Institute of Crop Science (340)
University of Hohenheim
Specific Field: Agronomy
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Grasping the complexity of intercropping – developing and testing an integrated decision support system for vegetable production in the North China Plain

Dissertation
in fulfillment of the requirements for the degree
“Doktor der Agrarwissenschaften”
(Dr. sc. agr. / Ph. D. in Agricultural Sciences)

submitted to the
Faculty of Agricultural Sciences
of the University of Hohenheim

by
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born in Würzburg

August 2010

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LIST OF ABBREVIATIONS AND ACRONYMS

ANOVA:	Analysis of Variance
ATPM:	Average temperature since previous measurement
CAU:	China Agricultural University
CC:	Chinese cabbage
CERES:	Crop-Environment Resource Synthesis
CO_2:	Carbon dioxide
CRHSY:	China Rural Household Survey Yearbook
CSY:	China Statistical Yearbook
cm:	Centimeter
cv.:	Cultivar
d:	Day
DAP:	Daily average temperature
DESTATIS:	Federal Statistical Office of Germany
DFG:	German Research Foundation
DM:	Dry matter
DSSAT:	Decision Support System for Agrotechnology Transfer
DUL:	Drained upper limit of available soil water
eds.:	Editors
e.g.:	For example
eqn.:	Equation
et al.:	Et alii (and others)
etc.:	Et cetera
Exp.:	Experiment

FAOSTAT:	Food and Agricultural Organization of the United Nations Statistical Databases
Fig.:	Figure
Fp:	Farmer’s practice
g:	Gram
GDD:	Growing degree days
GIS:	Geographic Information System
GLM:	General linear model
GRK:	Graduiertenkolleg
ha:	Hectare
HI:	Harvest Index
HSY:	Hebei Statistical Yearbook
IDW:	Inverse distance weighting
IRTG:	International Research Training Group
K:	Kelvin
kg:	Kilogram
km:	Kilometer
km^2:	Square kilometer
LAI:	Leaf area index
LAR_{max}:	Maximum leaf appearance rate
LAR:	Leaf appearance rate
LL:	Lower limit of soil water
ln:	Natural logarithm
m:	Meter
m^2:	Square meter

mm:	millimeter
MJ:	Mega Joule
MLAR:	Mean leaf appearance rate
MRGR:	Mean relative growth rate
N:	Nitrogen
NCP:	North China Plain
PAR:	Photosynthetically active radiation
Prcp.:	Precipitation
r^2:	Coefficient of determination
RGR:	Relative growth rate
RMSE:	Root mean square error
SAS:	Statistical Analysis Software
SAT:	Saturated limit of available soil water
SC:	Sweet corn
S.D.:	Standard deviation
SLA:	Specific leaf area
SM:	Spring maize
SSE:	Sum of squared errors
t:	Ton
TDM:	Total (above ground) dry matter
Temp.:	Temperature
T_b:	Base temperature
T_c:	Ceiling temperature
T_{o1}:	Lower optimum temperature

T_{o2}:	Upper optimum temperature
T_{opt}:	Optimum temperature
USDA:	United States Department of Agriculture
var.:	Variety
vs.:	Versus
WRB:	World reference base
z.B.:	Zum Beispiel
°C:	Degree Celsius
°E:	Degree East
°N:	Degree North
%:	Percent

1 General introduction

The situation in China

In the last two decades a change in paradigm in China's agricultural policy can be observed. After the years of hunger and famine end of the 1950s (Harms, 1996), food security became the major issue of agricultural policy in China. Production of staple crops was given highest priority to ensure a sufficient food supply to the urban centers. With the beginning of the market reforms, end of the 1970s the efforts became even more successful. Since 1978, yields of the major grain crops rice, wheat and maize nearly doubled in China (Fig. 1).

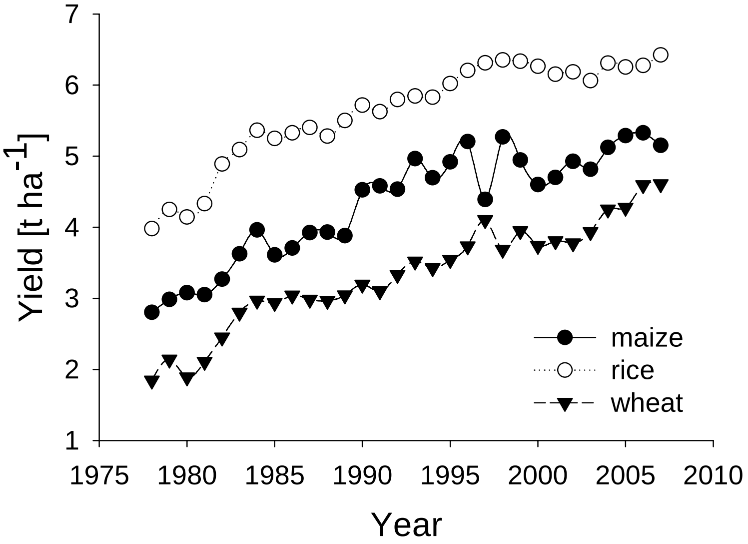

Fig. 1. Yields of the major grain crops of China (Source: FAOSTAT, 2008).

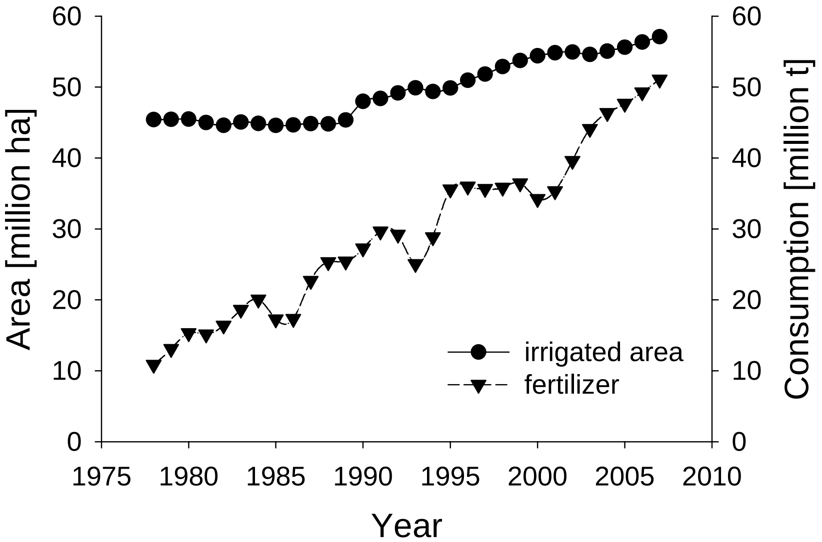

Fig. 2. Area under irrigation and consumption of fertilizer in China (Source: FAOSTAT, 2008).

