an increasing amount of *APAR* on the east side, and a decreasing trend on the west side of the strip (Fig. 9A). By moving the orientation from 0 (N–S) to 90° (E–W), *APAR* was reduced in western rows (W1, W2) 59 to 24%, and 70 to 40%; had small effects in the central row from, 83 to 97%; and increased in the eastern most row (E1) from 65 to 93%. Interesting is the negligible effect on available PAR in Row C from orientations of 0 to 45°. This trend of *APAR* is consistent with the trends of the solar view factor (Fig. 9B) and the directly available PAR_D (Fig. 9C). But, in addition, those two parameters give a more detailed understanding concerning the effect of strip orientation (both reach their lower limit in Row W1 and W2, and their upper limit in Row C and E1). At a strip orientation of 90°, western most rows are mostly shaded throughout the entire day, whereas the shaded period in the eastern and the central rows is reduced to very early and late hours with a low amount of PAR_D. The slightly lower amount of *APAR* in Row E1, compared to Row C, resulted from the lower amount of diffuse radiation (lower diffuse view factor) in Row E1. The difference that exists between the first rows on both sides at a north–south orientation simply reflects the diurnal distribution of the amount of PAR, that favored on this particular day Row E1.

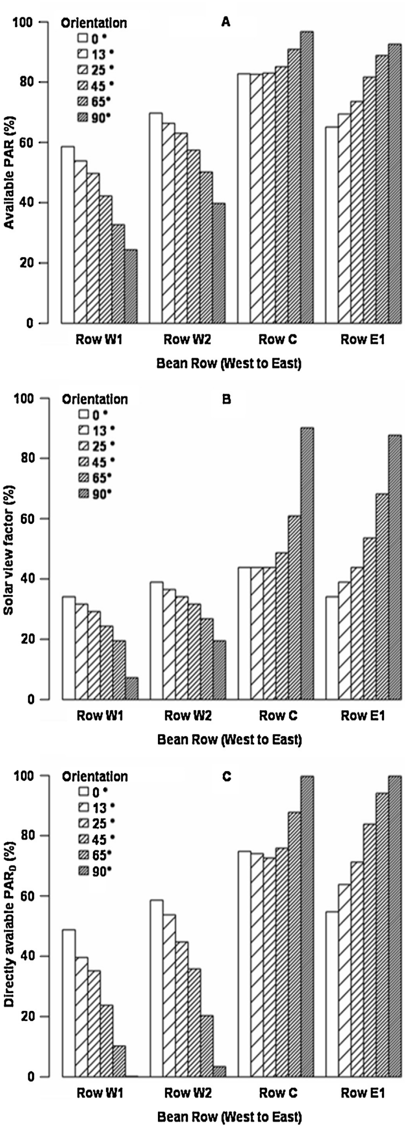

Fig. 9. Influence of strip orientations on a clear day. Available photosynthetically active radiation (PAR) in percentage of total PAR (A), solar view factor (B) and directly available PAR_D in percentage of total PAR_D (C). Bean rows W1-W2-C-E1 (from west to east) inside a bean strip oriented 0°, 13°, 25°, 45°, 65° and 90° counterclockwise from South, respectively.

3.2.2.3. Canopy architecture. The architecture of the maize canopy is described in the model by height, width, leaf area and leaf angle distribution. In the model, an ellipsoidal leaf angle distribution is assumed, which is a good approximation to real canopies (Campbell, 1986). The leaf area is randomly distributed, i.e. leaf area density is constant throughout the maize strip. One important decision in the design of an intercropping system is the appropriate crops. For each crop, the selection of a certain cultivar will have an influence on the light regime (e.g. plant height, more erect leaves or lower leaf area index). To investigate the influence of the maize canopy architecture on *APAR* in the bean strip, the model was run on a clear day changing single maize inputs: canopy height, leaf area index and leaf angle distribution (Fig. 10). First, the model was run with the measured maximum canopy height of 2.5 m, ± 40% (3.5 and 1.5 m). The leaf area index was adjusted to keep the leaf area density (LAI/height) at the original value of 1.4, and get a clear effect of canopy height. This was done for Row W1 (Fig. 10A) and Row C (Fig. 10B), respectively. Canopy height influences the shadow length and hence the diurnal trend of shading. The model captured well the prolonged or shortened shading period of an increased or decreased canopy height. The lower canopy height increased *APAR* in Row W1 by around 30% and in Row C by 16%, whereas the increased canopy height resulted in a 17 and 16% lower amount of *APAR* in Row W1 and Row C, respectively (Table 6). Increased *APAR* in Row W1, next to a shorter maize canopy, can be explained by the prolonged unshaded period around midday with a high amount of radiation. In contrast, the effect of an increased canopy height on the amount of *APAR* is less. The increased canopy height does not prolong the shading period significantly; however, it increases the path length of the light beam through the maize canopy, which has a smaller effect. Next, the model was run with the daily value of LAI of 3.5, ± 40% (4.9 and 2.1). The simulation for Row W1 showed a very small effect before noon, because of the low sun elevation and a short period of shading(Fig 10C). After midday, at the beginning of the shading period and with high solar elevation, a reduction of *APAR* with increasing LAI was simulated. Decreasing the LAI by 40% resulted in about 14% more *APAR* in Row W1, while a 40% higher LAI resulted in 8% light reduction (Table 6). The effect of LAI was less pronounced in the central row, as the shaded period is much shorter and under lower sun elevation angles than in Row W1 (Table 6). Finally, the effect of the leaf angle distribution was tested. The leaf angle distribution influences the direct extinction coefficient of direct light k_D (Eq. (18)), which in turn alters the reflection of direct radiation (Eq. (21)). The simulations in Row W1 indicated a pronounced effect only at high sun elevation angles shortly after the beginning of the shading period (Fig. 10D). The model captured well the theory of a lower transmittance of a canopy with more horizontal leaf angles at high sun elevation angles, as well as, a higher transmittance of a canopy with more vertical leaf angles (Campbell and Norman, 1998). However, the effect was relatively small compared to the previous discussed effects of canopy height and LAI. *APAR* increased by 2% with more erect leaves, and decreased around 4% for a canopy with more horizontal leaf angles. The effect of the different leaf angle distributions was almost

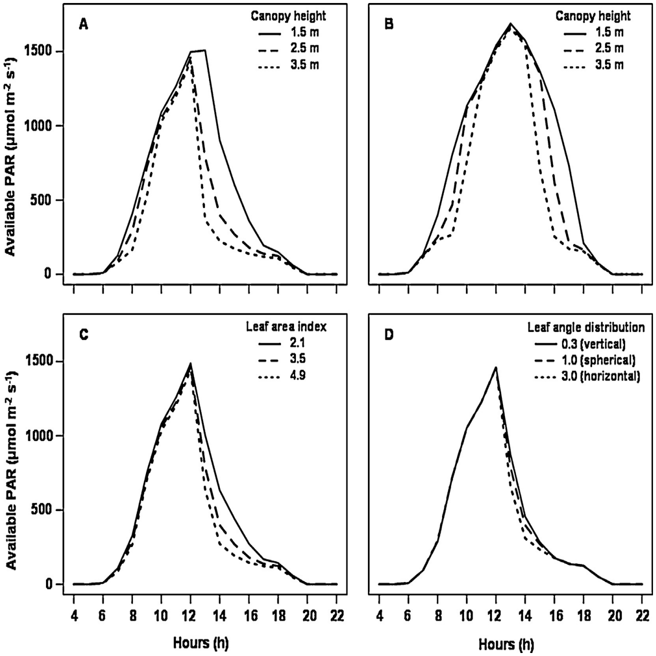

Fig. 10. Influence of maize canopy height with a leaf area density of 1.4 (A, B), leaf area index (C) and leaf angle distribution (D) on a clear day. Available photosynthetically active radiation (PAR) in Row W1 (A, C, D) and Row C (B).

negligible in Row C and did not exceed 0.5% (Table 6). Nevertheless, note the larger increase of *APAR* with a more horizontal leaf angle distribution, because of lower k_D and reflectance at low sun elevation angles, which predominate during the shaded period on Row C.

Field observations during the experiment suggested a more horizontal pattern of leaf growth in the border row (next to the bean strip) than in the inner rows of the maize strip. The maize border row mainly influenced *APAR* in Row W1 at the beginning of the shading period around noon. Therefore, a simulation was run for Row W1 on the same day with an *X* -value of 3 to check if the overestimation (PBIAS of 14%) of *APAR* with an *X* -value of 1, as shown in Fig. 1, can be reduced. The results indicated a significant improvement of the simulation with a PBIAS of 7%, which is mainly due to the better fit shortly after midday (Fig. 11).

In summary, the largest influence on *APAR* was simulated when the canopy height of the maize strip was changed, both in the border and the central row of the bean strip. The LAI also had a large effect on the light availability in the border row, but the effect on the central row was relatively small. Dramatic modifications in the leaf angle distributions to simulate canopies with more erect or prostrate leaf growth habits indicated only minor shifts in the light pattern simulated.

Table 6
Sensitivity of available PAR (APAR, μmol m^{-2} s^{-1}) at the top of the canopy in the first row on the west side and the central row of the bush bean strip to canopy height, leaf area index and leaf angle distribution of maize. Low denotes the lower value, Exp the experimental and High the higher value of the respective parameter, and the change in percentage compared to the experimental APAR.

Parameter	APAR_Low	APAR_Exp	APAR_High	Change_Low (%)	Change_High (%)
Row W1					
Canopy height	372.40	283.58	234.01	31.32	−17.48
Leaf area index	322.53	283.58	261.20	13.74	−7.89
Leaf angle distribution	289.86	283.58	273.29	2.21	−3.63
Row C					
Canopy height	504.15	435.04	363.84	15.89	−16.37
Leaf area index	448.99	435.04	425.29	3.21	−2.24
Leaf angle distribution	433.60	435.04	435.76	−0.33	0.17

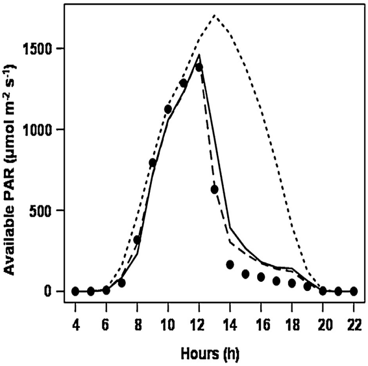

Fig. 11. Hourly observed (symbols) and simulated values of the available photosynthetically active radiation (PAR) at the top of the canopy in Row W1 of the bean strip with a spherical ($X = 1$, solid line) and a horizontal ($X = 3$, dashed line) leaf angle distribution, and incoming PAR above the maize canopy (dotted line) on a clear day.

4. Conclusions

The developed light partitioning model for strip intercropping systems proved to be robust under clear and cloudy sky conditions. For the agronomically important issues: width of the bean strip, strip orientation and maize canopy architecture (canopy height, LAI and leaf area distribution), the model showed reasonable results and provided a helpful explanatory tool for the simulated results. A sensitivity analysis indicated that the *APAR* reaching the top of the subordinate crop (bean) was most sensitive to the canopy height of the dominant crop (maize). The developed model shows a high potential for being used in evaluating strip design (width, orientation) and maize canopy architecture (cultivars) prior to labor and time consuming field trials. Further, the light model will be adapted in future studies to simulate the amount of *PAR* available across the strip of the dominant crop (maize). The spatially and temporarily modified light availability can be used as input – instead of total PAR – for a plant growth model in order to simulate the effect on plant growth and yield formation of the intercropped species.

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4 Chapter II: Growth of bean strip-intercropped with maize – Evaluation of the CROPGRO model

Publication II:

Munz, S., Claupein, W., Graeff-Hönninger, S. (2014): Growth of bean strip-intercropped with maize - Evaluation of the CROPGRO model.
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The measurements and simulations in Chapter I showed that the light availability for the smaller crop, strip-intercropped with maize, is modified both across the strip and throughout the day. The influence of the modified light availability on productivity of the smaller, subordinate crop will depend on the crop's ability to adapt to shading. In general, it was shown across many species that shade induces morphological and physiological adaptations on the leaf- and canopy-level, such as increased canopy dimensions and thinner, larger leafs. These shade adaptations aim at a higher interception of radiation, which in turn, increase photosynthesis and productivity. Chapter II addressed the questions of: how the legume crop bush bean responds on the leaf- and canopy-level to the shade levels experienced when strip-intercropped with the taller crop maize? How these responses influence photosynthesis, plant growth and yield formation? The study presents a comprehensive approach combining data derived from field experiments with plant growth modeling. In Chapter II, the process-oriented plant growth model CROPGRO was used based on light simulations derived by the model developed in Chapter I. Most processes in CROPRGO run on a daily scale. However, some processes, such as photosynthesis are calculated on an hourly basis and on the leaf-level. Furthermore, adaptations to shade are considered in the model. These were promising arguments to choose CROPGRO. In addition, the generic nature of CROPGRO facilitates to further integrate other crops, which is an important aspect considering the large crop variety in intercropping systems.

Growth of bean strip-intercropped with maize - Evaluation of the CROPGRO-model. Agronomy Journal 106, pp. 2235–2247.

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ABSTRACT

Optimizing strip-intercropping systems requires a comprehensive modeling approach to study competition effects, especially for solar radiation, and to integrate numerous crops. Therefore, we studied the radiation availability and its effect on canopy and leaf level and finally on total dry matter and yield formation of bush bean (*Phaseolus vulgaris* L. var. *nana*) strip-intercropped with maize. Nine rows of bush bean were sown on two sowing dates between strips of six rows of maize (*Zea mays* L.). The CROPGRO model was tested with an hourly input of solar radiation for its ability to simulate observed growth and yield formation of the two most shaded bush bean rows next to maize. Experimental results showed that bush bean had a good potential for strip-intercropping systems tolerating up to 30% shading due to an increased light interception by a larger canopy with a considerable increase in its leaf area. The CROPGRO model, calibrated on data of monocropped bush bean, captured well the effect of the strongly reduced radiation on total and pod dry matter in the most shaded bush bean row. This indicates the model's applicability on other intercropping systems exhibiting high levels of shading. Under a lower level of shading further from maize, cultivar parameters responsible for leaf area expansion and the maximum photosynthetic rate had to be increased to achieve a high accuracy of the simulations. Future studies should focus on measurements of photosynthesis, radiation distribution and absorption within the canopy, and leaf area expansion under shaded conditions to improve model simulations.

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5 Chapter III: Understanding interactions between cropping pattern, maize cultivar and the local environment in strip-intercropping systems

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The advantage of intercropping compared with monocropping arises from the complementary resource use of crop combinations. The combination of a taller C4-crop with erectophile leaves and a smaller, N-fixating C3-crop with a more horizontal leaf pattern has a large potential to use radiation more efficiently and compete to a minor degree for soil nutrients. As shown in Chapter II, bush bean tolerated up to 30% of shade; however, increased shade levels as experienced in the row adjacent to the maize strip considerably decreased the total and pod dry matter. Simulations with the light model developed in Chapter I indicated that a maize cultivar with decreased canopy height and leaf area index would allow more light to be transmitted to the smaller, neighboring crop. The overall productivity will depend on growth and yield formation of both crops under the modified light regime. The crops interact both with each other and the local environment. Therefore, in Chapter III, the influence of management (in particular irrigation), maize cultivar and weather conditions was investigated based on data derived from field experiments over seven growing seasons, four in Germany and three in China. Further, the influence of different crop arrangements, maize cultivar characteristics, latitude, and sky conditions on the light availability for the smaller crop was analyzed with the light model developed in Chapter I. The final aim of Chapter III was to: (i) gain an overall understanding of the processes influencing the productivity in strip-intercropping of maize with a smaller crop; and, (ii) to identify options and research needs for a further improvement of the overall productivity.