However, when looking at the amount of fertilizer, pesticides, and the area under irrigation, a similarly rapid increase could be observed (Fig. 2). It becomes obvious that a great share of the yield increases was solely based on the **increase of agricultural inputs**. Overuse of pesticides, along with unbalanced fertilization and irrigation caused severe environmental degradation (Ju et al., 2006). Hence, in rapidly developing China loss of arable land through the expansion of residential and industrial areas, and the construction of infrastructure was enormous. However, this loss only plays a minor role compared to the land loss caused by unsustainable agricultural practices (Brown, 1995; Chen et al., 2007). Soil erosion and salinisation, along with declining ground and surface water resources endanger the production base for future generations. The severe environmental problems coming to light all over the country force China to take political action. As a result, sustainable agriculture became a major issue, as it was taken up in the country's "eleventh five year plan". In the middle of the last century severe poverty and hunger in rural China obliged politicians to ensure short term food security. However, in the last decades aggravating environmental degradation made politicians and society realize the importance of long-term food security. This change in paradigm, from short-term to long-term food security, was not at least enabled by the positive economic development and unprecedented alleviation of poverty in rural China in the last decades. For the first time since the years of hunger, people's wellbeing reached a level that allowed a critical broadening of the view, and including the succeeding generations into the issue of food security.

One important policy measure, that strongly contributed to rural development and helped to increase farmers' incomes, was the abolishment of the grain procurement quota. Until the end of the agricultural reformation, which lasted from 1979 until 1997, farmers were obliged to deliver a certain amount of grain to the government at a predefined price. Within the transformation, land use rights returned to farmers and price liberalization took place (Huang, 1998). This led to an enormous increase in production of high value crops like fruits and vegetables. Production of vegetables more then doubled from 1990 until 2005. Production of cabbages even increased fourfold, while at the same time stagnation in production of cereals was observed (Fig. 3).

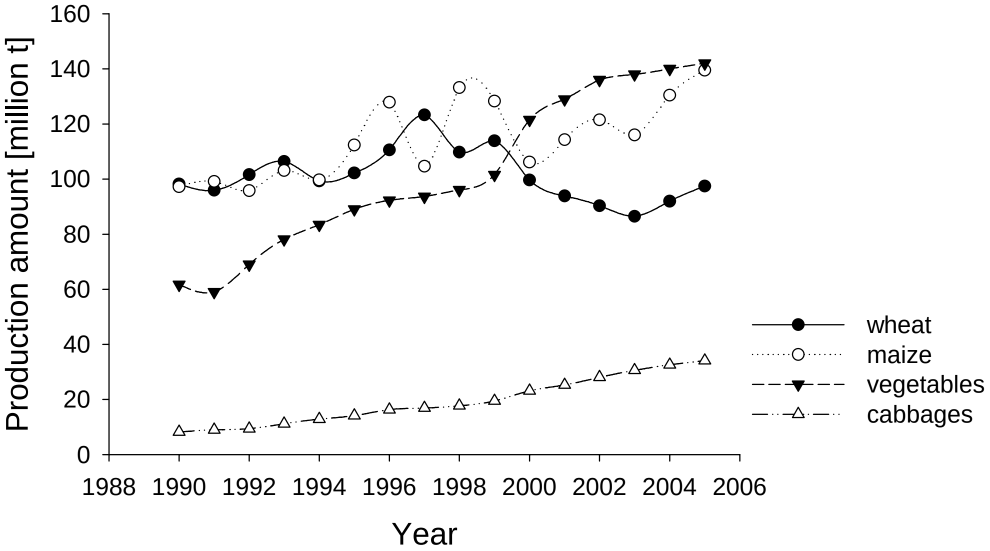

Fig. 3. Production amount of major grain crops, vegetables and cabbages (Source: FAOSTAT, 2008).

On one side **production of vegetables** plays an important role in reducing the ever widening rural-urban income gap in China. On the other side, vegetables demand high inputs of agrochemicals, which additionally exacerbate the environmental load caused by agricultural production. Chen (2003) surveyed vegetable production systems in the Beijing region and identified dramatic levels of over-fertilization. Especially nitrogen and phosphorus fertilization levels were far above the demand. Another survey conducted in Shandong province in 1997 and 1998 revealed much higher fertilization rates in vegetable production compared to wheat and maize production (Ma, 1999). For protected vegetable production average values were above 1500 kg N ha^{-1} $year^{-1}$. Such extreme fertilization levels not only lead to health hazardous concentrations of nitrogen in the final vegetable product (Zhong et al., 2002), and leaching of nutrients into ground water (Ju et al., 2006). Also the profitability of production was impaired. The development of input saving and more sustainable vegetable production systems is therefore urgently needed. Even a small increase in resource use efficiency can make a big difference on large scale. The potential impact related to reduction of inputs in vegetable production systems in China becomes obvious when comparing the share in world vegetable production of China and Germany (Fig. 4).

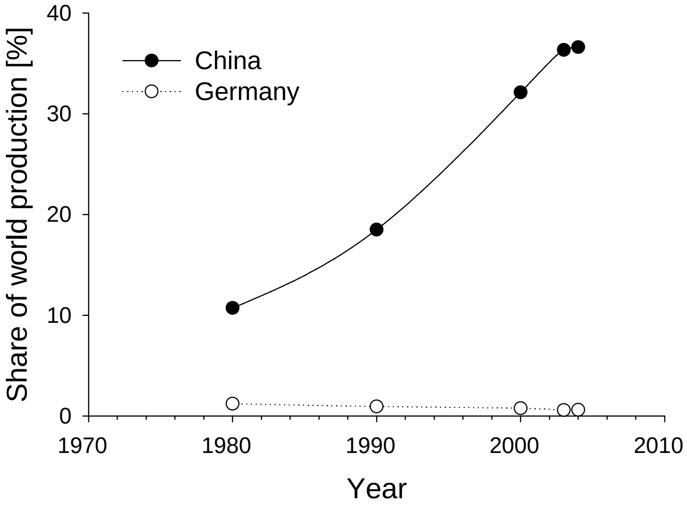

Fig. 4. Share of world vegetable production of China and Germany from 1980 to 2004 (Source: FAOSTAT, 2008).

The above described environmental degradation aggravates in the **North China Plain** (NCP), which is one of the most important agricultural regions of China, characterized by highly intensive production systems. It is East Asia's largest alluvial plain comprising approximately 300.000 km^2. The NCP lies in the eastern part of China between 32° to 40° N latitude and 100° to 120° E longitude. Approximately one fifth of China's total food is produced in the region (Zhang et al., 2004). The climate is a continental monsoon climate with precipitation accumulating in summer from July to September. Average yearly rainfall is 450-900 mm at an average yearly temperature of 11°C to 16 °C (China Meteorological Administration, 2007). To identify possibilities for a more sustainable resource use in the region, the **International Research Training Group** (IRTG) was initiated between University of Hohenheim and the China Agricultural University. The program entitled "Modeling Material Flows and Production Systems for Sustainable Resource Use in the North China Plain" was launched in 2004 and will last until 2013. The main objective of the project is the "quantification and multi-level assessment of material flows as consequence of changes in cropping systems in the North China Plain". Multi level modeling approaches shall help to identify, understand and explain interactions to contribute to the development of high yielding agricultural systems with small environmental impact. Altogether 11 subprojects of various scientific disciplines are involved. Chinese and German scientists work together on topics ranging from the management of soil organic matter, development of a decision support system for weed management, to property rights and access to credit in the study region. More information can be found at http://rtgchina.uni-hohenheim.de. The research project was co-founded by the German Research Foundation (DFG) [GRK 1070] and the Ministry of Education (MOE) of the People's Republic of China. The present research work was realized under the frame of the subproject 2.1: "Design, modeling and evaluation of improved cropping strategies and multi-level interactions in mixed cropping systems in the North China Plain".

The subproject specially deals with the fact that the admirable increases in yields and production, and the consequential positive impact on rural development in China are slowing down in recent years. It becomes obvious that the successes realized through input driven yield increases come to a hold. Input levels reached the upper limit already far before. To maintain a sensible level of prosperity, which has been the key factor for the creation of the "和谐社会" (harmonious society) and ensured peace and stability, alternative ways to increase yields have to be identified and developed.

Potential and complexity of intercropping

A production system that has strong potential to contribute to increasing yields and maintaining them at high levels is **intercropping**. The simultaneous cultivation of two or more crops in the same field is a traditional production system in China (Li et al., 2001). Differences in morphological, physiological and phenological traits between the two companion crops often enable a better utilization of available growth factors (Rodrigo et al., 2001; Willey, 1990). Thus a higher land use efficiency (Dhima et al., 2007; Zhang et al., 2007), is realized by a more efficient use of water (Mandal et al., 1996; Morris and Garrity, 1993; Reddy and Willey, 1981; Walker and Ogindo, 2003), nutrients (Benites et al., 1993; Li et al., 2001; Rowe et al., 2005) and solar radiation (Awal et al., 2006; Tsubo et al., 2001). When comparing yield levels of intercropping systems to their monocropping equivalents increased yields were observed in maize-peanut (Awal et al., 2006), maize-bean (Tsubo and Walker, 2002), wheat-cotton (Zhang et al., 2007), wheat-maize (Li et al., 2001), and wheat-chickpea (Mandal et al., 1996) systems. Additionally weed and pest pressure can be reduced (Haugaard-Nielsen et al., 2001, Liebmann and Dyck, 1993), and erosion controlled due to a better soil cover (Vandermeer, 1989).

However, it takes comprehensive understanding, knowledge and experience to grasp its **complexity** and make an intercropping system produce high yields. While managing conventional monocropping systems, the growth conditions of a single crop have to be optimized. In an intercrop the situation becomes a lot more complex. First of all, the requirements of two different crops have to be accounted for. Nutrient demand, soil water conditions, and availability of light have to be sufficient for growth and development of both companion crops. Additionally, a tolerable degree of competition has to be managed to facilitate an increased resource capture. In that context the farmer has various options to optimize a system adapted to his local soil and climatic conditions. After identifying two suitable cropping partners, the design and management of the system will greatly decide its success. Influential factors are morphological, physiological, and phenological characteristics of the selected cultivars, the spatial arrangements between and within the two crops, as well as the fertilization, irrigation, weed, pest and other management strategies. The two crops influence each other below and above ground, which leads to a change in micro-climate and other environmental factors (Fig. 5). Those changes in the environment will again feed-back on the crops' growth conditions, and create a highly complex effect-response-cycle.

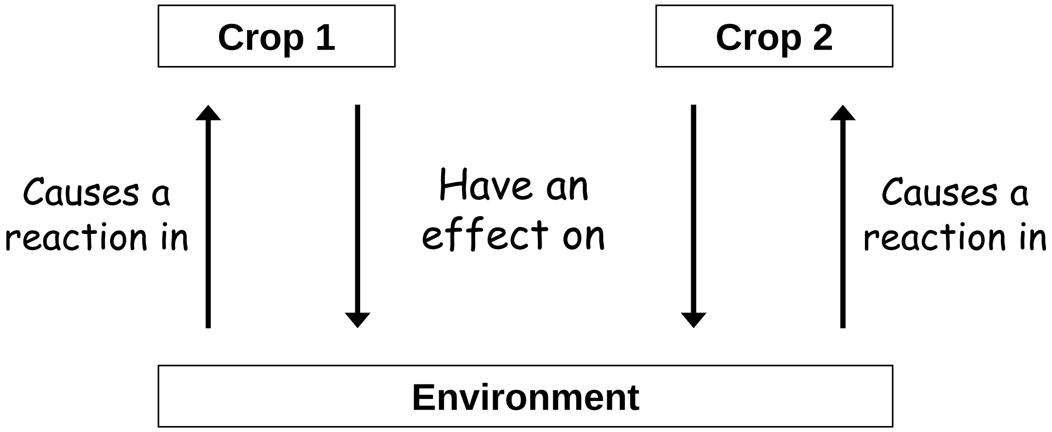

Fig. 5. Effect-response relationships in an intercropping system (Source: Vandermeer, 1989. adapted and modified).

For the present Ph.D. study **Chinese cabbage** (*Brassica rapa* ssp. *pekinensis*) and **maize** (*Zea mays* L.) were selected as companion crops. As described above, the great potential of intercropping, both from an agronomic and environmental point of view, lies in its improved resource capture. Mixed cultivation of two closely related species e.g. sorghum (*Sorghum bicolo*r) and sugar cane (*Saccharum officinarum*) will hardly result in an increased capture of soil water, soil nutrients and solar radiation compared to their monocropping equivalents. Additionally, there is a high risk of susceptibility to the same pests and diseases, and the analogical morphology and growth character cannot contribute to an improved soil cover and erosion control. Therefore, the combination of two **crops** that differ in **physiological, phenological** and **morphological characteristics** is much more promising with regard to resource use efficiency and realization of high yield levels. Additionally the risk of complete crop failure can be minimized (Vandermeer, 1989). Maize and Chinese cabbage constitute two crops that differ in almost any above mentioned respect (Table 1).

Table 1. Overview of physiological, phenological and morphological differences between maize and Chinese cabbage.

Plant characteristic	Trait	Maize	Chinese cabbage
Carbon cycle	Physiological	C4	C3
Harvest product	Phenological	Generative (seeds)	Vegetative (leaves)
Height	Morphological	Tall	Small
Rooting system	Morphological	Deep	Shallow
Cotyledons	Various	Monocot	Dicot
Canopy structure	Morphological	Erectophile	Planophile

The two crops were additionally selected as they are of highest agronomic and economic importance in the NCP (CSY, 2008; Chen, 2003). Furthermore the intercropping of maize and Chinese cabbage in rows is a traditional and still popular way to realize the production of the two crops on the same land in one year in the NCP. Beginning to middle of August, farmers transplant seedlings of Chinese cabbage between the rows of spring maize. At the point of harvest of spring maize about a month later, the Chinese cabbage crop is already completely established and creates a satisfying yield.

Crop simulation models

To understand and describe complexity in agricultural production systems, **process-oriented crop simulation models** are a valuable tool. The ever increasing demand for information in the agricultural sector can hardly be satisfied by pure conventional field experimentation. Computer simulation models constitute a powerful and inexpensive tool to describe plant growth processes, and the interactions with the environment. Especially the possibility to test a wide range of management options is an important feature. The CROPGRO model is a generic model that simulates the soil-plant-atmosphere system. It is based on the SOYGRO (Wilkerson et. al., 1983), BEANGRO (Hoogenboom et al., 1994) and PNUTGRO (Boote et al., 1987) models, which had been developed since the beginning of the 1980s. The generic character of CROPGRO enabled its adaptation to various types of crops, like tomato (*Lycopersicon esculentum* L.; Scholberg et al., 1997), chickpea (*Cicer arietum* L.; Singh and Virmani, 1994) or the forage grass *Brachiaria decumbens* (Giraldo et al., 2001). CROPGRO is part of the Decision Support System of Agrotechnology Transfer (DSSAT), which includes a range of other crop models and simulates a total of 28 crops (Jones, et al. 2003). By linking the different crop models, crop rotations and consecutive cropping seasons can be simulated (Thornton et al. 1997, Singh et al. 1999). DSSAT is one of the most widely used crop simulation models in the world. Its applications range from fertilizer management (Gabrielle et al., 1998; Hodges, 1998), irrigation management (Gerdes et al., 1994) and variety evaluation (Brisson et al., 1989), to yield forecasting and climate change studies (Alexandrov and Hoogenboom, 2001; Saarikko, 2000). A more detailed introduction to the structure of CROPGRO can also be found in the third article below.