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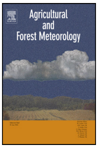

Understanding interactions between cropping pattern, maize cultivar and the local environment in strip-intercropping systems

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ABSTRACT

Strip-intercropping systems combine the possibility to increase productivity and resource-use-efficiency with the facilitation to accommodate machinery. In strip-intercropping systems with maize, competition for light strongly influences the total productivity. Therefore, we studied plant growth and yield formation in maize grown in strips with a neighboring, shorter crop (e.g. bush bean) over three growing seasons in the North China Plain (NCP) with irrigation and over four growing seasons in south-western Germany without irrigation. The chosen locations represented different latitudes, weather, and management conditions. Based on these data, interactions between the local environment, mainly radiation and water availability, and the planted maize cultivars were investigated. Further, a light partitioning model was used to study the effect of strip width, maize canopy height and leaf area index (LAI), latitude, and sky conditions on the light availability across the strip of bush bean over the co-growing period with maize. Experimental results showed an increase of maize yield in border rows in years with sufficient water supply. On average, maize yields calculated for strips consisting of 18 to four rows showed an increase by 3 to 12% at the German and 5 to 24% at the Chinese sites, respectively. Among the three cultivars included in this study, yield in border rows increased mainly by a larger number of kernels per plant. Those were achieved by a larger number of ears per plant in the German cultivars and by larger number of kernels per ear in the Chinese cultivar, respectively. Simulations of the light availability across the strip of the neighboring, shorter bush bean crop indicated that increasing the strip width might only reduce shading in the border rows when the bush bean is grown at lower latitudes under a high fraction of direct radiation. When grown at higher latitudes, the selection of a maize cultivar with reduced height and LAI are suitable options to increase the light availability for the shorter crop. However, shade levels in the border rows of the shorter crop remain high at around 25%. For the future improvement of the productivity of strip-intercropping systems, the selection of suitable maize cultivars and shade-tolerant cultivars and species will be decisive.

1. Introduction

Intercropping, or the cultivation of two or more crops simultaneously on the same field is a common practice in low-input, smallholder farming systems in developing countries. An option of intercropping more common in highly modernized agricultural systems is arranging the intercrops in alternating strips (Vandermeer, 1989). The cultivation of two or more crops in strips combines the positive effects of intercropping, such as a higher productivity and resource-use-efficiency (e.g. Willey, 1990; Zhang and Li, 2003), with the facilitation to accommodate machinery. Studies on strip-intercropping of maize and soybean were initiated in US farming systems facing an ongoing mechanization, which challenged growing the two crops in alternating rows or pairs of rows (Pendleton et al., 1963). Decisive for the productivity of both crops are the interspecific interactions in the border rows at the edges of the strips. In general, the dominant crop maize yielded higher in border rows due to a higher radiation interception. On the contrary, yields in the border rows of the subordinate crop soybean

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Abbreviations: LAI, leaf area index; TKW, thousand kernel weight; PAR, photosynthetically active radiation; DSSAT, decision support system for agrotechnology transfer; HI, harvest index.

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were reduced by competition for water and nutrients, but mainly because of the decreased light availability (Jurik and Van, 2004). In many cases the higher yields in maize border rows were offset by the decrease in the border rows of soybean yields, e.g., a 20% yield increase in maize and a 20% yield decrease in soybean in four and six rows alternating strips (Pendleton et al., 1963); 26% higher yields of maize and 27% lower yields of soybean in alternating eight rows (West and Griffith, 1992); maize and soybean under irrigated and rainfed conditions showed a 26 and 19% yield increase of maize and a 28 and 22% decrease of soybean yields (Lesoing and Francis, 1999). Other studies showed a total yield advantage with a 20–24% yield increase in maize border rows and only a 10–15% decrease in soybean border rows (Ghaffarzadeh et al., 1994). However, the studies mentioned vary in location, strip width and maize cultivar. Thus, it remains difficult to conclude suggestions for the optimized planting pattern adapted to other locations.

A large variety of narrow strip-intercropping systems, e.g. of wheat-cotton (Zhang et al., 2008), maize-wheat (Li et al., 2001; Knörzer et al., 2011), maize and soybean (Gao et al., 2010), and others including vegetable species (Feike et al., 2010) exist in the North China Plain (NCP). In addition many studies have been conducted about, e.g. interspecific interactions between the intercrops (Li et al., 2001, 2011; Zhang and Li, 2003), radiation-use-efficiency (Gao et al., 2010) and evapotranspiration of the intercrops (Gao et al., 2013). The high interest in intercropping systems in the NCP can be explained by the challenge of increasing yields on limited resources of arable land with less input of irrigation water, fertilizers, and pesticides in the face of the future food security, the severe overuse of inputs and its related environmental problems (Fan et al., 2012; Meng et al., 2012).

The narrow-strip intercropping systems practiced in the NCP showed considerable yield advantages compared with monocropping in numerous studies (e.g. Gao et al., 2010; Li et al., 2001). Gao et al. (2010) showed a total yield increase of 65 and 71% in a system of one and two rows of maize (planted at a higher density in intercropping) alternated with three rows of soybean compared with both crops grown as monocrops.

However, these labor-intense narrow strip-intercropping systems are likely to be challenged by an ongoing shift from rural labor to urban areas with higher income possibilities. The resulting scarcity of manual labor in rural areas led to a steady decrease in intercropping systems as shown recently for a representative area in the NCP by Feike et al. (2012). Growing the crops in wider strips would allow the use of machinery and decrease the need of manual labor. However, the possible yield advantage of maize grown in wider strips has never been studied under the growing conditions in the NCP. The overall productivity will finally depend on the yield increase of maize and the degree of shading promoted by the maize strips to the strip of the subordinate crop. Ghaffarzadeh (1999) emphasized in a summary about strip-intercropping systems in Iowa (USA), that there is a need to study the influence of different maize cultivars on the overall productivity. However, to the best knowledge of the authors, no respective study has been published. Simulations by Munz et al. (2014) with a light partitioning model for strip-intercropping systems indicated that the shading by the maize strips might be reduced by a maize cultivar with reduced plant height and reduced leaf area index (LAI). A crucial aspect hindering the optimization of strip-intercropping systems is the high demand of labor and time to study plant growth, yield formation and the microclimate within strips, and the large number of possible plant arrangements and species combinations. Hence, the use of plant growth models is regarded as crucial in further improving our understanding of the processes that influence the productivity with the aim to identify the optimum plant arrangement for each location (Knörzer et al., 2011; Munz et al., 2014).

Table 1
Sowing, silking and harvest date of maize for the growing seasons in China (2009–2011) and Germany (2009–2012).

Growing season	Sowing date	Silking date	Harvest date
China, 2009	1 May	8 July	15 September
China, 2010	4 May	12 July	15 September
China, 2011	4 May	9 July	21 September
Germany, 2009	24 April	16 July	12 October
Germany, 2010	21 April	24 July	21 October
Germany, 2011	26 April	18 July	18 October
Germany, 2012	27 April	20 July	10 October

Therefore the objectives of this study were to: (i) evaluate plant growth and yield formation of maize strip-intercropped with a shorter subordinate crop under the growing conditions in the NCP and in south-western Germany, two locations that mainly differ in latitude, seasonal water availability (rainfall and irrigation) and temperature; (ii) evaluate the influence of maize on the light availability for the shorter subordinate crop across different locations (latitudes) by changing important parameters, such as the strip width of both crops, and the canopy height and LAI of maize based on a plant growth and a light partitioning model; and (iii) identify parameters for further improvement of strip-intercropping systems with the dominant crop maize.

2. Materials and methods

2.1. Experimental design

Field experiments were conducted in Germany during the growing seasons 2009 to 2012 and in China from 2009 to 2011. In Germany, the experiments were carried out at the experimental station “Ihinger Hof” of the University of Hohenheim in southwestern Germany (48°44′N, 8°55′E; 477 m a. s. l.). In China, experiments were conducted at two different locations in the North China Plain; in 2009, at the CAU Experimental Station in Quzhou (Hebei; 36°52′N, 115°0′E, 37 m a. s. l.) and in 2010 and 2011 at the experimental station of the Institute of Agricultural Sciences in Fangshan, Beijing (Beijing; 39°41′N, 116°8′E, 50 m a. s. l.). According to the World Reference Base (IUSS Working Group WRB, 2007) soils are classified as Calcaric Cambisol (Quzhou and Fangshan), Orthic Luvisol (Ihinger Hof 2009–2011) and Vertic Luvisol (Ihinger Hof 2012), respectively.

In China, the cultivar ‘Xianyu335’ (Tieling Pioneer Seed Research Co., Ltd., Shenyang, China) was sown in the first week of May with a row spacing of 0.6 m and a plant density of 8.3 plants m^{-2} in 2009 and 6 plants m^{-2} in 2010 and 2011. The respective dates of sowing, silking, and harvest for each growing season in China are listed in Table 1. Fertilization of nitrogen (urea)/phosphorus (mono calcium phosphate)/potassium (potassium-chloride) were 200/140/170 kg ha^{-1} in 2009, 80/60/100 kg ha^{-1} in 2010, and 250/60/100 kg ha^{-1} in 2011. The amount of urea applied varied due to large differences of pre-sowing soil mineral nitrogen content among years and locations. In the study area in China, rainfall is concentrated mainly during the summer months and for maize water supply is limited during its early vegetative growth. Hence, during all years maize was irrigated shortly after sowing with 50 mm. Additional irrigation depended on rainfall, and thus varied over the years. The total irrigation amount was 280 mm in 2009, and 50 mm in 2010 and 2011. In 2010, necessary additional irrigation was not possible due to the limited water availability for irrigation. Independent irrigation of each crop was facilitated by parallel dams between the crops of around 30 cm width and 20 cm height.

In Germany, the early-maturing dent-maize (*Zea mays* L.) cultivars ‘Companero’ (Agromais GmbH, Everswinkel, Germany) and

Table 2
The different experimental strip lengths and widths of maize (in number of rows and meters), the adjacent vegetable strips (m), and the number of treatments and repetitions of the vegetable strips for the growing seasons in China (2009–2011) and in Germany (2009–2012).

Growing season	Strip length (m)	Strip width maize (n rows)	Strip width maize (m)	Strip width vegetables (m)	Treatments vegetables (n)	Repetitions per treatment (n)
China, 2009	30	12	7.2	7.2	1	4
China, 2010	25	7	4.2	3.5	2	3
China, 2011	25	7	4.2	3.5	2	3
Germany, 2009	30	16	12.0	10.0	1	4
Germany, 2010	45	14	10.5	4.5	3	3
Germany, 2011	45	12	9.0	4.5	2	3
Germany, 2012	15	6	4.5	4.5	2	3

'NK-Ravello' (Syngenta Seeds GmbH, Bad Salzuflen, Germany) were sown in rows with a row spacing of 0.75 m and a density of 8.5 plants m^{-2} during the last two weeks of April in the 2009–2010 and 2011–2012 growing seasons, respectively. The dates of sowing, silking, and harvest are listed in Table 1. Nitrogen fertilizer was broadcast and incorporated before sowing with an amount of 160 kg N ha^{-1}, applied as nitro-chalk in 2009 and 2012, ammonium sulphate in 2010, and urea in 2011. The cultivation was rainfed throughout all years.

All experiments comprised maize strips alternately intercropped with strips of vegetables. Treatments of vegetable strips and the adjacent maize strips were randomized in blocks. Lengths and widths of maize and vegetable strips of each experimental year are listed in Table 2. To allow a future regular mechanized management of such cropping systems, the distance between the border rows of maize and the vegetables was defined by the sum of half the row distances of both crops, i.e. 55 in China and 62.5 cm in Germany, respectively. For our study on strip-intercropped maize, it was first and foremost important to evaluate the number of maize rows that are potentially influenced by the adjacent vegetable strip, which were then investigated during the following experimental years. For this purpose, in the first year of the experiment, maize was planted in wide strips of 7.2 and 12 m in China and Germany. In the subsequent years, the maize strips comprised at least six rows to assure conditions comparable to monocropped maize in the center row of the strip. The width of the adjacent vegetable strips was also wider with 7.2 and 12 m in China and Germany in the first year, but then kept constant at 3.5 m in China and 4.5 m in Germany in the following years.

2.2. Data collection

During the growing season, maize canopy height and total number of appeared leaf tips (5th leaf was marked) of 10 plants were determined regularly until silking. At harvest maturity, total dry matter, grain yield and yield components, namely ear number and thousand kernel weight (TKW) were determined from a sampling area of 2 m^2. Samples were oven-dried at 70 °C until constant weight. Kernel number per plant was calculated based on grain yield, TKW, and plant population. Leaf area index (LAI) was calculated based on the average of the measured leaf area of at least three plants and the corresponding plant population per m^2. In 2009, LAI was determined three times until the maximum LAI at silking both in China and Germany. From 2010 to 2012, measurements were only conducted at silking to determine the maximum LAI in the experiments in Germany. LAI was measured destructively with a LI-3100 Area Meter (LI-COR, Lincoln, USA) in Germany. In China, LAI was calculated based on measured length and maximum width of each leaf multiplied by 0.75 (Montgomery, 1911). The measurements described were conducted on the east side of the maize strips individually for row one (first border row), row two, and the center row of the maize strips for all growing seasons and locations. In 2009, rows three and five were also measured in Germany as well as rows three and four in China. Data from the experiments in 2009 in China and Germany were derived from Feike (2010, and personal communication) and used in this study to compare plant growth and yield formation over a larger number of growing seasons.

2.3. Statistical analysis

To detect significant differences between individual rows within the maize strip, a mixed model was fitted using the mixed procedure of SAS 9.2 (SAS Institute, 2009), which can be described by: $y = \mu + \beta + t + \varepsilon$, where y is the observed value for the individual maize row, μ is the mean overall value, β the fixed effect for the individual maize row, t is the spatial trend effect and ε is the error effect. An initial model with a treatment effect for the different vegetable treatments applied between the maize strips did not show a significant effect on the measured maize parameters. Therefore, a large number of repetitions (Table 2) were available for further analysis of individual rows within the maize strips. The spatial trend effect accounts for the lack of randomization inherent in strip intercropping experiments as row positions within the

Table 3
Average solar radiation (SRAD), rainfall (mm), and average daily maximum (T_{max}) and minimum temperature (T_{min}) during the growing seasons and SRAD (MJ m^{-2} d^{-1}) and rainfall (mm) during the critical period around silking of maize in China (2009–2011) and Germany (2009–2012).