However, to make a model a reliable **decision support tool** and enable the prediction of crops' behavior under different soil and climate conditions, accurate parameterization and testing of the model is needed. Therefore field experimentation over several years and locations is required to reliably develop and test the model for a new species and/or management option. Additionally the testing of crops' behavior under controlled environments has shown to be an important asset for accurately parameterizing plant growth and development (Grimm et al., 1994; Hoogenboom et al. 1994).

The simulations of CROPGRO model constitute the core part within the newly developed **integrated decision support system** (IDSS). The decision support system integrates the findings of the survey (first and second article), and final model predictions are linked to a geographic information system (GIS) to regionalize the results over the entire NCP (sixth article). A detailed description of the IDSS is illustrated in Fig. 13.

2 Greenhouse experiments and field experiments

To enable the simulation of growth and development of Chinese cabbage, the CROPGRO model had to be adapted to Chinese cabbage. In addition to the field experiments, described below, crop growth parameters were collected under semi-controlled conditions. Two nearly identical **greenhouse experiments** were conducted to determine the effect of temperature on growth and development of Chinese cabbage. Both experiments were conducted in the 'Klimatron' at the horticulture research station of Hohenheim University, Germany (48°42'42 N, 9°11'57 E). The experiments were run in autumn 2007 and spring 2008. Four temperature treatments were applied: two greenhouse chambers with semi-controlled environments, one ambient greenhouse chamber (two sides of the greenhouse chamber are open) and one open field treatment. Temperature was controlled through active warming and passive cooling in the greenhouse chambers to realize the intended temperature difference of 4 °C between the different intended treatments. To account for cultivar specific differences within Chinese cabbage varieties, three cultivars were tested in both experiments, namely cv. 'Beijing No.3' and cv. 'Kasumi' in both experiments, and cv. 'Qiulu 75' and cv. 'Spring Sun' in 2007 and 2008 respectively. The design was a split-plot design with three replications. Temperature treatment constituted the main-plot and cultivar the sub-plot. The arrangement of the different cultivars within the main-plot is illustrated in Fig. 6.

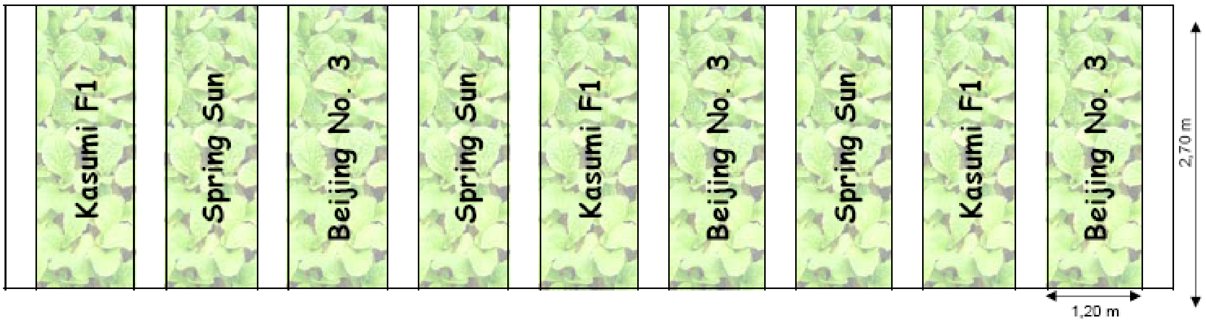

Fig. 5. Overview of experimental design of one treatment of the spring experiment (Source: Nerlich, 2009).

Fig. 6. University of Hohenheim's Klimatron and the Chinese cabbage cultivated in the different greenhouse chambers in autumn 2007.

Plant samples were taken in seven to 20 days intervals in both experiments. Per measurement five plants per treatment and replication were destructively measured. The measurements included number of outer leaves and number of head leaves, height and diameter of plant and head, stem length, as well as fresh and dry weight of all above ground plant parts (leaves, stem and head). Additionally leaf area index was determined destructively using a LI-3100 Area Meter (LI-COR, Lincoln, Nebraska, USA).

Climate data collection was automated. Data was measured one meter above the soil surface in all treatments and logged in 12 minutes intervals, including photosynthetically active radiation (PAR), CO_2 concentration and ambient air temperature.

In total four **field experiments** were conducted as part of the Ph.D. study (Table 2). In all experiments wide strips of Chinese cabbage were planted next to wide strips of sweet corn or spring maize to determine inter-specific effects between the two crops (Fig. 7). Plant and microclimate measurements were conducted in certain distance to the neighboring crop. In this way cause and effect relationships within the system could be quantified.

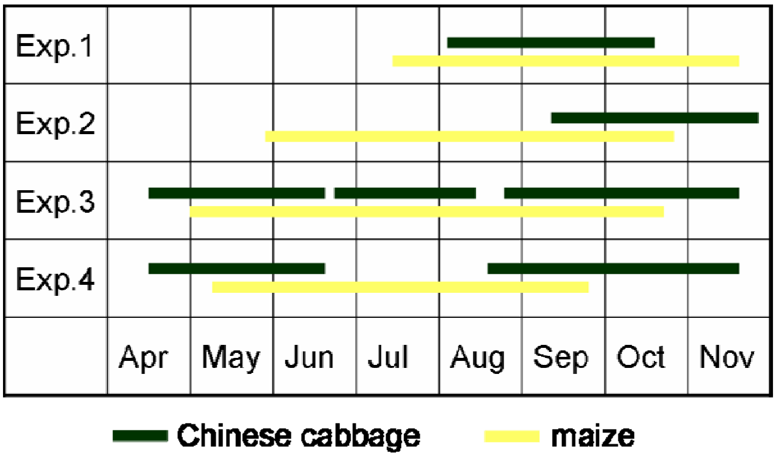

Fig. 7. Cropping calendar of the four field experiments in Germany and in China.

Table 2. Overview of spring maize (SM), sweet corn (SC) and Chinese cabbage (CC) cultivars used in the four experiments.

Experiment	Set	Year	Location	CC cultivar	SM/SC cultivar	Season
1	1	2008	Uni Hohenheim	Kasumi	Golden Nugget (SC)	Summer
2	1	2008	Ihinger Hof	Yuki	Golden Nugget (SC)	Autumn
3	1	2009	Ihinger Hof	Spring Sun	Companero (SM)	Spring
	2	2009	Ihinger Hof	Kasumi	Companero (SM)	Summer
	3	2009	Ihinger Hof	Beijjng No.3	Companero (SM)	Autumn
4	1	2008	Quzhou	Spring Sun	Xian Yu 335 (SM)	Spring
	2	2008	Quzhou	Beijjng No.3	Xian Yu 335 (SM)	Autumn
	1	2009	Quzhou	Spring Sun	Xian Yu 335 (SM)	Spring
	2	2009	Quzhou	Beijjng No.3	Xian Yu 335 (SM)	Autumn

The first experiment (Exp.1) was conducted at the research station for horticulture of Hohenheim University (48°42’43” N, 9°11’56“ E, 389 m.s.l.), southwest Germany in late summer 2008. The soil was a loess-derived luvisol (WRB). Average yearly rainfall is 697 mm with an average temperature of 8.8 °C. One set of Chinese cabbage was planted end of July next to sweet corn. The second and third experiment (Exp.2 and Exp.3) were performed approximately 20 km west of Exp.1 at Hohenheim University’s research station Ihinger Hof (48º44’39” N, 8º55’10” E, 484 m.s.l.) in 2008 and 2009 (Fig. 8). The average rainfall per year is 690 mm with an average temperature of 7.9 °C. The soil was a keuper with loess layers. In Exp.2 one set of Chinese cabbage (cv. Yuki) was planted end of August next to sweet corn. In Exp.3 three consecutive sets of Chinese cabbage were planted. Three different cultivars, which are adapted to the specific seasons, were used. For all plantings transplants were used, which were obtained from a local vegetable seedling producer. Before planting 160 kg N ha^{-1} were applied as Calcium Ammonium Nitrate for every set of Chinese cabbage in all three experiments. If natural precipitation did not occur soon after transplanting, Chinese cabbage was irrigated according to demand in the first two weeks after planting. The alternating strips of maize and Chinese cabbage did not allow randomization in the first three experiments (Fig. 9). However, four replications were realized.

Fig. 9. Chinese cabbage between strips of sweet corn (left) and strips of maize (right) in Exp.2 and Exp.3, respectively.

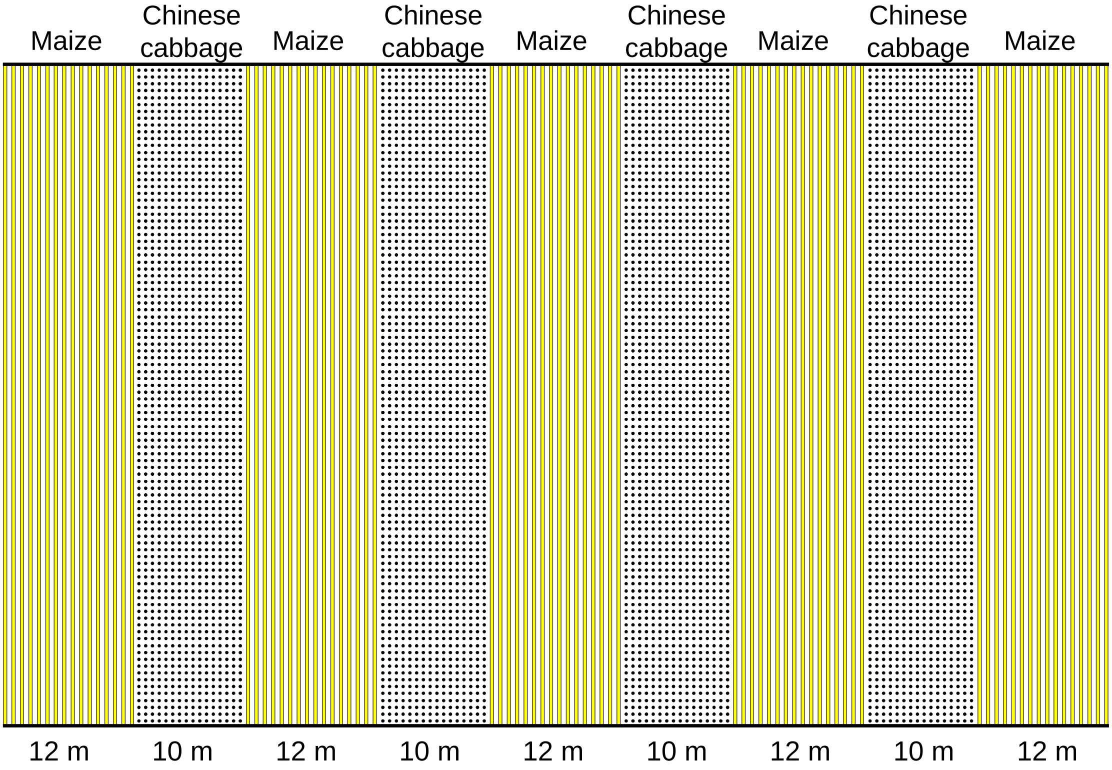

Fig. 10. Experimental design of Exp.3 at Ihinger Hof. The designs of Exp.1 and Exp.2 were similar, with slightly different strip width and length.

The fourth experiment (Exp.4) was conducted in the southern part of Hebei province, China in 2008 and 2009. The Quzhou experimental station of the China Agricultural University is located 36°52’21” N latitude and 115°01’05“ E latitude at an altitude of 36 meters above sea level. Average annual rainfall is 416 mm with an average temperature of 14.3 °C. The soil is a calcaric fluvisol (WRB). In both years two sets of Chinese cabbage were planted next to spring maize in spring and autumn. Very high temperatures of frequently above 35 °C impede the production of Chinese cabbage between middle of June and beginning of August. For spring planting transplants were used, which were produced by a local vegetable seedling producer. For the autumn plantings seeds were directly sown into the field. According to local practice, phosphorus and potassium were applied additionally to nitrogen fertilization. For all sets of Chinese cabbage compound fertilizer (15-5-15) was applied at a rate of 800 kg ha^{-1} before planting and 400 kg ha^{-1} before canopy closure. As rainfall concentrates on the summer months, additional irrigation was necessary to ensure plant growth, both in spring maize and Chinese cabbage. To test the potential for water saving under strip intercropping conditions two irrigation strategies were applied: “Farmer’s practice” and “Farmer’s practice -20%” (-30% in 2009). The design was a completely randomized block design (Fig. 11).