Growing season	SRAD (MJ m^{-2} d^{-1})		Rainfall (mm)		T_{max} (°C)	T_{min} (°C)
	Growing season	Critical period[a]	Growing season	Critical period	Growing season	
China, 2009	18.3	18.8	334.2	96.2[b]	29.1	19.1
China, 2010	18.8	18.1	221.2	65.9	29.8	19.8
China, 2011	18.4	16.2	555.3	343.6	28.6	18.6
Germany, 2009	17.2	19.2	504.6	192.4	20.9	10.4
Germany, 2010	16.0	17.8	442.6	141.6	19.1	9.1
Germany, 2011	17.1	17.0	358.5	95.2	21.2	9.7
Germany, 2012	17.4	19.1	371.0	158.5	21.7	10.1

[a] Critical period from 10 days before to 21 days after silking.

[b] Critical period extended to 28 days before silking during the three growing seasons in China to include substantial rainfall (45.5 mm) from 28 to 25 days before silking during the growing season 2011 in China.

Table 4
Total dry matter, grain yield, harvest index, kernel number per plant and thousand kernel weight (TKW) of maize in rows 1–4 and the center row in 2009, and in rows 1, 2, and the center row in 2010 and 2011 in China. Means of each year in one column sharing the same letter are not significantly different from each other ($\alpha = 0.05$).

Growing season	Row	Total dry matter (kg ha^{-1})	Grain yield (kg ha^{-1})	Harvest index	Kernel number plant^{-1}	TKW
2009	1	24,263^{b}	13,488^{c}	0.56^{b}	532^{c}	306^{a}
	2	21,100^{ab}	11,412^{b}	0.54^{b}	478^{bc}	288^{a}
	3	18,107^{a}	9855^{a}	0.54^{b}	432^{ab}	275^{a}
	4	19,627^{a}	9908^{ab}	0.48^{a}	424^{a}	283^{a}
	Center	19,457^{a}	9457^{a}	0.49^{a}	391^{a}	293^{a}
2010	1	23,656^{b}	11,376^{b}	0.48^{b}	580^{b}	326^{b}
	2	18,846^{a}	7657^{a}	0.40^{a}	408^{a}	311^{a}
	Center	18,007^{a}	7002^{a}	0.39^{a}	380^{a}	306^{a}
2011	1	26,091^{b}	12,404^{a}	0.49^{a}	553^{a}	374^{b}
	2	20,654^{a}	11,651^{a}	0.56^{b}	581^{a}	334^{a}
	Center	21,083^{a}	11,678^{a}	0.56^{b}	592^{a}	328^{a}

strips are fixed. According to Knörzer et al. (2010) the spatial trend was modeled by different covariance structures. All models with a spatial trend and a baseline model without spatial trend were compared based on the Akaike Information Criteria (AIC; Wolfinger, 1996). The model with the best fit (lowest AIC) was further used for an analysis of variance (ANOVA) based on the adjusted means of each individual maize row with a significance level of 5%. Pairwise comparisons were performed and a letter display was derived with the algorithm from Piepho (2004). The described analysis was performed individually for each location and year.

2.4. Modeling of canopy height, LAI, and light transmission

2.4.1. Canopy height and LAI

Daily values of maize canopy height and LAI were derived with the maize simulation model IXIM (Lizaso et al., 2011), which is integrated into the Decision Support System for Agrotechnology Transfer (DSSAT; Jones et al., 2003; Hoogenboom et al., 2012). The model IXIM was run with the experimental weather, soil and management data and each cultivar was calibrated to accurately predict silking date, leaf number, LAI, and canopy height. The calibration of the cultivar 'Companero', 'NK-Ravello', and 'Xianyu335' were made with data under non-limiting growing conditions in the years 2009, 2012, and 2009, respectively. Daily values of canopy height and LAI of maize cultivars differing from the experimental cultivars 'Companero' and 'Xianyu335' were derived by changing the species coefficient "CANH", defining the maximum maize canopy height (m), and the cultivar coefficient "AX" which defines the surface area of the largest leaf (cm^{2} leaf^{-1}). Canopy height of bush bean (*Phaseolus vulgaris* L. var. *nana*) was simulated with the CROPGRO green bean model version as well integrated into DSSAT (Boote et al., 1998). The simulation of the canopy height of bush bean was based on data and calibrations by Munz et al. (2014).

2.4.2. Light transmission

The daily values of canopy height and LAI of the respective maize cultivar and the canopy height of bush bean were used as inputs to calculate the quantity of photosynthetically active radiation (PAR) transmitted through the maize strip to the top of the canopy of the neighboring bush bean strip. For the calculations, a light partitioning model for strip-intercropping systems was used. Briefly described, the model calculates the length of the light beam traversing the maize canopy onto the top of a neighboring, shorter crop in certain distance from the maize strip based on solar position (elevation and azimuth), strip orientation, strip widths, and canopy height of the crops. Transmission of PAR to the neighboring, shorter crop depends on the length of the light beam traversing the maize strip, the LAI of maize, and the extinction coefficient. Light attenuation follows the Beer-Lambert-Law. Transmission of direct and diffuse PAR are performed separately. Details about model calculations are given in Munz et al. (2014). The model can be applied at any time step and was run in our study on a temporal resolution of 20 min to assure high accuracy. Model calculations were performed for the period of strong competition for light during a rapid maize canopy height and LAI development, which occurs during the growing period of bush bean. Depending on different air temperature conditions between the study locations, the simulations

Table 5
Total dry matter, grain yield, harvest index, ear and kernel number per plant, thousand kernel weight (TKW) and leaf area index (LAI) of maize in rows 1, 2, 3, 5 and the center row in 2009, and in rows 1, 2 and the center row from 2010 to 2012 in Germany. Means of each year in one column sharing the same letter are not significantly different from each other ($\alpha = 0.05$).

Growing season	Row	Total dry matter (kg ha^{-1})	Grain yield (kg ha^{-1})	Harvest index	Ear number plant^{-1}	Kernel number plant^{-1}	TKW (g)	LAI
2009	1	22,142^{a}	13,160^{b}	0.59^{c}	1.89^{c}	577^{b}	266^{a}	3.1^{a}
	2	20,739^{a}	11,448^{a}	0.55^{b}	1.69^{bc}	500^{a}	270^{a}	3.2^{a}
	3	19,687^{a}	10,296^{a}	0.52^{a}	1.47^{ab}	470^{a}	257^{a}	3.3^{a}
	5	19,930^{a}	10,116^{a}	0.52^{a}	1.28^{a}	455^{a}	262^{a}	3.3^{a}
	Center	20,908^{a}	10,753^{a}	0.51^{a}	1.44^{a}	487^{a}	265^{a}	3.3^{a}
2010	1	17,155^{a}	8957^{a}	0.52^{a}	1.05^{a}	440^{b}	239^{a}	2.3^{a}
	2	16,668^{a}	8628^{a}	0.52^{a}	1.05^{a}	409^{ab}	242^{a}	2.5^{a}
	Center	15,793^{a}	8078^{a}	0.51^{a}	1.03^{a}	399^{a}	239^{a}	2.3^{a}
2011	1	16,998^{a}	8565^{a}	0.50^{a}	1.17^{a}	398^{a}	254^{a}	3.6^{a}
	2	18,081^{b}	9131^{a}	0.51^{a}	1.45^{b}	424^{a}	254^{a}	3.6^{a}
	Center	18,789^{b}	9121^{a}	0.49^{a}	1.42^{b}	408^{a}	264^{a}	3.8^{a}
2012	1	25,797^{c}	14,678^{c}	0.57^{b}	1.86^{b}	627^{b}	275^{a}	4.0^{a}
	2	22,125^{b}	11,574^{b}	0.53^{a}	1.56^{a}	492^{a}	276^{a}	4.1^{a}
	Center	19,974^{a}	10,383^{a}	0.52^{a}	1.47^{a}	438^{a}	279^{a}	3.9^{a}

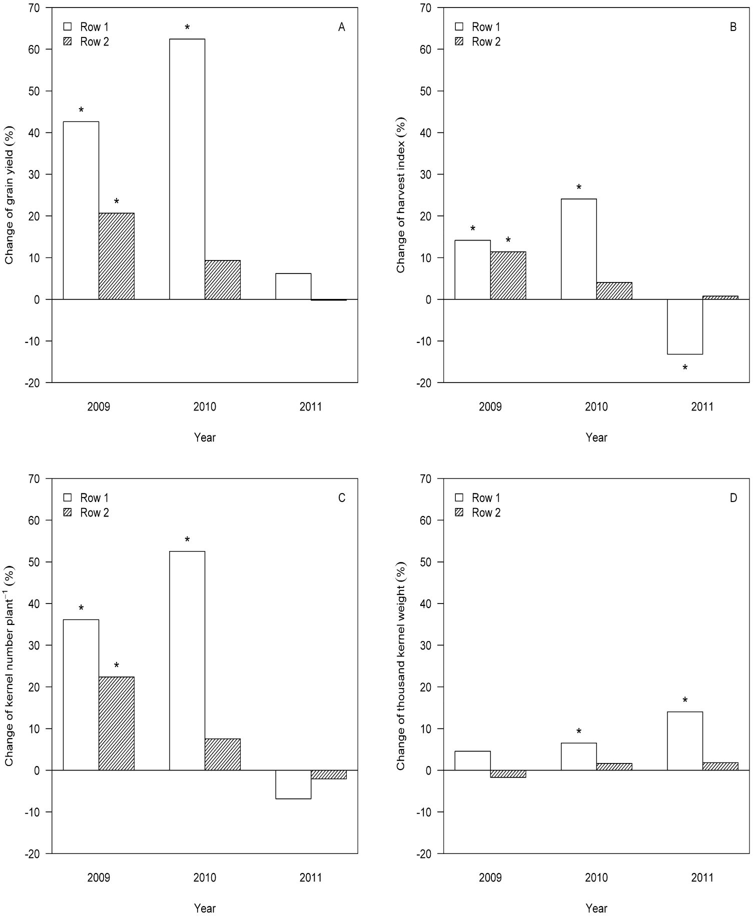

Fig. 1. Change (%) of grain yield (A), harvest index (B), kernel number per plant (C), and thousand kernel weight (D) in the maize rows 1 and 2 in comparison to the center row (monocropping) of each growing season from 2009 to 2011 in China. * denotes significant difference from the center row of the maize strip for the respective growing season at $\alpha = 0.05$.

of light transmission were run from day of year (DOY) 159–227 in China and from DOY 166–234 in Germany, respectively.

3. Results and discussion

3.1. Growing conditions

Differences in the total amount and in particular the temporal distribution of rainfall between growing seasons in Germany and China, provided diverse environments to study and evaluate the performance of strip-intercropped maize. Yield formation of maize is strongly affected by solar radiation and water stress during the critical period from ten days before to three weeks after silking (Andrade et al., 1999, 2002). To include rainfall events shortly before this period, we extended the critical period to 21 and 28 days before silking during the growing seasons in Germany and China, respectively.

During the three growing seasons in China, considerable differences of cumulative rainfall occurred both during the growing season and the critical period around silking (Table 3). Rainfall conditions were most favorable in 2011 with a total of 560 mm during the growing season and 340 mm rainfall around silking, which limited any necessary additional irrigation requirements. In 2009, low amounts of rainfall, especially during the critical period were compensated for by frequent additional irrigation. 2010 was a very dry year with 220 mm during the growing season and only 66 mm around silking. Availability of irrigation water was not sufficient and noticeable water stress occurred. Apart from 2011, where solar radiation was reduced during the critical period, differences in solar radiation and temperature were very little between the three growing seasons.

In Germany, solar radiation and temperature were lower in 2010 compared to similar conditions during the other three growing seasons (Table 3). Cumulative rainfall per growing season varied

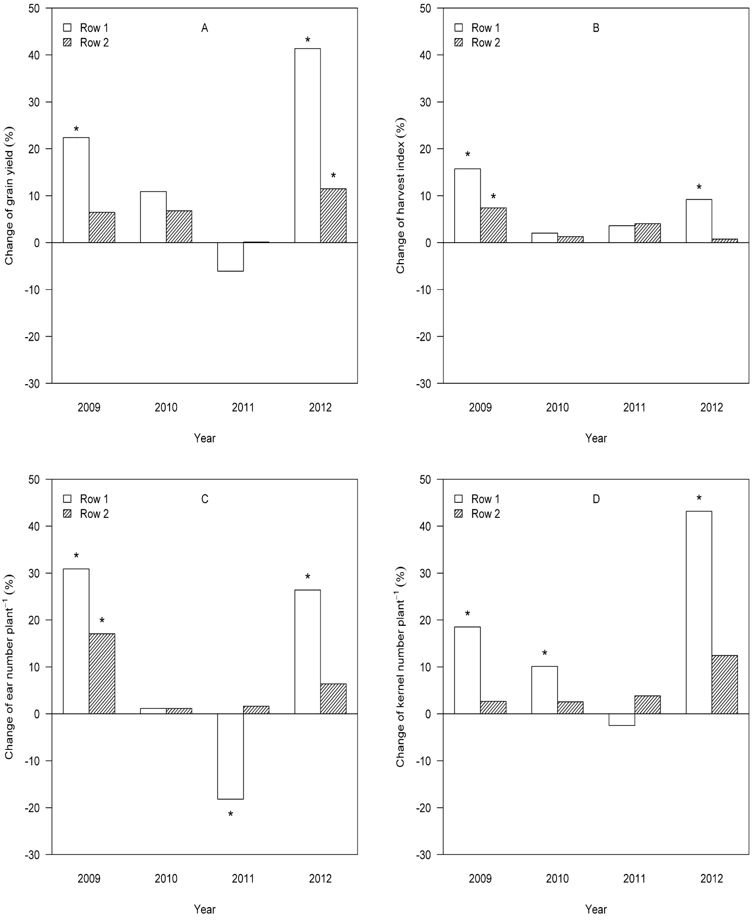

Fig. 2. Change (%) of grain yield (A), harvest index (B), ear number per plant (C), and kernel number per plant (D) in the maize rows 1 and 2 in comparison to the center row (monocropping) of each growing season from 2009 to 2012 in Germany. * denotes significant difference from the center row of the maize strip for the respective growing season at $\alpha = 0.05$.

largely, with the maximum of 500 mm in 2009 and low amounts of 360 and 370 in 2011 and 2012, respectively. During the latter comparably drier years, large differences of rainfall distribution occurred with only 90 mm in 2011 and 160 mm in 2012 (43% of total rainfall) during the critical period.

3.2. Maize rows influenced by the adjacent vegetable strip

Experiments in 2009 with wide strips of maize indicated that the influence of the vegetable strip on maize growth was limited to the first two border rows of maize in China and Germany (Tables 4 and 5). Total dry matter and grain yield did not show significant differences between rows three, four, five and the center row. The differences in maximum LAI between the two locations (ranging across the strip between 4.9 and 5.3 in China (data not shown) and 3.1 and 3.3 (Table 5) in Germany) did not affect the observed pattern across the maize strip. Hence, the third maize row and onwards were assumed to represent monocropping conditions. These results are in accordance to Ghaffarzadeh (1999), who concluded that the edge effect is mainly apparent in the border row; might extend to the second row; however, the center rows within a maize strip of four or more rows are equivalent to that of monocropped maize. Based on these results, the experimental strip width of maize was set to at least six rows (Table 2), and plant growth and yield formation across the entire maize strip were assessed by measurements conducted in the first two border rows and in the center row.

3.3. Plant growth, yield and yield components

Because of the considerable differences of growing conditions both between locations and growing seasons, first results are presented for each location and year, and subsequently all results are discussed together in the end.

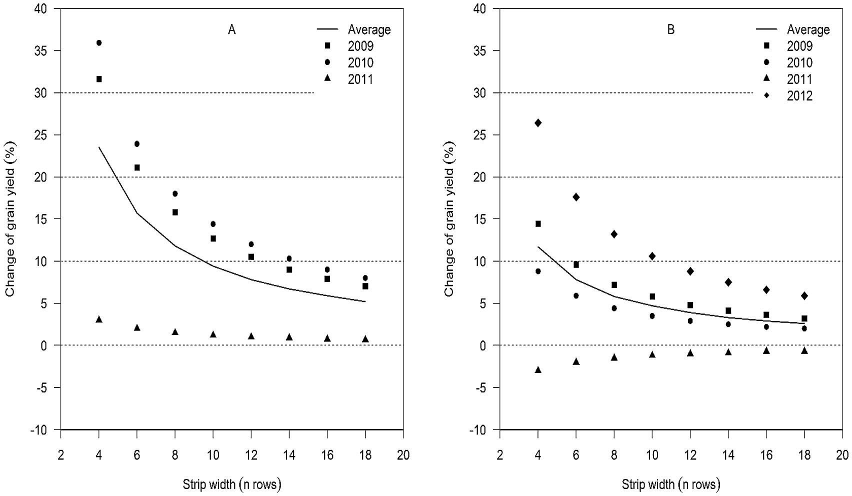

Fig. 3. Change of grain yield (%) of maize strips consisting of 4 to 18 rows in comparison to the center row (monocropping) in China (A) and Germany (B) for each growing season and their average.

Total dry matter, yield and yield components for the three growing seasons in China are shown in Table 4. Across all three growing seasons total dry matter was significantly increased in row one by 25% in 2009, 31% in 2010, and 24% in 2011 compared to the center row. In 2009, grain yield in row one and two was significantly higher by 43 and 21%, which resulted in a significant increase of the harvest index (HI) by 14 and 11% (Fig. 1A and B). In the second year, grain yield and HI showed the largest increase compared to the center row among all three years with 62 and 24% in row one, respectively. The main reason for the yield increases in 2009 and 2010 was a significantly larger kernel number per plant, with an increase of 14, 11, and 24% in the two border rows in 2009, and row one in 2010, respectively (Fig. 1C and D). In 2010, TKW also increased significantly by 7%. In 2011, the increase of grain yield in row one was small with only 6%, which resulted in a significant reduction of HI by 13% (Fig. 1A and B). The yield increase in row one was achieved by compensating the lower kernel number per plant by a 14% increase in the TKW (Fig. 1D). Throughout all three

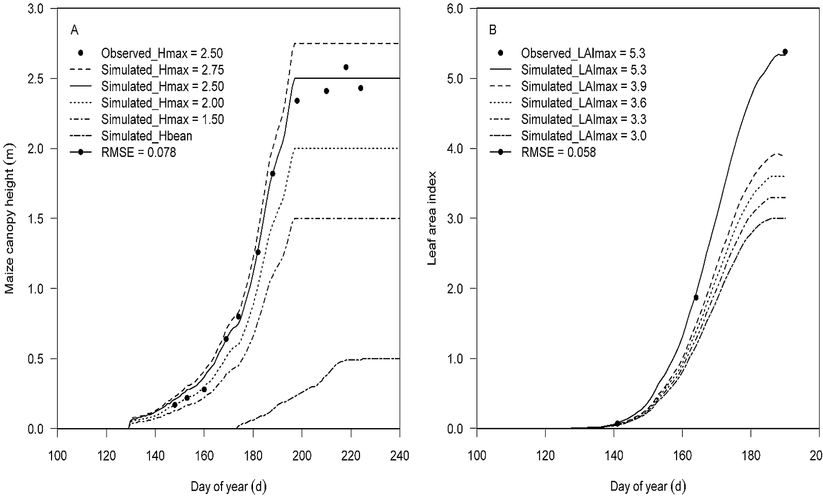

Fig. 4. Observed (growing season 2009) and simulated development of canopy height of maize (Hmax) and bush bean (Hbean) in Germany (A), and of the leaf area index in China (B). The root mean square error (RMSE) of the simulations is presented for the observed maximum maize canopy height of 2.5 m (A) and the maximum leaf area index of 5.3 (B).

Table 6
Simulations of the diffuse and solar view factor (%), direct and transmitted available PAR (APAR, as a fraction of total PAR in %) and the average leaf area index (LAI) traversed by the light beam in row 1, row 2 and the center row within the strip of the neighboring, shorter bush bean crop grown with maize in alternating strips of three, six and nine meters width, in China and Germany in 2009, respectively.

Growing season	Strip width (m)	Bush bean row	Diffuse view factor (%)	Solar view factor (%)	Direct APAR (%)	Transmitted APAR (%)	Average LAI traversed by light beam (–)
China, 2009; Fd-PAR[a]: 0.71	3	1	37.2	35.2	45.7	17.1	6.9
	3	2	43.2	40.1	54.7	18.8	6.8
	3	Center	45.9	43.0	58.9	23.7	6.9
	6	1	45.6	44.4	52.0	11.5	9.8
	6	2	53.6	51.2	63.0	12.0	10.0
	6	Center	65.7	62.8	77.6	11.7	11.2
	9	1	48.8	47.9	53.9	9.7	11.5
	9	2	57.2	55.2	65.3	9.8	12.0
	9	Center	75.5	73.6	85.2	6.5	15.9
Germany, 2009; Fd-PAR: 0.72	3	1	38.3	33.1	44.2	22.9	4.6
	3	2	44.7	37.6	52.5	23.7	4.6
	3	Center	47.8	40.1	56.7	26.8	4.6
	6	1	46.4	42.7	51.0	16.2	6.7
	6	2	54.9	49.2	61.3	16.1	6.9
	6	Center	67.7	60.5	76.9	13.5	7.7
	9	1	49.4	46.7	53.1	13.5	8.1
	9	2	58.3	53.4	63.7	13.5	8.5
	9	Center	77.2	71.7	85.1	7.8	11.1

[a] Fd-PAR is the fraction of diffuse PAR in total PAR averaged over the simulated co-growing period of maize and bush bean.

growing seasons, the cultivar 'Xianyu335' did not exhibit prolificacy in any row of the strip.

Total dry matter, yield, yield components, and LAI for the four growing seasons in Germany are shown in Table 5. In 2009, grain yield in row one and two was significantly increased by 22 and 6%, respectively (Fig. 2A). Total dry matter was also higher in row one, but only by 6%, and the difference was not significant. The relative differences between total dry matter and grain yield in the border and the center rows led to a significantly increased HI in row one and two by 16 and 7%, respectively (Fig. 2B). Among yield components large differences of ear number and kernel number per plant were found between border and center rows. In row one and two, ear number was significantly increased by 31 and 17%, respectively (Fig. 2C). The TKWs did not show any significant differences. However, kernel number per plant was 19% higher in row one (Fig. 2D).

The 2010 growing season, was characterized by below-average temperatures and radiation, which considerably reduced total dry matter and grain yield in comparison to 2009 (Table 5). Leaf area index (LAI) was much lower with an average of 2.4 (±0.1) compared to the other years where LAI ranged between 3.1 and 4. In the two border rows one and two, total dry matter and grain yield increased by 9 and 6%, and 11 and 7%, respectively. Among the yield components, only kernel number per plant showed differences, and significantly increased by 10% in row one (Fig. 2D).

In contrast to previous results, total dry matter and grain yield were highest in the center row in 2011 (Table 5). Total dry matter was significantly decreased in row one by 10%, and grain yield, even though not significant was 6% lower (Fig. 2A). The number of ears per plant was significantly decreased by 18% in row one (Fig. 2C).

In 2012, a year with below-average but well-distributed rainfall, row one achieved the highest total dry matter (25,800 kg ha^{-1}) and yield (14,680 kg ha^{-1}) among all four experimental years in Germany (Table 5). In row one and two, total dry matter and grain yield were significantly increased by 29 and 11%, and 41 and 11%, respectively (Fig. 2A). The larger increase of grain yield in row one resulted in a HI increase of 9% (Fig. 2B). The reason for a higher grain yield in row one was a significantly greater number of ears (26%) and kernels (43%) per plant (Fig. 2C and D).

In summary, maize yield increased in the border rows in years with a sufficient water supply. The fact that the highest yield increase in Germany was observed in 2012 indicated that the amount of rainfall during the critical period around silking was the decisive factor. The yield increase across both locations and cultivars depended mainly on the kernel number per plant. In Germany, a larger kernel number per plant was achieved by a larger number of ears per plant (prolificacy), whereas the Chinese cultivar did not exhibit prolificacy, but produced a larger number of kernels per ear. In addition kernel weight was increased in the border rows in China. Our results are in line with other studies that showed an increase of yield in the border rows of maize strips alternated with strips of shorter crops (soybean, oat) if water is not a limiting factor (Ghaffarzadeh et al., 1997; Lesoing and Francis, 1999; Smith and Carter, 1998; Francis et al., 1986). In the border rows, the number of ears and kernels and the kernel weight were increased in the first two studies mentioned.

In years with insufficient water availability (rainfall and/or irrigation), yield, ear and kernel number were decreased in the first border row in Germany. On contrary, in China the first border row showed the largest increase of yield and kernel number compared to the center row. The observed differences between the two locations in our study might be explained by the irrigation dams at the Chinese location reducing water loss from soil layers beyond the dams leading to a higher soil water availability for the maize plants at the strip border. Gao et al. (2010) showed that maize roots spread laterally toward a neighboring soybean strip under full irrigation. Further studies are needed to investigate root distribution and soil water availability under limiting water conditions, in particular in the border area between the crops.

In general, the number of kernels per plant is very sensitive to environmental stresses during the critical period around silking and was correlated to plant growth rate during this period under a wide range of environmental conditions (Andrade et al., 1999, 2002). In the studies mentioned, an increased ear and kernel number was observed in maize grown at lower plant population densities due to higher irradiation interception per plant, which in turn increased the plant growth rate. Alternating strips of maize and a shorter crop modifies the microclimate in maize border rows compared to center rows. According to studies by Jurik and Van (2004) in alternating strips of maize-soybean-oat, incoming radiation and wind speed are particularly increased in maize border rows. The increased radiation availability potentially increases the plant growth rate in maize border rows; however, during dry periods an increased radiation and wind speed might aggravate water stress, and the plant growth rate subsequently decreases in maize border rows. In addition, water stress around silking can negatively affect pollination by delaying silking in reference to pollen-shedding (Hall et al., 1981). Thus, the observed variation of kernel numbers and grain yield per plant across the maize strips in our study resulted most probably from effects of radiation and water availability on the plant growth rate during the critical period around silking. The similar amount of solar radiation across the locations during the critical period around silking, indicates that kernel number of maize in border rows in China was probably not limited by a low plant growth rate. The number of kernels set at the second ear depends on whether the plant growth rate around silking surpasses a certain threshold (Andrade et al., 1999). Therefore, the differences in ear number between the German and the Chinese cultivars indicate that the Chinese cultivars exhibit a lower level of prolificacy or a higher threshold for setting kernels at the second ear. However, the Chinese cultivar showed a higher variability in adjusting a decreased kernel number by increasing the kernel weight. Lesoing and Francis (1999) found a negative correlation between the increase of kernel number and the increase of kernel weight in maize border rows strip-intercropped with soybean. Further, the authors suggest that the larger the potential for kernel set, the lower the potential to increase also the kernel weight. These results are in agreement to our results for the Chinese cultivar with the lowest increase of kernel number and the highest increase of TKW in 2011. The observed differences in yield components among the cultivars in our study and the results by Lesoing and Francis (1999) should be further explored by comparing the yield formation of maize cultivars with different levels of prolificacy. These studies might reveal if maize yields are more stable under variable conditions of water availability if a cultivar with a high potential of kernel set per plant is used, as it increases the number of kernels available for a later yield adjustment under more favorable conditions during the kernel filling rate (Andrade et al., 2005). Lower thresholds of the plant growth rate for kernel set resulted in a greater kernel number (lower number of barren plants or plants with low numbers of kernels) at low nitrogen or water availability as reported by Echarte et al. (2013) for newer Argentinean maize hybrids.

3.4. Total strip evaluation

The optimization of strip-intercropping systems is aiming for the highest potential yield advantage compared to the same crops grown as monocrops. If maize, a tall growing species, is integrated into intercropping systems, the management of light-competition will influence strongly the overall productivity of both crops. To examine different options to increase the overall productivity, we first calculated the potential yield advantage of different maize strip widths across the experiments in China and Germany. We then used a light partitioning model to estimate the effect of different strip widths (equal for both crops) on the quantity of light transmitted to the top of the canopy of the subordinate, shorter crop, grown between the maize strips. Subsequently, the option of selecting maize cultivars of different canopy height and LAI is examined with respect to their influence on light transmission to the neighboring crop. Finally, we considered the influence of different latitudes, strip widths, canopy height and LAI under varying sky conditions on light transmission to the neighboring crop to gain a global understanding of the interactions between location, cropping pattern and maize cultivar selection.

3.4.1. Yield potential of different strip widths among the two locations

A key question in designing maize strips is the optimal number of maize rows to maximize productivity. For this purpose, grain yields were calculated for different strip widths with data from Tables 4 and 5 of row one, two and the center row, and compared to monocropped maize based only on the grain yield in the center row of the strip. Results for each growing season in China (A) and Germany (B) are presented in Fig. 3 for strip widths consisting of four to 18 maize rows. Even though results were not significant in three out of seven experimental years, the trend among all years could be reasonably explained by the diverse environmental conditions. Hence, we assume that the derived data is useful to set a range of expected maize yield for the two investigated regions. Given the higher yield in the first border row in six out of seven experimental years, the yield increased on average with decreasing strip width from 5.2 to 23.5% in China and 2.6 to 11.7% in Germany, for strips consisting of 18 to four maize rows. The average yield change expected for the two study regions is in agreement to the 5 to 26% yield increase of maize alternated with soybean in strips of four to twelve rows width as reported in a literature study of Smith and Carter (1998); however, on the contrary, the authors showed that the accompanying soybean yields were decreased by 8.5 to 33%. Increasing yields in maize accompanied by decreased soybean yields with a declining strip width were also found by Francis et al. (1986), who summarized results from several experiments in Eastern and Midwestern USA. In their study, they concluded that the productivity (measured as the land equivalent ratio) of the intercrops depends on the rainfall conditions, and might also be affected by cultivar and strip width. In years with adequate rainfall, the total productivity will depend mainly on the light availability across the strip of both crops (Jurik and Van, 2004). The fact that the highest yield increase was observed in years with narrow vegetable strips (3.5 m in 2010 in China and 4.5 m meters in 2012 in Germany, respectively), i.e. shorter distances between the subsequent maize strips, indicated that light competition between the maize strips most likely did not negatively influence the higher yield potential in the border rows of maize when alternated in narrow strips. Therefore, we used a light transmission model to examine how planting

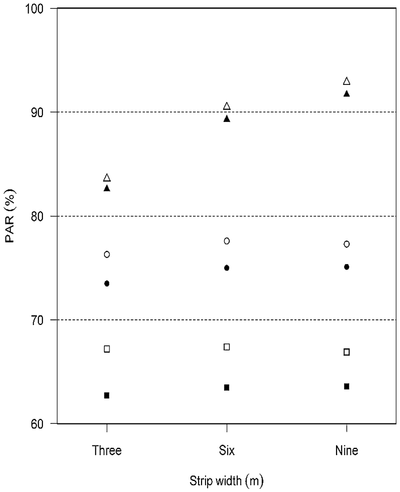

Fig. 5. Simulated PAR (%, compared to total PAR) available in row 1 (■, □), row 2 (●, ○) and the center row (▲, △) within the strip of the neighboring, shorter bush bean crop grown between maize strips. Simulations for strip widths of three, six and nine meters for the experimental site in China (closed symbols) and Germany (open symbols) during the growing season in 2009. Strip widths are equal for maize and bean.