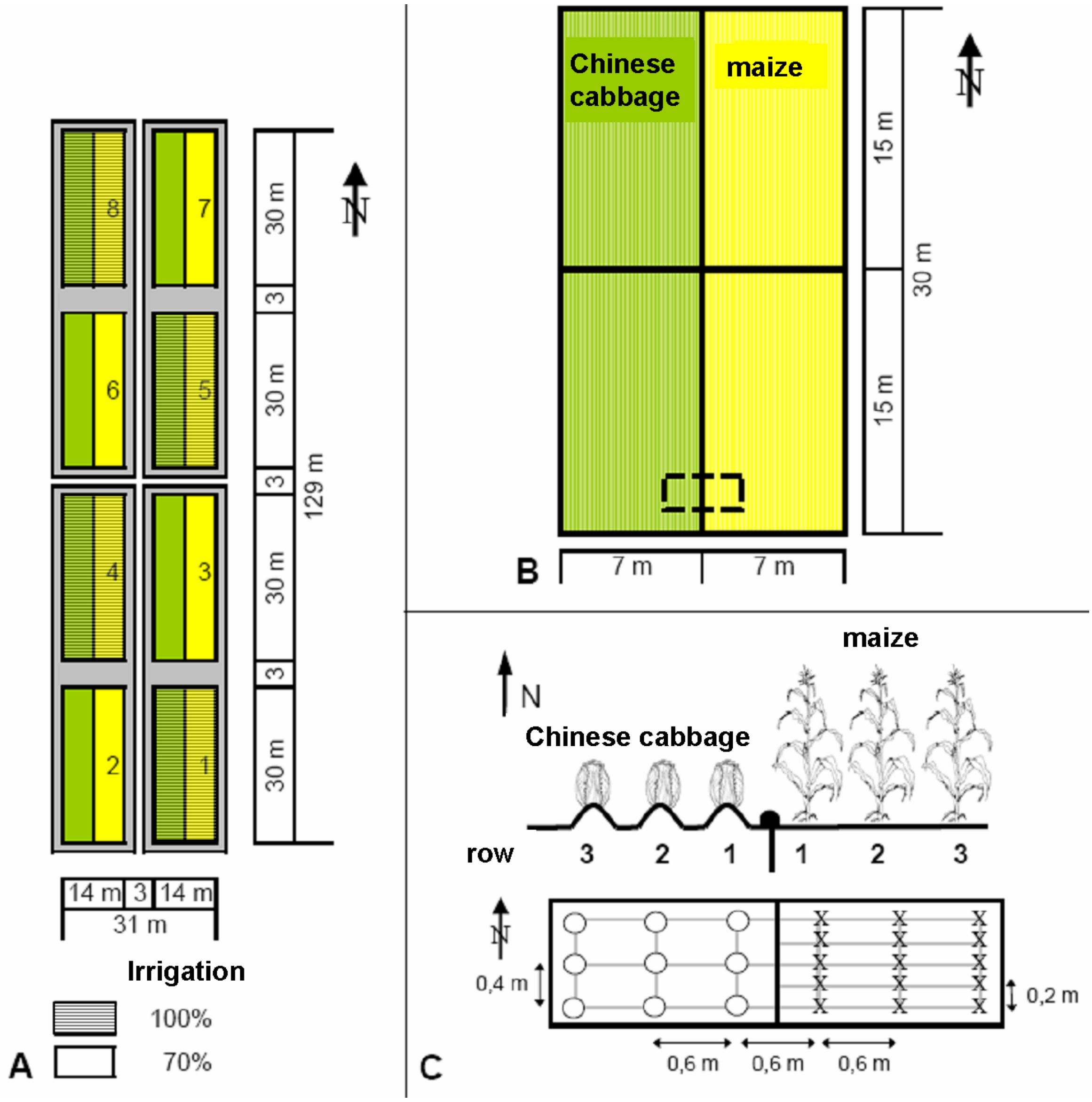

Fig. 11. Overview of the entire experimental design of Exp.4 (A), a single plot with irrigation dams (B) and the arrangement of the plants within the plots (C) (Source: Müller, A., 2009; adapted and modified).

Plant samples were taken in two to four weeks intervals in the respective experiments. Destructive measurements were conducted in two consecutive days in Chinese cabbage and maize. Hence, a good linkage between the results obtained from the intercropped crops was possible. For Chinese cabbage the destructive measurements were identical to the measurements in the greenhouse experiment described above. Each row constituted one treatment, of which three plants were harvested. For the final harvest date the amount of examined plants was doubled. In maize the destructive plant measurements included plant height, number of leaves, number of cobs, seed number, and fresh and dry matter of all plant parts. Again leaf area index was determined destructively using the LI-3100 Area Meter (LI-COR, Lincoln, Nebraska, USA). Five plants were measured per treatment and replication, with the double amount examined at final harvest. Additionally to the destructive measurements, plant height (and diameter in CC), leaf number and phenological stages were determined on a weekly basis.

In all experiments, daily maximum and minimum temperature, precipitation and solar radiation were measured at standard weather stations located at most 300 meters from the experimental sites. An overview of the differences in incoming radiation between Germany and China is presented in Fig. 12.

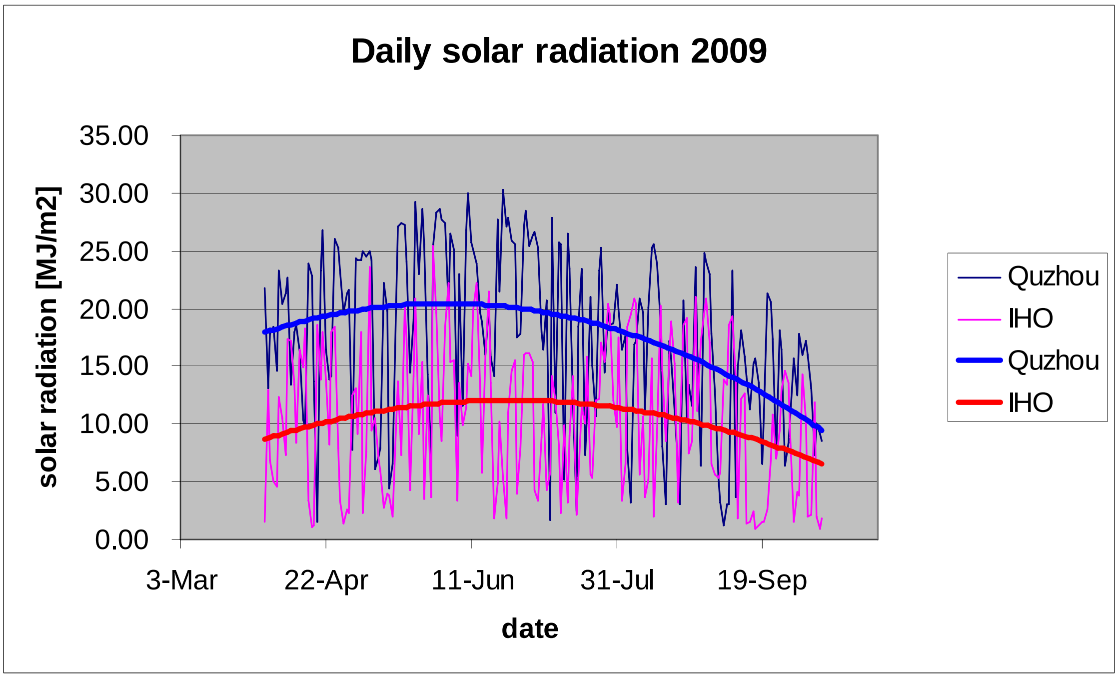

Fig. 12. Comparison of incoming radiation at the experiment sites in Germany (IHO) and China (Quzhou) in 2009. The thin lines represent the daily values; the thick lines the polynomial regression fit to the daily values.

3 Objectives and outline

The main objectives of the present study were to assess the status quo of vegetable intercropping systems in the NCP, and to develop a methodology to enable the testing of the production potential of vegetable intercropping systems by the use of greenhouse experiments, field experiments, crop models and a geographic information system (GIS). The overall goal of the thesis was to accomplish an integrated decision support system (IDSS) for vegetable production systems in the NCP. An overview of the conceptual framework of the IDSS is illustrated in Fig. 13.

The specific objectives of the Ph.D. thesis were to:

1. detect and describe vegetable intercropping systems practiced by farmers in the NCP, understand their production techniques as well as underlying motives and concepts,
2. elaborate how to adjust the traditional systems to fit the rapidly changing socio-economic and socio-technical frame conditions in rural China,
3. accurately parameterize Chinese cabbage based on greenhouse experiments for its integration as a new crop into the CROPGRO simulation model,
4. test the validity of the model based on field experiment data,
5. develop a methodology to quantify resource competition (light) in a Chinese cabbage/maize intercropping system,
6. determine the production potential of Chinese cabbage under conventional and intercropping conditions based on model simulations by linking the results to a GIS to regionalize them over the entire NCP.