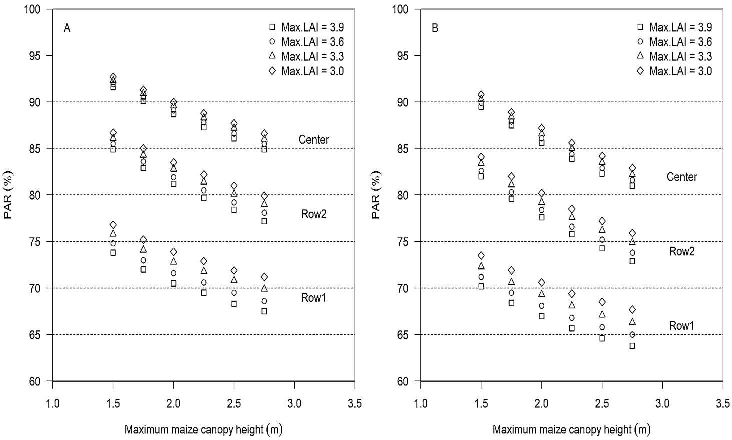

Fig. 6. Influence of the maximum maize canopy height and leaf area index on simulated PAR (%, compared to total PAR) available in row one, 2 and the center row within the strip of the neighboring, shorter bush bean crop grown between maize strips in China (A) and Germany (B) for the growing season 2009. Strip widths of maize and bean are three meters.

patterns of different strip widths do alter the degree of shading across the strip of the neighboring, shorter crop.

3.4.2. Influence of maize strip width on light availability across the strip of the neighboring, shorter crop

To examine the effect of alternating strips with different widths on the light availability across the strip of a shorter crop next to maize, simulations were run with input data derived by the maize simulation model IXIM calibrated with the data of maize canopy height and LAI from 2009 in China and Germany. Canopy height of bush bean was simulated with the CROPGRO green bean model version based on bush bean data from 2012 in Germany (Munz et al., 2014). The simulated inputs are illustrated in Fig. 4A for the maize and bean canopy height in Germany, and in Fig. 4B for the LAI in China in 2009. The distance between successive bush bean rows was 0.5 m.

Our simulations for the first two border rows and the center row in a three, six and nine meters wide strip intercropping-system of maize alternated with the shorter bush bean crop, showed that only PAR in the center row of the shorter crop increases with strip width from around 83 to 93% compared to total PAR, in China and Germany, respectively (Fig. 5). In the two border rows, the effect of increasing strip width is only marginally and even slightly decreasing from strips of six to nine meters width, with on average 67 and 63% in row one, and 77 and 75% in row two, in Germany and China, respectively.

To understand the effect of an increasing strip width for both crops on the quantity of light transmitted to the strip of the adjacent shorter crop, two opposite effects have to be considered. On one hand, a larger strip width leads to a larger proportion of direct (‘solar view factor’) and diffuse (‘diffuse view factor’) radiation directly reaching (without traversing the maize strip) the canopy of the shorter crop next to maize, further denoted as ‘Direct APAR’. On the other hand, an increased strip width of maize will increase the path length of a light beam through the maize strip before reaching the canopy of the shorter adjacent crop. Thus, the leaf area of maize traversed by the light beam (further given as the daily average) is increased, which in turn decreases the quantity of PAR transmitted

Table 7
Influence of different latitudes (24, 36, 48, and 60°N), strip widths (3, 6, and 9 meters), canopy heights, and LAIs on simulated PAR (%, compared to total PAR) available in row 1 within the strip of the shorter companion bush bean crop grown between maize strips on a cloudy (fraction of diffuse PAR = 1.0), a variable (fraction of diffuse PAR = 0.6), and a clear day (fraction of diffuse PAR = 0.2). Note that simulations were run on the same day as in Fig. 7.

Latitude (°N)	Strip width (m)	PAR (%) cloudy day (Frac_Diff = 1.0)		PAR (%) variable day (Frac_Diff = 0.6)		PAR (%) clear day (Frac_Diff = 0.2)	
		Min[a]	Max[b]	Min[a]	Max[b]	Min[a]	Max[b]
60	3	61.0	69.5	53.9	66.7	46.8	64.0
60	6	58.2	66.7	56.0	66.5	53.8	66.3
60	9	56.8	65.1	56.3	65.7	55.8	66.3
48	3	64.6	72.5	58.9	71.2	53.3	69.8
48	6	61.5	70.7	60.1	71.0	58.8	71.2
48	9	60.0	68.1	60.0	69.6	59.9	71.1
36	3	66.2	74.1	61.7	73.5	57.2	72.9
36	6	63.6	71.7	62.6	72.8	61.5	73.9
36	9	62.8	70.9	62.8	72.5	62.7	74.0
24	3	67.1	74.8	63.1	74.6	59.1	74.5
24	6	65.4	74.4	64.3	75.0	63.2	75.6
24	9	63.7	72.0	63.8	73.7	64.0	75.4

[a] Maize canopy height = 2.75 m and LAI = 3.9.
[b] Maize canopy height = 1.5 m and LAI = 3.0.

to the canopy of the shorter adjacent crop, further denoted as 'Transmitted APAR'. The marginal change of PAR experienced in row one grown in strip widths from three to nine meters can be well explained by an increase of 'Direct APAR' from 44 to 53%, and on the contrary, an almost equal decrease of 'Transmitted APAR' by 9% from 23 to 14% in Germany (Table 6). 'Direct APAR' increased because of an 11 and a 14% larger diffuse and solar view factor; plus, 'Transmitted APAR' decreased due to an almost two-fold increase of the average LAI of maize traversed by the light beam. Simulations for row one in China and row two in China and Germany, can also be explained by the same opposite effects. The experienced increase of PAR in the center row with a larger strip width was achieved by a comparably larger effect on the diffuse and solar view factor which increased by 29 and 32%, and led to 28% higher 'Direct APAR' with only a 19% decrease of 'Transmitted APAR'. Even though the LAI traversed was increased even more in the center row than in the border rows, the influence was less given the considerably shorter duration of shading. Interestingly, almost an equal quantities of PAR simulated for the different locations. The maximum LAI and maize canopy height were higher in the growing season 2009 in China with 5.3 compared to 3.3, and 2.7 compared to 2.5 m in Germany, respectively. These results point out the important influence of different latitudes, which resulted in a daily average of the maximum solar elevation of 73.9° in China compared to 61.0° in Germany during the simulation period. The higher solar elevation shortened the shading period, which is expressed by a higher solar view factor of e.g., 33% in Germany compared to 35% in row one in China, respectively. However, the considerably higher LAI led to a much lower quantity of 'Transmitted APAR' of 17 compared to 23% in row one in China and Germany, respectively. With increasing the distance from the maize strip, the influence of the LAI decreases, resulting in the quantities of PAR being more similar between the two locations.

In general, these results suggest that a narrow strip pattern of three meters width, which increases the maize yield per area, will at least not negatively affect the quantity of light available in the two most shaded rows of a shorter crop grown between the maize strips. However, in order to decrease the high level of shading in these two rows, other options than increasing the strip width, such as the selection of a maize cultivar with reduced canopy height and LAI, should be considered.

3.4.3. Influence of different maize cultivars on light availability across the strip of the neighboring, shorter crop

The sensitivity study by Munz et al. (2014) showed that the shading in the first row of bush bean next to maize can be minimized at greatest extent by a reduced canopy height and LAI of maize; different leaf angle distributions showed only minor effects. Therefore, we used the maize simulation model IXIM to simulate different daily increases of maize canopy height and LAI of the two cultivars 'Companero' and 'Xianyu335' that were initially calibrated on the data from the experiments in 2009. For a high level of comparability between the two locations, both cultivars were calibrated to reach the same maximum canopy heights of 1.5, 1.75, 2, 2.25, 2.5, and 2.75 m at silking. In the previously shown Fig. 4A, the simulations are illustrated for the cultivar 'Companero'. Likewise, we simulated the development of the LAI with different maxima of 3.9, 3.6, 3.3, and 3 at silking as illustrated for the cultivar 'Xianyu335' in Fig. 4B.

Simulations of light transmission were run for all combinations of the mentioned canopy heights and LAIs for a strip width of three meters. The results for rows one, two and the center row during the growing season 2009 in China and Germany, are shown in Fig. 6A and B, respectively. In general, PAR increased linearly in all rows across the bush bean strip with a decrease in canopy height and LAI. The slopes were very similar across rows and locations, and resulted on average in a 10% increase of PAR from the highest to the lowest canopy height and LAI. Interestingly, there was a larger impact of different LAIs on PAR in rows that were closer to the maize strip. This can be explained by a larger influence of the LAI when the shading period is longer. In contrast to previous simulations (Fig. 5), PAR was on average 3.4% higher in China compared to Germany. These differences resulted from the previously mentioned higher solar elevation angle which again points out the relevant importance of different latitudes on PAR availability.

3.4.4. Influence of different latitudes on light availability for the subordinate companion crop

Finally, simulations were run for row one grown at different latitudes in steps of 12° from 60°N to 24°N on a cloudy, variable and clear day shortly after silking, when the shading effect of maize is the largest. Different sky conditions were simulated by setting the diurnal fraction of diffuse PAR to 1, 0.6, and 0.2 for a cloudy, a variable, and a clear day, respectively. Maize canopy height, LAI and strip width were set to 2.5 m, 3.9, and 3 m, respectively. In general, moving from 60 to 24°N, day length becomes shorter, and the solar elevation angle and PAR at noon increase. In the model, diffuse radiation is assumed to originate with the same proportions from all sky angles (Munz et al., 2014). Hence, on a cloudy day the fraction of PAR received in row one next to the maize strip is constant during the day (Fig. 7A). The model captured well the described differences across latitudes, and simulated an increase of PAR from 60.7 to 66.8% from 60 to 24°N in row one on a cloudy day. Under variable sky conditions with a proportion of 40% of direct PAR, differences between latitudes became larger, resulting in 9% more PAR available at 24° compared with 60°N (Fig. 7B). The shorter day length and the higher maximum solar elevation angle increased the fraction of PAR directly received in row one. On a clear day, with a fraction of direct PAR of 0.8, almost no radiation was transmitted through the maize strip during early and late hours at high latitudes. Hence, differences became largest under clear sky conditions with 60.5, 58.6, 54.8, and 48.4% of PAR in row one at latitudes of 24, 36, 48, and 60°N, respectively.

During the simulated co-growing period of maize and bean the average fraction of diffuse PAR was 0.72 in China and 0.71 in Germany in 2009 which corresponds closely to the small differences simulated in Fig. 7B. In order to gain an overall understanding of the magnitude of the effects of latitude, strip width, maize cultivar, and sky conditions on the PAR availability in row one of bush bean, the model was run on the same day as previously for the strip widths three, six, and nine meters with either the minimum inputs of canopy height and LAI (1.5 m and 3.0) or their maximum (2.75 m and 3.9 m), respectively. The simulations indicated that with an increasing fraction of direct PAR the effect of a reduced maize canopy height and LAI becomes larger with a light gain of e.g., 8.5 on a cloudy day to 17.2% on a clear day for a strip width of three meters at 60°N (Table 7). In contrast to the marginal effect of different strip widths under the experimental conditions (Fig. 4), the simulations showed an increase in the available PAR with wider strip widths under a higher fraction of direct PAR. These differences were pronounced, particularly when bean was alternated with maize of large canopy height (2.75 m) and LAI (3.9), with an increase of 9.0, 6.7, 5.5, and 4.8% from a strip width of three to nine meters on a clear day at latitudes of 24, 36, 48, and 60°N, respectively. Alternating with maize of 1.5 m height and a LAI of 3.0, resulted in a very small light gain with increasing strip width between 1.0 and 2.3% at latitudes between 24 and 60°N on a clear day.

In summary, the simulations indicated that the light availability increased similarly both in the two border rows and the center row from a reduced maize canopy height. Whereas, reducing the LAI of maize showed in particular a large effect on available PAR in row one. The option of increasing PAR by wider strips will become more

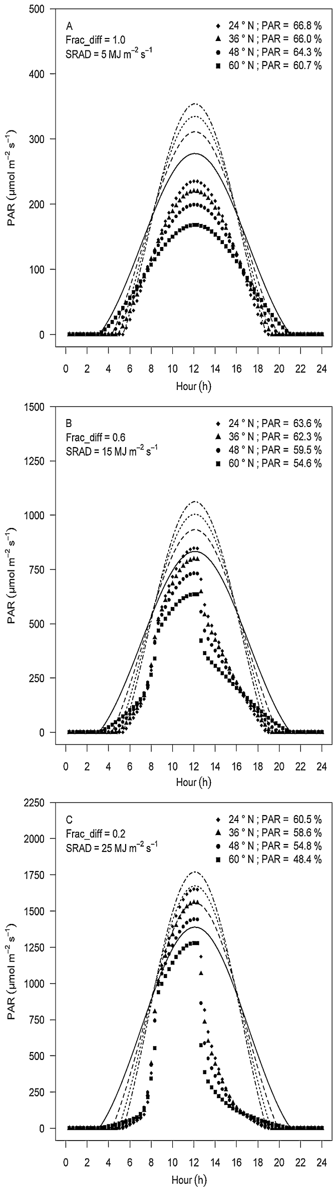

Fig. 7. Influence of different latitudes (24, 36, 48, and 60°N) on simulated PAR (%, compared to total PAR) available in row 1 situated on the west side within the strip of the neighboring, shorter bush bean crop grown between maize strips on a cloudy (A, fraction diffuse PAR = 1), a variable (B, fraction diffuse PAR = 0.6), and a clear day (C, fraction diffuse PAR = 0.2) after silking on day of year = 196 (maize canopy height = 2.5 m and LAI = 3.9). Strip widths of maize and bean are three meters. Notice the change in vertical scale between graphs A, B, and C.

important under sky conditions with a larger fraction of direct PAR. However, to give suggestions about the optimal planting pattern, it will be decisive to know the degree of shading which is tolerated by the shorter crop. Further, effects of light quantity and quality on plant morphology and light interception and the competition for resources below ground have to be taken into account to gain an overall understanding of the processes that drive whole-system productivity (Zhu et al., 2014).