To accomplish the described objectives, an integrative research approach was applied. Due to the complete lack of literature on vegetable intercropping systems in China, a qualitative inquiry was conducted in the North China Plain. Starting in autumn 2007 researchers, extension workers and farmers were interviewed to assess the status quo of vegetable intercropping systems in the region. The **first article** (*Renewable Agriculture and Food Systems*, published) presents common vegetable intercropping systems practiced by farmers. Furthermore underlying motives and concepts, as well as knowledge transfer with respect to intercropping were revealed.

The changes in the socio-economic and socio-technical frame-conditions for farmers in the NCP were analyzed in the **second article** (*IFSA 2010*, published). It was shown that the rapid structural changes seriously endanger the traditional intercropping systems. Two strategies were developed that might help to overcome the problem and make intercropping a viable production system for the future. The use of crop simulation models was regarded as a crucial part in improving intercropping systems.

To enable the simulation of Chinese cabbage under monocropping and intercropping conditions, its integration into the CROPGRO model had to be accomplished. In the **third article** (*Agronomy Journal*, submitted) the first and most crucial step, the determination of temperature response was described. Using the results of the greenhouse and field experiments, cardinal temperatures were identified, which were then used to define the phenology model of Chinese cabbage in CROPGRO.

The development and testing of the model is the topic of the **fourth article** (*Agronomy Journal*, submitted). Including information of published sources, plant growth parameters were determined for two Chinese cabbage cultivars. The validated model was then used in a sensitivity analysis to test different fertilization and irrigation levels and describe the possibility of late sowing of Chinese cabbage in southern Hebei, China.

The **fifth article** (*GIL 2010*, published) describes the methodological approach to determine available radiation in Chinese cabbage strips, being intercropped with maize. Based on the point data obtained over the course of the day by measurements with handheld PAR-meters, the share of total daily available radiation can be calculated for any place within the strip. Refining the presented method allowed the estimation of light competition in Chinese cabbage strips of different width.

The estimated shares of available radiation constituted the basis for the simulations presented in the **sixth article** (*Agronomy Journal*, submitted). Modeling the potential production of strip intercropped Chinese cabbage was conducted using long-term weather data of 12 meteorological stations combined with five prevailing soil texture types of the North China Plain. The results were finally linked to a geographic information system.

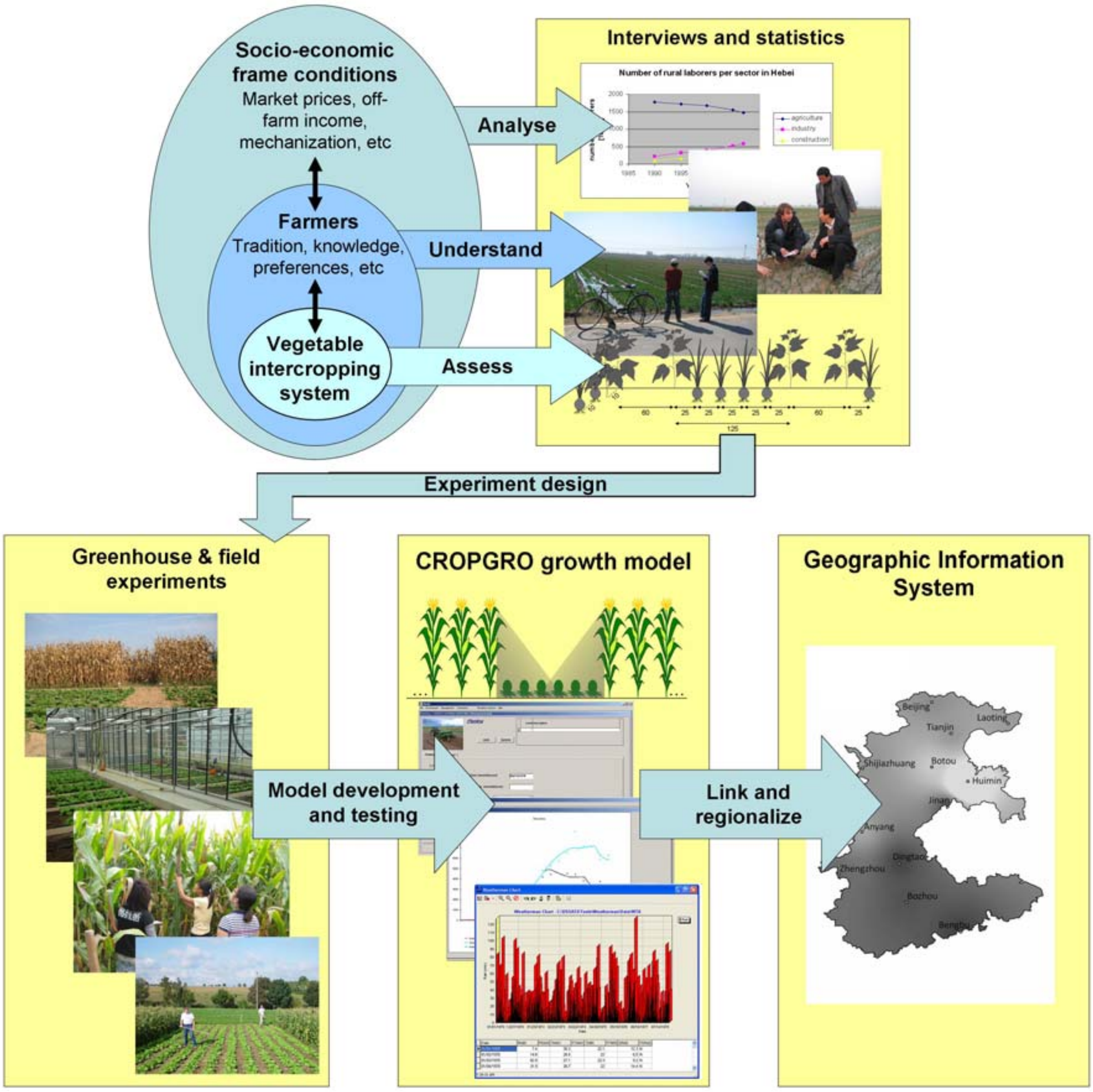

Fig. 13. Conceptual framework of the integrated decision support system developed within the frame of the thesis.

4 Publications

The cumulative thesis consists of six published, accepted or submitted papers. Publication I, III, IV and VI were published, or submitted to international high standard referenced journals. Publications II and V were peer-reviewed and published in conference proceedings. For citation of the publications I, II and V please use the references given below. Due to copyright issues only abstracts of these three publications can be presented in the present version of the thesis; the full papers can be accessed via the presented links.

PUBLICATION I

Feike, T., Q. Chen, S. Graeff-Hönninger, J. Pfenning, and W. Claupein. 2010. Farmer-developed vegetable intercropping systems in southern Hebei, China. Renewable Agriculture and Food Systems 25(4):272-280. doi: 10.1017/S1742170510000293 (published).

PUBLICATION II

Feike, T., Q. Chen, J. Pfenning, S. Graeff-Hönninger, G. Zühlke, and W. Claupein. 2010. How to overcome the slow death of intercropping in China. In: Darnhofer, I. and Grötzer, M. (eds.): Building sustainable rural futures. Proceedings of the 9th European IFSA Symposium, pp. 2149-2158. ISBN: 978-3-200-01908-9 (published).

PUBLICATION III

Feike, T., J. Pfenning, S. Graeff-Hönninger, Q. Chen, and W. Claupein. 2010. Adaptation of CROPGRO to Chinese cabbage I. Estimation of cardinal temperatures. Agronomy Journal (submitted).