4. Conclusions

Maize grown in narrow strips alternated with a neighboring, shorter crop, will maximize grain yield per area compared to monocropping under adequate water supply in particular during the critical period around silking. Supplemental irrigation and a large proportion of annual rainfall around silking of maize favor yield stability in border rows under the growing conditions at the Chinese sites. Increased grain yield was mainly influenced by a larger number of kernels per plant, either due to an increased ear number of the German cultivars or an increased kernel number per ear of the Chinese cultivar. Simulations of light transmission through the maize strip to the adjacent strip of a shorter crop (bush bean in our study) indicated that a light gain in the most shaded border rows of bush bean will be achieved: (i) primarily by the selection of a maize cultivar with reduced canopy height and LAI; (ii) by growing the crops at lower latitudes (24 > 60°N); and (iii) by increasing the strip width under a higher fraction of direct PAR. Thus, regarding the whole-system productivity, the optimum strip width will finally depend on the productivity and light transmission of the maize cultivar, and the shade level tolerated by the neighboring, shorter crop. Therefore, future research should focus more on the performance of different cultivars of maize and the subordinate crop to: (i) select crops and cultivars suitable under the shade levels that likely occur in a strip-intercropping system with maize; and (ii) highly productive maize cultivars with a reduced canopy height and LAI.

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6 General discussion

The major aim of this thesis was to identify options and develop an approach to optimize intercropping systems relevant for the future agricultural production in the North China Plain. Special emphasis was given on above-ground competition for light between maize and smaller neighboring crops, namely Chinese cabbage and bush bean. Chapter I formed the basis of simulating the light availability for the smaller neighboring crop next to maize. The influence of the modified light availability on plant growth and yield formation of the smaller legume crop bush bean was studied in Chapter II based on field experiments and simulations with the process-oriented plant growth model CROPGRO. Chapter III completed the assessment of the modified light availability on the overall performance of maize and the smaller legume crop bush bean by investigating: (i) plant growth and yield formation of maize; and, (ii) the influence of the cropping pattern and maize architecture on light availability for the smaller neighboring crop. These different aspects were discussed at the end of each of the Chapters I-III, and will not be repeated individually in this chapter.

The general discussion will combine all aspects of the previous Chapters I-III with the aim to evaluate the potential of intercropping in Chinese agriculture under the current challenges of sustainably increasing productivity. Furthermore, the models either developed or evaluated in this thesis will be discussed for their applicability and future improvements. Finally, this chapter deals with the overall goal of this thesis, the optimization of intercropping systems, with special regard to crops planted in alternating strips.

6.1 Intercropping potential under sustainable intensification of agriculture in China

The need for a sustainable intensification of agriculture is acknowledged as a global challenge under decreasing resources, a growing world population, an extension of bioenergy production and the changed human diet, particularly in fast developing countries, such as India and China (Spiertz and Ewert, 2009). China, as the most populous nation with very limited land and water resources and an enormous economical growth, plays an important role in global food security. On a national level, China faces an enormous challenge to ensure food security in the future, as the past production increases were merely input-driven with serious negative environmental impacts. This background explains the large efforts and numerous recent publications from Chinese scientists dealing with the intensification of the agricultural production in a sustainable way (e.g. Fan et al., 2012; Shen et al., 2013; Zhang et al., 2011). Shen et al. (2013) reviewed options to increase the productivity of Chinese cropping systems and in summary designated the combination of different options as a ‘double high technology system’. This technology system addresses three components: (i) better crop management (plant density, sowing date and management adapted to the local climatic conditions); (ii) higher nutrient use efficiency by optimizing nutrient supply and demand ratios especially in the rhizosphere; and, (iii) improved management of soil organic matter to increase overall soil quality. The proposed technology aims at closing the gap between potential crop yields and the actual yields on farmers´ fields; for instance, maize yields achieved on farmers´ fields were only around 50% of the potential maize yield, mainly due to insufficient crop management practices (Meng et al., 2013). Despite the optimization of crop management, cropping systems changed over the past and are likely to change in the future as well. For example in the NCP, the most important crops, wheat and maize, were produced in an annual rotation until the 1970s. Then, breeding improvement led to fast maturing maize varieties, which facilitated growing winter wheat and summer maize in one year. Nowadays, this system is seriously challenged by the large irrigation requirements for winter wheat during spring, and current research focuses on growing only three crops in two years replacing winter wheat – summer maize rotation in one year by spring maize and winter fallow (Meng et al., 2012). This example, and the above mentioned new technology system, clearly indicate the interdisciplinary approach (e.g. agronomy, plant nutrition, breeding) needed for further improvements of the agricultural production. Furthermore, an increased consumption of dairy products in China will likely lead to higher production shares of maize and protein-rich crops, such as soybean, for feed production. The particular focus of the present thesis was on the current situation and future challenges of the agricultural production in China. However, in general, the sustainable intensification of agriculture is not restricted to China; moreover it is a global challenge for agricultural production (Tilman et al., 2002, 2011). Additionally, negative environmental impacts related to agriculture merely based on monocropping are also an issue of global importance (Malézieux et al., 2009).

Besides improving the productivity and resource use efficiency of monocropping systems, another less studied option, is the combination of different crops on the same field at the same time, known as intercropping (Vandermeer, 1989). The most important feature of intercropping is the complementary use of resources over space and time by species that differ in physiology, morphology and/or phenology. Thus, intercropping provides an additional possibility to increase the productivity per land area compared to monocropping systems by a higher use efficiency of radiation, water and nutrients (Dhima et al., 2007; Walker and Ogindo, 2003; Gao et al., 2010b). Furthermore, the susceptibility to environmental stresses and diseases varies among different crops and the modification of the local growth environment can decrease stresses and disease pressure resulting in higher yield stability under changing environmental conditions (Altieri and Nicholls, 2013; Vandermeer, 1989). For instance, shading provided by walnut trees alleviated water stress in wheat plants grown in an alley agroforestry system in France (Dufour et al., 2013). Intercropping systems play an important role in low-input subsistence farming systems in Africa, Latin America and Asia (Vandermeer, 1989). For instance in intercropping systems of annual crops, the combination of a C4-crop, such as maize, millet and sorghum combined with a smaller legume crop, e.g. cowpea and common bean, presents a highly efficient and productive cropping system (Ofori and Stern, 1987). On the other hand, there are also intensively managed intercropping systems, e.g. in north-eastern China which use the dominating intercropping pattern of annual crops, including maize, with growing the crops in narrow strips, comprising of e.g. two rows of maize alternated with six rows of wheat (Li et al., 2001; Mu et al., 2013; Zhang and Li, 2003) or with three rows of soybean (Gao et al., 2010b). In comparison, in US and Argentinean farming systems, maize and soybean are grown in alternating strips of four to twelve rows width to allow for mechanized management (e.g. Lesoing and Francis, 1999: Jurik and Van, 2004; Verdelli et al., 2012). Yields in the latter farming systems were slightly above or equal to their monocropping equivalents, but the narrow strip-intercropping systems in China showed large yield advantages (Li et al., 2001; Gao et al., 2010b). However, despite their high productivity, the share of intercropping in the agricultural production in China decreased over the last decades mainly due to ongoing mechanization and a lower availability of labor in rural areas (Feike et al., 2010). Consequently, intercropping systems in China have to be optimized spatially to facilitate mechanized management.

In general, on a global scale, the key question is how to optimize strip intercropping systems to maximize their productivity. Based on the experiences from US and Argentinean farming systems, it is difficult to conclude on optimized cropping patterns as the experiments vary in many aspects, such as location, strip width and cultivars. However, what can be concluded from the experiments conducted is that there is a lack of an approach towards

a comprehensive understanding of the important factors that influence the productivity of the intercrops. Under these conditions, it is likely that strip intercropping systems have not yet reached their maximum potential.
The optimization of intercropping systems has generally received less attention than monocropping systems and an interdisciplinary approach as described previously for monocropping systems in China does not exist, neither in China nor worldwide. Furthermore, the small area and share of intercropping as part of the total agricultural production highly questions whether investment of time and money into the optimization of intercropping systems will increase in the future. Therefore, modeling is an essential tool to gain more knowledge and suggestions for further research and improvements and is feasible to pursue.

6.2 Modeling strip-intercropping systems

6.2.1 Modeling above-ground competition for light

In China, research focused strongly on below-ground competition in cereal-cereal and cereal-legume intercropping systems. This focus can be explained by the relay-cropping character of these intercropping systems, which reduces the competition above-ground to a shorter time period. However, as shown by Knörzer et al. (2011), the modified temporal and spatial availability of radiation across the strip of each crop also influences the overall productivity of the crops. This study found that both wheat and maize received over their respective growing periods 10% more radiation in the border rows compared with the center rows of the strips. In strip intercropping systems with crops of large height differences, the influence of radiation will become even more decisive and many studies attributed the largest influence on yield to the modified light regime (e.g. Jurik and Van, 2004; Lesoing and Francis, 1999). As shown in Chapter I in this thesis, PAR at the top of the canopy of bush bean was reduced by more than 40% in the row adjacent to the maize strip. Furthermore, a comprehensive modeling approach was developed and validated that includes the major aspects of cropping design in strip intercropping systems. In general, simulations of light transmission in plant canopies can be divided into two approaches, a statistical and a geometrical approach. The main difference between the two approaches is that the statistical approach divides the plant canopy into turbid layers; whereas, in the geometrical approach the plant canopy is represented by a geometrical figure (Lemeur and Blad, 1974). Regarding intercropping canopies, both approaches were used for the simulation of light distribution in both heterogeneous and homogeneous intercrop canopies, i.e., the canopies of both plants differed vertically and/or horizontally or not (e.g. Ozier-Lafontaine et al., 1997; Sinoquet and Bonhomme, 1992; Wallace et al., 1990). Tsubo and Walker (2002) studied radiation interception in alternating rows of bean and maize. The authors compared the statistical with the geometrical method, finding that both methods showed a high accuracy in simulating the instantaneous and daily radiation interception by the canopy of both crops. However, only the geometrical method was able to capture differences of light interception within a single row of each crop. In general, it can be stated that the geometrical model is more suitable to capture light distribution in heterogeneous plant canopies; and, in addition, requires less computation. In the case of strip intercropping, there are large distances between the crops; but, the strip of each crop is homogeneous. This homogeneity of the strip of each crop can be well presented geometrically by a rectangular hedgerow. Therefore, in the present thesis, the geometrical approach was used. As proved in Chapter I, the geometrical approach is very suitable for simulating light availability within the strip of the smaller crop between maize strips. Furthermore, the geometrical representation facilitates: (i) testing different cropping designs (e.g. strip width, orientation); and (ii) integrating other crops and cultivars defined by their plant architecture (height, width, LAI, leaf angle distribution). Solar calculations in the model are based on latitude and time, which allows simlations for any location and time.

Modeling the light availability across the maize strip still remains to be a complex task. Various canopy layers of maize plants receive laterally full sunlight during early hours on the east side and during late hours on the west side of the maize strip. Especially on clear days, available PAR varies largely across the maize strip; during early hours, the first two rows receive more PAR than the center row; whereas, during the afternoon PAR availability is very similar across the strip (Fig. 6.1A). In contrast, under cloudy conditions PAR is mainly diffuse and the differences among the mentioned rows remain quite constant over the course of the day, and are in general smaller than under clear sky conditions (Fig. 6.1B). The measurements presented were conducted at ear height of maize with a line quantum sensor of 30 cm length (PAR/LE line sensors, SOLEMS S.A., Palaiseau, France) located perpendicular to the row orientation centered at the maize stem. However, theoretically, leaves oriented towards the strip of the smaller crop might receive full sunlight and cast shade on leaves that are oriented towards the maize strip. In general, a simple model should be favored instead of a more complex one due to the larger potential errors of simulations based on a larger number of parameters. As shown in Chapter I, representing the entire maize strip as a homogeneous rectangular hedgerow was sufficient to simulate the light availability across the strip of the smaller, neighboring crop.

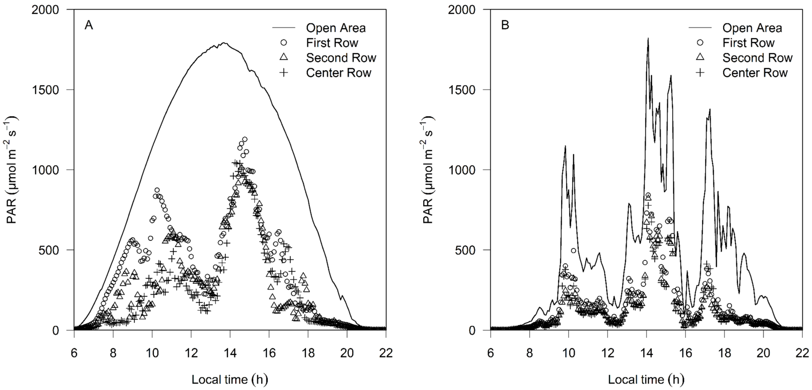

Fig. 6.1: Diurnal distribution (in five-minute intervals) of the photosynthetically active radiation (µmol m^{-2} s^{-1}) above the maize canopy (Open Area, solid line) and at ear height in the first (○), second (△), and center row (+) on the east side of a six rows-wide maize strip alternated with nine rows of bean grown in south-western Germany. Measurements conducted under clear (A) and variable sky conditions (B).

On the other hand, for simulating the light availability within the canopy of maize, a model with a higher complexity is needed. A promising approach - based on the light model developed in Chapter I - would be to divide the maize canopy into different horizontally and vertically spaced cells (e.g. at each leaf layer) for individual rows across the maize strip, as illustrated in Fig. 6.2. The calculations would be generally similar to the ones underlying the light model in Chapter I. However, calculations would have to be done for each cell within the canopy of an individual maize row, considerably increasing the computation requirements. In addition, transmittance through the canopies of both crops has to be taken into account when leaf layers of maize at a canopy height lower than the height of the smaller, neighboring species are regarded. Special emphasis should be given on the first two border rows on each side of the strip. As shown in Chapter III, plant growth and yield formation were similar across the other rows of the strip, which indicated that light simulations for a monocropping situation probably sufficiently accounts for the light availability in the center rows of the maize strip.

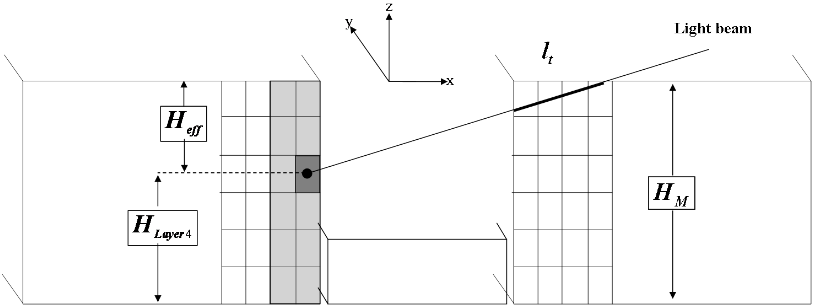

Fig. 6.2: Geometrical representation of a strip-intercropping system and illustration of the division of an individual maize row (grey) in different horizontally and vertically spaced cells. The point within the cell (dark grey) of interest (•) is defined by the distance between the point and the neighboring maize strip; and, the height of the maize canopy (H_m) and of the point of interest within the maize canopy (e.g. of the 4th leaf layer; H_{Layer4}) and their difference (H_{eff}). l_t (bold line) is the path length of the light beam traversing the maize canopy. Further details and underlying calculations are given in Munz et al., 2014 (Chapter I of this thesis).

Recent technical and computational advancements are aiming at a 3-dimensional representation of plant canopies which allows for very detailed calculations of light distribution within plant canopies (Barillot et al., 2011; Vos et al., 2010). The simulations of light distribution in intercropping canopies can highly benefit from these advancements.

The calculation of the light distribution among crops, and the influence of cropping pattern, the architecture of crops and cultivars is a very important point for the purpose of designing optimized strip-intercropping systems. However, the final aim of the optimization is to achieve the largest productivity. Therefore, the most important question is how the modified light regime influences plant growth and yield formation of the crops.

6.2.2 Modeling plant growth and yield formation

The light availability varies both across the strip of each crop and throughout the day. Therefore, a high temporal resolution is crucial to capture the influence of the modified growth environment on plant growth and yield formation. Most detailed plant growth models run on a daily scale, however some include an hourly simulation of certain processes, e.g. the CROPGRO model provides hourly leaf-level photosynthesis calculations. Furthermore, as the variety of crops included in intercropping systems is large, a generic model is most suitable as it facilitates the introduction of many crops. For those two reasons, the CROPGRO model was tested and described in Chapter II of this thesis. The study showed that CROPGRO, a model developed for monocropping situations, was also able to capture effects of reduced radiation on growth and yield formation of strip-intercropped bush bean when each of the investigated bush bean rows was calibrated specifically. Further the study mentioned showed that besides the effect of the total reduction of radiation, the modified shares of direct and diffuse radiation influence to a large extend canopy photosynthesis. Larger shares of diffuse radiation, as experienced when crops are shaded, results in a better distribution within the plant canopy and photosynthesis increases (Sinclair et al., 1992; Healey et al., 1998). Leafs at lower canopy layers operate at lower light intensities (i.e. steeper slope of the light response curve), where small increases of light intensity result in considerable increases of photosynthesis (Greenwald et al., 2006). This behavior was captured well by CROPGRO, and can be further explored as diffuse radiation remains a part of light distribution and photosynthesis hardly studied in general; and, in particular, becomes more important with the increasing impact of shading. Furthermore, the CROPGRO model simulated the potential influence of decreased light on the specific leaf area and canopy dimensions quite well. However, the errors of the simulations of the actual responses for the parameters mentioned resulted from inaccurate partitioning of assimilates to the different plant organs. Further studies should investigate more on the quantitative effect of reduced radiation on source- and sink-relationships between different plant organs. Consequently, there would be no necessity to calibrate the model row-specifically which, in turn, enables simulations under environmental conditions outside the experimental range.

Modeling plant growth in intercropping based on monocropping models offers a very promising way for the future as shown in Chapter II of the present study and by other authors, which extended monocropping models to account for the competition in mixed-cropping (Brisson et al., 2004) and strip-intercropping (Knörzer et al., 2011) of annual crops.

In the case of modeling maize in strip-intercropping systems, in the present thesis the maize simulation model IXIM (Lizaso et al., 2011) was used. In contrast to the limitation of CERES-maize, as mentioned by Knörzer et al. (2011), IXIM also simulates canopy height. IXIM was used to simulate different daily increases of canopy height and LAI (Chapter III). These daily values were used as inputs for the developed light model to evaluate the influence of different maize architectures on light availability for the smaller, neighboring crop bush bean. With respect to the previously mentioned difficulties in simulating the light availability within the maize canopy in strip intercropping, the IXIM model, comparably to CROPGRO, provides hourly calculations of leaf-level photosynthesis. This feature would be a promising starting point to integrate light simulations on the leaf-level and further simulate its influence on plant growth and yield formation of maize. As shown and discussed in Chapter III, the increased radiation availability in border rows of maize influenced the yield formation of maize, mainly by increasing the kernel number per ear in China and per plant (larger number of ears) in Germany, respectively. The kernel number per plant was the most decisive parameter and is in general a good predictor of final yield (Otegui et al., 1995). The number of kernels set is highly susceptible to environmental stresses around silking (Andrade et al., 2002). Therefore, it still remains a difficult task to accurately simulate the kernel number of maize under a wide range of conditions. For an accurate simulation of maize yield in the border rows of the maize strip, the representation of the effect of solar radiation and water stress are most important. In addition, the increased number of ears per plant is an important component determining yield of strip-intercropped maize. The IXIM model used in the present thesis, allows for a very detailed simulation of kernel number based on both kernel number per ear and ear number per plant (prolificacy). Several coefficients are available in IXIM to define the prolificacy level and potential kernel number per plant of a cultivar (Lizaso et al., 2011). Therefore, the features available in IXIM, such as the hourly leaf-level photosynthesis, the integration of cultivar-specific prolificacy, plant height and width, provide a promising basis to simulate growth and yield formation of strip-intercropped maize.

6.3 Optimization of strip-intercropping systems

The general aim of the current thesis was to combine field experiments and modeling approaches to suggest options for optimizíng the productivity of strip-intercropping systems. For this purpose, data was exchanged between the developed light model (Chapter I) and the plant growth models CROPGRO (Chapter II) and IXIM (Chapter III). Even though the present study did not accomplish the task to model the light availability, plant growth and yield formation of maize, the derived data and discussed literature clearly indicated that maize is the dominant species, i.e., competition by the neighboring crop bush bean for water and nutrients can be regarded as rather small. Furthermore, maize yields will increase with decreasing strip width as the proportion of the number of border rows increases. Under water restricted conditions, the increased radiation will aggravate water stress which might decrease maize yields as shown and discussed in Chapter III. Kernel number per ear and number of ears per plant are the yield parameters mostly affected under the growing conditions present in the borders of the maize strip, and should be of major focus to increase maize yields. Furthermore, light simulations indicated that increasing the strip width only marginally affects the light availability in the smaller crops's rows mostly shaded next to maize; whereas, planting maize cultivars with reduced canopy height and LAI will reduce this shading. In summary, these results suggest that maize cultivars with: (i) a high potential of kernel set; (ii) a higher water stress tolerance; and, (iii) reduced canopy height and LAI, would be most promising to produce both higher and more stable yields and positively influence the growth of the neighboring smaller crop by allowing for greater radiation transmission. The importance given to each of the components will be determined by the local weather and management conditions and the shade tolerance of the neighboring crop. For instance, under rainfed cultivation in Germany tolerance to water stress becomes more important than under supplemental irrigation in China. Moreover, the Chinese cultivar, in contrast to the German cultivars, did not produce more than one ear per plant; therefore, a more prolific maize cultivar should be of greater importance.

Most studies on strip-intercropping of maize and soybean in the US showed that the increase of maize yields was offset by a similar decrease of soybean yields due to shading. A crop and/or cultivar tolerating higher levels of shade would increase yields of both the smaller crop and as well result in higher yield potentials of maize by facilitating a higher plant density in maize border rows, which, in turn, increases maize yields per area. Therefore, the selection of shade tolerant crops and cultivars will be highyl relevant for a future increase in overall productivity.

Identifying the most important plant traits enables both the selection among available cultivars and can guide breeding for future cultivars. As summarized by Lithourgidis et al., (2011), breeding cultivars for intercropping is a very complex task as interactions with the companion crop also influence growth performance. Furthermore, as breeding requires the investment of a lot of time and money, specific breeding programs for intercropping can only be justified if the respective intercropping system is of major importance, covers a large area and is sufficiently unique (Davis and Woolley, 1993). Given the actual minor importance of intercropping for agricultural production in China, it is unlikely that specific breeding programs will be initiated. As stated by Davis and Woolley (1993) a significant interaction between genotype and cropping system is more likely if the competition between the crops is large. In Chapter II and III it was shown that, in particular, growth on the leaf- and canopy-level of bush bean were largely influenced; whereas, maize growth was more conservative among the strip, and the main influence was found on kernel and ear number per plant. These results suggest that cultivars available for monocropping are more likely suitable for maize than for the smaller crop in strip-intercropping systems.

In general, the higher yield potential of modern maize hybrids was related to a higher number of kernels per plant (Tollenaar et al, 1992; Otegui, 1995). Furthermore, the shorter maturity of modern maize hybrids would as well allow for a longer period of compensation growth of the smaller shaded crop after maize harvest, resulting in less yield reduction and an overall yield increase, as experienced in the currently practiced relay intercropping systems in the NCP. These are two examples for cultivar features of modern maize hybrids bred for monocropping from which strip-intercropping with maize and a smaller crop may also benefit.

To optimize yields of the smaller shaded crop there are two ways: (i) to modify the co-growing period of the intercrops temporarily to alleviate competition during shade-sensitive growth stages; and, (ii) to modify the cropping design spatially and/or select different maize cultivars to reduce shading to the tolerated degree during the respective growth stage of the smaller crop. To pursue the two approaches mentioned, the shade tolerance during the respective growth stages has to be known. As shown in Chapter II, bush bean tolerated up to 30% of shade during its entire growth period; however, at higher shade levels total and pod dry matter decreased considerably. Further research should focus on the reasons behind this apparent threshold of shade tolerance. The gained knowledge can be integrated into plant growth models (e.g. CROPGRO) which facilitate in studying the influence of different temporal shade levels during the growing period. In general, bean (*Phaseolus vulgaris* L.) is more susceptible to shade during reproductive growth (Gentry, 1968). Taking this into account, an agronomic option would be to sow an early-maturing maize cultivar and delay sowing of bean or to plant a later-maturing bean cultivar. This would shorten the period of competition during the reproductive period of bean; and, in turn, might increase the final bush bean yield and overall productivity (Davis et al., 1987; Santalla et al., 2001). In addition, to this temporal optimization, the light model developed can be used to optimize the cropping pattern (strip width and maize cultivar) spatially by assuring that the light availability during the co-growing period meets the shade-tolerance of the smaller crop.

In summary, large research efforts have been undertaken to increase the productivity of both Chinese agriculture and agriculture globally in a sustainable way. Beyond this, the improvements of the efficiency of monocropping systems, intercropping provides an additional possibility to increase both productivity and efficiency. In the present thesis a promising approach, which combines a specific light partitioning model with process-oriented monocropping plant growth models, was developed.

The future optimization of intercropping systems will depend strongly on the efficiency of the research efforts because of: (i) the complexity of the interactions both between the crops and the crops and the environment; (ii) the large number of possible crop combinations and arrangements; and, (iii) the minor share of time and money invested in intercropping research. Therefore, of major importance in intercropping research is to prevent reinventing the wheel by identifying aspects in common with and already studied in monocropping systems. Consequently, research efforts can then be reduced and focus can be given to the aspects particularly inherent to intercropping systems.

7 Summary

Due to a growing world population, an extension of bioenergy production and the larger proportion of meat and dairy products in the human diet, with the latter particularly in India and China, the demand for agricultural products will further increase. Under decreasing resources and negative environmental impacts related to past intensification, more sustainable agricultural production systems need to be developed in order to meet the future demand for agricultural products.

China, as the most populous nation with an enormous economic growth since the end of the 1970's, plays a major role in global agricultural production. On a national level, agricultural production has to be increased by 35% during the next 20 years. However, land and water resources in China are very limited.

With this in mind, the Sino-German International Reseach Training Group (IRTG) entitled 'Modeling Material Flows and Production Systems for Sustainable Resource Use in Intensified Crop Production in the North China Plain' was initiated by the Deutsche Forschungs-Gemeinschaft (DFG) and the Chinese Ministry of Education (MOE). The present doctoral thesis was embedded in the IRTG and focused, in particular, on exploring combinations of different crops produced on the same land at the same time, known as intercropping. In general, the higher productivity in intercropping, compared with monocropping, arises from the complementary use of resources (radiation, water, and nutrients) over space and time by crops that differ in physiology, morphology and phenology.

The decisive question is how to optimize intercropping systems over space and time. To address this question, the present doctoral thesis combined field experiments with modeling approaches with the following aims: (i) to investigate the light availability on high temporal and spatial resolutions; (ii) to develop and validate a model that simulates the light availability for the smaller crop and accounts for the major aspects of cropping design; (iii) to determine the effect of the modified light availability on growth of maize and the smaller, shaded crop; (iv) to evaluate the plant growth model CROPGRO for its ability to simulate growth of the smaller, shaded crop; (v) to investigate the interactions between maize cultivar, cropping design and local growth conditions; and, (vi) to identify promising cropping designs and detect future research needs to increase the productivity of strip-intercropping systems.

For this purpose, field experiments comprising of strip-intercropping with maize (*Zea mays* L.) and smaller vegetables, including bush bean (*Phaseolus vulgaris* L. var. *nana*), were carried out over three growing seasons from 2010-2012 in southwestern Germany and in the North China Plain. Growing the crops in strips facilitates mechanized management, addressing the ongoing decrease of intercropping in China due to labor scarcity in rural areas. The crop combination of maize, a tall C4-crop with erectophile leaves, and bush bean, a small, N-fixating C3-crop with a more horizontal leaf orientation, was chosen due to the large potential for a complementary resource use. Special emphasis was given on the competition for light as it plays a major role in this cropping system due to the large height differences between the crops. In this context, measurements of the photosynthetically active radiation (PAR) were conducted on high spatial (individual rows across the strip) and temporal resolutions (five-minute intervals) at the top of the bush bean canopy over a two-month co-growing period with maize. The collected data formed the basis of the simulation study towards investigating competition for light and its influence on plant growth with modeling approaches.

Experimental results showed that maize yields increased in the border rows of the strip due to a higher lateral incoming radiation in years with a sufficient water supply. On average, maize yields calculated for strips consisting of 18 to four rows increased by 3 to 12% and 5 to 24% at the German and Chinese sites, respectively. Analysis of yield components revealed that yield increases in the border rows of the maize strip were mainly determined by a larger number of kernels per plant. On the other hand, shading by the taller adjacent maize induced considerable shade adaptations of bush bean, such as larger canopy dimensions and a substantially increased leaf area index due to thinner, larger leaves. These shade adaptations increased light interception, and indicated that bush bean could tolerate shading up to 30%, resulting in a total and pod dry matter similar to that of monocropped bush bean. These results suggested that there is a good potential for utilizing bush bean in strip-intercropping systems in combination with taller crops. However, higher shade levels (>40%) resulted in considerable decreases of total and pod dry matter.

The high temporal and spatial resolution of the PAR measurements clearly revealed a highly heterogeneous diurnal distribution of PAR across the bush bean strip. The developed light model simulated this heterogeneity with a high accuracy under both clear and cloudy conditions. Comparison of simulated and observed hourly values of PAR across several rows within the strip of bush bean showed a root mean square error (RMSE) ranging between 47 and 87 µmol m^{-2} s^{-1} and a percent bias (PBIAS) ranging be-

tween -3.4 and 10.0%. Furthermore, the model reasonably captured the influence of different widths of the bush bean strip, strip orientations and maize canopy architecture (height, leaf area index, and leaf angle distributions). Simulations run for different latitudes and sky conditions, including different strips widths, maize canopy heights and leaf area indices (LAI), indicate that: (i) increasing the strip width might only reduce shading in the border rows of the smaller crop at lower latitudes under a high fraction of direct radiation; (ii) at higher latitudes, the selection of a maize cultivar with reduced height and LAI are suitable options to increase the light availability for the smaller crop.

The present doctoral thesis presents the first approach to use the monocrop plant growth model CROPGRO to simulate growth of a legume crop grown in an intercropping system. The CROPGRO model was chosen because it provides an hourly simulation of leaf-level photosynthesis, and algorithms that account for the effects of radiation intensity on canopy dimensions and specific leaf area. CROPGRO, calibrated on data of monocropped bush bean, captured, quite well, the effects of the strongly reduced radiation on leaf area, and total and pod dry matter in the most shaded bush bean row. This indicated the models' applicability on other intercropping systems exhibiting high levels of shading. Under a lower level of shading, cultivar and ecotype parameters had to be calibrated individually for a respective row within the bush bean strip to achieve a high accuracy of the simulations. Model simulations aided in explaining the effects arising from different shares of direct and diffuse radiation on canopy photosynthesis. This is a very important point to be further explored as diffuse radiation remains a part of light distribution and photosynthesis hardly studied in general; and, in particular, becomes more important with the increasing impact of shading.

The simulation of the light availability, plant growth and yield formation within the strip of maize can be handled in a similar way as described for the smaller crop, bush bean. Modifications of the light model and a suitable plant growth model are presented and discussed.

In conclusion, the main outcomes of this thesis indicate that the selection of cultivars adapted to the modified light environment have the largest potential to increase the productivity of strip-intercropped maize and bush bean. The most important characteristics of suitable maize cultivars include: (i) a high potential of kernel set; (ii) a higher water stress tolerance; and, (iii) reduced canopy height and LAI. The importance given to each of the components would subsequently be determined by the local weather and management conditions and the shade tolerance of the neighboring crop. On the other hand, to optimize yields of the smaller shaded crop, we present two options: (i) to modify the co-growing period of the intercrops temporarily to alleviate light competition during shade-sensitive growth stages; and, (ii) to modify the cropping design spatially and/or select different maize cultivars to reduce shading to the tolerated degree during the respective growth stage of the smaller crop. When the shade tolerance during the respective growth stages is determined, the light model developed can be used to optimize the cropping system temporarily and spatially.

In this thesis, a promising approach, which combines a specific light partitioning model with process-oriented monocropping plant growth models, was developed. All models included in the approach can be applied at any location, and their generic nature also facilitates the integration of other crops. These attributes present a highly valuable contribution to intercropping research as their future optimization will depend strongly on the efficiency of the research efforts given: (i) the complexity of the underlying processes that determine the productivity; and, (ii) the minor share of time and money invested in intercropping research. Intercropping research has to prevent reinventing the wheel by identifying aspects in common with and already studied in monocropping systems and focus on aspects particularly inherent to intercropping systems.

8 Zusammenfassung

Die Nachfrage nach landwirtschaftlichen Produkten wird weiter ansteigen, aufgrund der anwachsenden Weltbevölkerung, der Ausweitung der Bioenergieproduktion und des größeren Anteils von Fleisch- und Milchprodukten in der menschlichen Ernährung, das Letztere gilt insbesondere für Indien und China. Im Zuge abnehmender Ressourcen und negativer Umweltauswirkungen der Intensivierung in der Vergangenheit, müssen nachhaltigere landwirtschaftliche Produktionssysteme entwickelt werden, um die zukünftige Nachfrage nach landwirtschaftlichen Produkten zu decken.
Als bevölkerungsreichstes Land mit einem enormen wirtschaftlichen Wachstum seit den 1970er Jahren, nimmt China eine wichtige Rolle in der globalen landwirtschaftlichen Produktion ein. Auf nationaler Ebene, muss die landwirtschaftliche Produktion in den nächsten 20 Jahren um 35% gesteigert werden. Die Land- und Wasserressourcen in China sind jedoch sehr begrenzt.
Vor diesem Hintergrund wurde das deutsch-chinesische internationale Graduiertenkolleg (IRTG) mit dem Titel „Modellierung von Stoffflüssen und Produktionssystemen für eine nachhaltige Ressourcennutzung in intensiven Acker- und Gemüsebausystemen in der nordchinesischen Tiefebene“ von der Deutschen Forschungsgemeinschaft (DFG) und dem chinesischen Bildungsministerium (MOE) initiiert. Die vorliegende Doktorarbeit wurde im Rahmen des IRTG durchgeführt. Der spezielle Fokus galt der Untersuchung von Kombinationen von verschiedenen Ackerkulturen, die gemeinsam auf derselben Ackerfläche innerhalb derselben Vegetationsperiode, bekannt als Mischanbau, kultiviert werden. Im Allgemeinen beruht die höhere Produktivität des Mischanbaus, im Vergleich zur Reinkultur, auf der räumlichen und zeitlichen komplementären Nutzung von Ressourcen (Licht, Wasser und Nährstoffe) durch Kulturpflanzen unterschiedlicher Physiologie, Morphologie und phänologischer Entwicklung.
Die entscheidende Frage ist, wie Mischanbausysteme räumlich und zeitlich optimiert werden können. In diesem Kontext wurden in der vorliegenden Doktorarbeit, Feldversuche mit Modellierungsansätzen kombiniert. Die Ziele im Einzelnen waren: (i) Untersuchung der Lichtverfügbarkeit auf einer hohen zeitlichen und räumlichen Auflösung; (ii) ein Modell zur Berechnung der Lichtverfügbarkeit für die kleinere Kulturpflanze, unter Berücksichtigung der wesentlichen Aspekte des Anbausystems, zu entwickeln und

zu validieren; (iii) Bestimmung des Einflusses der veränderten Lichtverfügbarkeit auf das Wachstum von Mais und der kleineren Kulturpflanze; (iv) das Pflanzenwachstumsmodell CROPGRO zu evaluieren bezüglich der Fähigkeit das Wachstum der kleineren, beschatteten Kulturpflanze zu simulieren; (v) die Wechselwirkungen zwischen Maissorte, Anbaudesign und lokalen Wachstumsbedingungen zu untersuchen; und, (vi) viel versprechende Anbaudesigns zu identifizieren und zukünftigen Forschungsbedarf zu erkennen, mit dem Ziel die Produktivität von Streifenmischanbau-Systemen zu steigern.

Für diese Zielsetzung wurden Feldversuche mit Streifenmischanbau von Mais (*Zea mays* L.) mit kleineren Gemüsearten, einschließlich Buschbohne (*Phaseolus vulgaris* L. var. *nana*), über drei Wachstumsperioden von 2010 bis 2012, in Südwest-Deutschland und in der Nordchinesischen Tiefebene durchgeführt. Der Anbau der Kulturen in Streifen ermöglicht den Einsatz von Maschinen, mit dem Ziel dem fortwährenden Rückgang des Mischanbaus in China, aufgrund des Mangels an Arbeitskräften in ländlichen Regionen, entgegenzuwirken. Die Kombination von Mais, einer hochgewachsenen C4-Kulturpflanze mit erektophilen Blättern, mit Buschbohne, einer kleinen, N-fixierenden C3-Kulturpflanze mit horizontaler Blattausrichtung, wurde aufgrund des großen Potentials einer komplementären Ressourcennutzung gewählt. Der Konkurrenz um Licht wurde besondere Aufmerksamkeit gewidmet, da ihr eine wesentliche Rolle in Anbausystemen von Kulturpflanzen mit großen Höhenunterschieden zukommt. In diesem Zusammenhang wurden Messungen der photosynthetisch aktiven Einstrahlung (PAR) mit hoher räumlicher (einzelne Reihen innerhalb des Streifens) und zeitlicher (im Intervall von fünf Minuten) Auflösung über dem Pflanzenbestand von Buschbohne, während einer zweimonatigen gemeinsamen Wachstumsperiode mit Mais, durchgeführt. Die erhobenen Daten bildeten die Grundlage für Simulationen zur Untersuchung der Lichtkonkurrenz und deren Einfluss auf das Pflanzenwachstum mit Modellansätzen.

Die experimentellen Ergebnisse zeigten, dass die Maiserträge in den Randreihen der Streifen, aufgrund der erhöhten lateralen Einstrahlung, in Jahren mit ausreichender Wasserversorgung, ansteigen. Im Mittel zeigten Berechnungen für Maisstreifen bestehend aus 18 bis vier Maisreihen, einen Anstieg der Erträge um 3 bis 12% und 5 bis 24% an den Versuchsstandorten in Deutschland bzw. in China. Die Analyse der Ertragskomponenten ergab, dass der Ertragsanstieg in den Randreihen der Maisstreifen vor allem durch eine höhere Anzahl an Körnern pro Pflanze bestimmt wurde. Zum anderen induzierte die Beschattung durch die benachbarten größeren Maispflanzen erhebliche Schattenadaptionen der Buschbohne, wie z.B. eine größere räumliche Ausdehnung der Pflanzen und einen beträchtlich erhöhten Blattflächenindex, durch dünnere, größere Blätter. Diese Schattenadaptionen erhöhten die Lichtaufnahme, und deuteten darauf hin, dass Buschbohne eine bis zu 30%ige Beschattung toleriert, gemessen an einer Gesamt- und Hülsen- Trockenmasse vergleichbar zu Buschbohne in Reinkultur. Aufgrund dieser Ergebnisse, kann die Buschbohne als gut geeignet für den Streifenmischanbau mit einer größeren Kulturpflanze erachtet werden. Höhere Beschattungsgrade (>40%) führten jedoch zu einer beträchtlichen Verringerung der Gesamt- und Hülsen- Trockenmasse.

Die hohe zeitliche und räumliche Auflösung der PAR-Messungen zeigten deutlich die hohe Heterogenität der PAR-Verteilung über den Tag und innerhalb des Buschbohnen-Streifens. Das entwickelte Lichtmodel simulierte diese Heterogenität mit hoher Genauigkeit, sowohl unter klaren, als auch unter bewölkten Bedingungen. Der Vergleich zwischen simulierten und beobachteten stündlichen PAR-Werten von mehrere Reihen innerhalb des Buschbohne-Streifens, resultierte in einen ‚root mean square error' (RMSE) zwischen 47 und 87 µmol m^{-2} s^{-1} und einen ‚percent bias' (PBIAS) zwischen -3.4 und 10%. Des Weiteren erfasste das Modell in nachvollziehbarer Weise den Einfluss von unterschiedlichen Breiten des Buschbohnen-Streifens, der Ausrichtung der Streifen und der Architektur der Maispflanzen (Höhe, Blattflächenindex und Verteilung der Blattstellungswinkel). Simulationen, durchgeführt für verschiedene Breitengrade und Bedeckungsgrade des Himmels, einschließlich unterschiedlicher Streifenbreiten, Höhen und Blattflächenindices (LAI) des Maises, ließen erkennen, dass: (i) eine Erhöhung der Streifenbreite die Beschattung in den Randreihen der kleineren Kulturpflanze nur an niedrigeren Breitengraden und einem hohen Anteil an direkter Einstrahlung verringert; und, (ii) an höheren Breitengraden, eine Maissorte mit geringerer Höhe und LAI geeignete Möglichkeiten darstellen, um die Lichtverfügbarkeit für die kleinere Kulturpflanze zu erhöhen.

In der vorliegenden Doktorarbeit wurde erstmalig das Pflanzenwachstumsmodell CROPGRO, welches für Reinkulturen entwickelt wurde, für die Simulation einer Leguminose in einem Mischanbausystem verwendet. Das CROPRGO-Modell wurde ausgewählt, da es eine stündliche Berechnung der Photosynthese auf Blattebene ermöglicht, und Algorithmen besitzt, die den Einfluss der Einstrahlungsintensität auf die räumliche Ausdehnung der Pflanzen und die spezifische Blattfläche berücksichtigen. CROPRGO, kalibriert mit Daten von Buschbohne in Reinkultur, konnte den Einfluss der stark verringerten Einstrahlung, in der am meisten beschatteten Buschbohnenreihe, auf Blattfläche, Gesamt- und Hülsen-Trockenmasse gut erfassen. Dies deutet auf die Anwendbarkeit des Modells in Mischanbausystemen mit hohen Beschattungsgraden hin. Unter geringeren Beschattungsgraden mussten ‚cultivar'- und ‚ecotype'-Parameter für die entsprechende Buschbohnenreihe individuell kalibriert werden, um eine hohe Genauigkeit der Simulationen zu erzielen. Simulationen des Modells konnten die Effekte gut erklären, die aus den unterschiedlichen Anteilen direkter und diffuser Einstrahlung auf die Photosynthese des Pflanzenbestandes resultieren. Dies ist ein sehr wichtiger Aspekt, der weiter untersucht werden sollte, da diffuse Einstrahlung als Teil der Lichtverteilung und Photosynthese im Allgemeinen kaum untersucht wurde, und im Speziellen, mit zunehmendem Einfluss von Beschattung wichtiger wird.

Simulationen der Lichtverfügbarkeit, des Pflanzenwachstums und der Ertragsbildung innerhalb des Maisstreifens können in vergleichbar Weise, wie für die kleinere Kulturpflanze Buschbohne beschrieben, durchgeführt werden. Anpassungen des Lichtmodells und ein geeignetes Pflanzenwachstumsmodell werden in der vorliegenden Doktorarbeit aufgeführt und diskutiert.

Schlussfolgernd zeigten die wesentlichen Ergebnisse der vorliegenden Doktorarbeit, dass die Auswahl von Sorten, angepasst an die veränderten Lichtbedingungen, das größte Potential für eine Steigerung der Produktivität von Mais und Bohne im Streifen-Mischanbau besitzt. Die wichtigsten Eigenschaften von geeigneten Maissorten sind: (i) ein hohes Potential zur Anlage von Körnern; (ii) eine hohe Wasserstress-Toleranz; und, (iii) verringerte Pflanzenhöhe und LAI. Welche Bedeutung den einzelnen Komponenten zukommt, wird durch die Schattentoleranz der benachbarten Kulturpflanze, die lokalen Wetterbedingungen und die Bewirtschaftungsweise bestimmt. Zur Optimierung der Erträge der kleineren, beschatteten Kulturpflanze, präsentieren wir zwei Möglichkeiten: (i) eine zeitliche Anpassung der gemeinsamen Wachstumsperiode der Mischanbaupartner, um die Lichtkonkurrenz während den Wachstumsstadien geringerer Schattenverträglichkeit zu reduzieren; und, (ii) das Anbaudesign räumlich anzupassen oder unterschiedliche Maissorten auszuwählen, um die Beschattung auf den Grad zu verringern, welchen die kleinere Kulturpflanze während bestimmter Wachstumsphasen toleriert. Wenn die Schattentoleranz einer Kulturpflanze während der entsprechenden Wachstumsstadien bestimmt ist, kann das entwickelte Lichtmodell zur zeitlichen und räumlichen Optimierung des Anbausystems angewendet werden.

In der vorliegenden Doktorarbeit wurde ein vielversprechender Ansatz entwickelt, der ein spezifisches Lichtmodell mit prozess-orientierten Pflanzenwachstumsmodellen für Reinkulturen verbindet. Alle in diesem Ansatz integrierten Modelle können an jedem Standort angewendet werden, und ihre generische Art ermöglicht die Eingliederung anderer Kulturpflanzen. Diese Eigenschaften stellen einen sehr wertvollen Beitrag zur Mischanbau-Forschung dar, da dessen zukünftige Optimierung in großem Maße von der Effizienz der Forschungsbemühungen abhängen wird, in Anbetracht der: (i) Komplexität der produktivitätsbestimmenden Prozesse; und, (ii) der geringere, in die Mischanbau-Forschung, investierte Anteil an Geld und

Zeit. Die Mischanbau-Forschung muss verhindern das Rad neu zu erfinden, in dem mit dem Anbau in Reinkultur gemeinsame und bereits untersuchte Aspekte erkannt werden und der Fokus auf dem Mischanbau eigene Aspekte gelegt wird.

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