PUBLICATION IV

Feike, T., Q. Chen, S. Graeff-Hönninger, J. and W. Claupein. 2010. Adaptation of CROPGRO to Chinese cabbage II. Model development and testing. Agronomy Journal (submitted).

PUBLICATION V

Feike, T., S. Munz, S. Graeff-Hönninger, Q. Chen, J. Pfenning, G. Zühlke, and W. Claupein. 2010. Light competition in Chinese cabbage/maize strip intercropping systems. GI-Edition - Lecture Notes in Informatics (LNI) "Precision Agriculture Reloaded – Informationsgestützte Landwirtschaft", pp. 65-68 (published).

PUBLICATION VI

Feike, T., Q. Chen, S. Graeff-Hönninger, Y. Pan and W. Claupein. 2010. Production potential of strip intercropped Chinese cabbage in the North China Plain. Agronomy Journal (submitted).

5 Farmer-developed vegetable intercropping systems in southern Hebei, China

Publication I

Feike, T., Q. Chen, S. Graeff-Hönninger, J. Pfenning, and W. Claupein. 2010. Farmer-developed vegetable intercropping systems in southern Hebei, China. Renewable Agriculture and Food Systems 25(4):272-280. doi: 10.1017/S1742170510000293 (published).
http://journals.cambridge.org/action/displayFulltext?type=6&fid=7911812&jid=RAF&volumeId=25&issueId=04&aid=7911811&bodyId=&membershipNumber=&societyETOCSession=&fulltextType=RA&fileId=S1742170510000293#cjofig_fig003

The survey, which constitutes the data base of the ***first paper,*** *was conducted to put the research work of the entire Ph.D. thesis on a solid foundation. Agricultural research often faces the problem of being disconnected from the realities farmers and rural communities are facing. The extensive travels throughout the North China Plain, and the intense discussions with senior researchers, rural extension agents and especially farmers allowed valuable insights, which greatly contributed to a comprehensive understanding of the actual situation of farming systems in the region in general, and vegetable intercropping in specific.*

Abstract

In the last decades production of vegetables has steadily increased in China. As vegetable production often has higher input requirements with regard to irrigation water, fertilizer and plant protection measures, the environmental impact is many times over that of grain production. In the North China Plain (NCP), which is also referred to as China's granary, degradation of arable land has reached an alarming rate. To reduce the ongoing resource depletion new cropping systems have to be developed and disseminated that enable the production of high value crops in an environmentally friendly way. According to various sources, intercropping is widely practiced in the NCP; however, no literature focuses on intercropping systems that include vegetables. To understand and describe the current situation of vegetable intercropping in the region, a qualitative inquiry was conducted from autumn 2007 to spring 2008 in the southern part of Hebei province, which is located in the center of the NCP. Semi structured in-depth interviews were used to question researchers, extensionists and farmers on the occurrence, methods, potentials and constraints of vegetable intercropping. Additionally the survey tried to interrogate farmers underlying motivation and concepts and grasp the knowledge transfer involved. The results show that a huge variety of vegetable intercropping systems is practiced; apart from pure vegetable systems like spinach-garlic, intercropping with maize or cotton and agroforestry systems are widespread. Farmers' main motivations to practice those labor intensive systems are to maximize the output from their small farm land (0.5 ha in average) and positive effects on plant health. The systems were mainly developed by the farmers themselves. Promising systems were picked up by the state extension service, tested and improved, and later disseminated on larger scale. Even though farmers were often very confident about the vegetable intercropping systems they practice, researchers and especially extensionists were skeptical, whether intercropping is a viable option under the rapidly changing production conditions in rural China.

6 How to overcome the slow death of intercropping in China

Publication II

Feike, T., Q. Chen, J. Pfenning, S. Graeff-Hönninger, G. Zühlke, and W. Claupein. 2010. How to overcome the slow death of intercropping in China. In: Darnhofer, I. and Grötzer, M. (eds.): Building sustainable rural futures. Proceedings of the 9th European IFSA Symposium, pp. 2149-2158. ISBN: 978-3-200-01908-9 (published).
http://ifsa.boku.ac.at/cms/fileadmin/Proceeding2010/2010_WS5.3_Feike.pdf

A huge variety of highly sophisticated vegetable intercropping systems was identified and presented in the first paper. The practiced systems are highly interesting from the viewpoint of agronomic research. However, the ongoing change in production factor endowment, with people moving out of agriculture, means the end to the very labor intensive vegetable production systems in the long run. Ideas have to be developed and ways to be found, how to overcome the problem and maintain the potential agronomic and environmental advantages of the traditional systems. Hence, the ***second paper*** *presents two possible solutions, how to adjust the traditional systems to make them fit to the demands of modern agriculture.*

Abstract

Intensified research efforts in the last decade proved the agronomic and environmental advantages of several intercropping systems practiced in China. However, as the socio-economic frame conditions for farming are changing rapidly, two questions remain: What is the future of intercropping in China; and how to adapt the intercropping systems to fit the demands of modern agriculture. To answer these questions, the findings of a survey conducted in the North China Plain were connected with an extensive analysis of available statistics on farm structures, inputs, and production factor endowment. The survey revealed that farmers in most cases practice intercropping to make intensive use of their limited land resources. It was shown that intercropping is more widespread in remote rural regions, compared to suburban areas, which are close to the economic centers. In the remote regions farmers have to make a living purely from farming, while farmers close to the cities generate at least parts of their income off-farm. What can be seen on spatial scale is also most likely to happen on temporal scale. Looking at the available statistics, it becomes obvious that in the last decade more and more people move out of agriculture into other sectors. At the same time farmers have more capital to invest into machinery. As a result, the ongoing mechanization of Chinese agriculture has a tremendous impact on the design of cropping systems, with hand-labor intensive systems like intercropping going to disappear in the long run. The paper presents two possible solutions to overcome this dilemma. Either the intercropping systems have to be adjusted to the available machinery, or new machinery has to be developed to mechanize the existing row-intercropping systems. For the first approach, the traditional row-intercropping systems have to be changed to strip-systems, which can be sown and harvested by machine, but still maintain the benefits of an intercrop. To optimize such systems with regard to resource use efficiency, the use of crop simulation models is recommended to be a viable research tool. For the second approach, the case of an “interseeder” is presented, which was developed in Japan to mechanize the traditional soybean-wheat row intercropping system. Due to the very low working capacity and the very high purchase price, the machine did not become a commercial success. It is recommended to develop more flexible machinery, which can be adjusted to different crops combinations and spacing. It is concluded that only an integrative research approach is able to adjust the intercropping systems to upcoming demands. Only systems that suit farmers’ requirements can considerably benefit the environment.

7 Adaptation of CROPGRO to Chinese cabbage I. Estimation of cardinal temperatures

Publication III

Feike, T., J. Pfenning, S. Graeff-Hönninger, Q. Chen, and W. Claupein. 2010. Adaptation of CROPGRO to Chinese cabbage I. Estimation of cardinal temperatures. Agronomy Journal (submitted).

Two possible solutions to overcome the slow death of intercropping were suggested in the second paper: either the adjustment of the machinery to the traditional intercropping systems, or the adjustment of the cropping system to the existing machinery. The latter can only be realized by converting the traditional row systems into mechanized strip systems. Such radical changes in the cropping systems design has a tremendous impact on the resource availability and production potential of the system. To test the performance of the adjusted cropping systems, crop simulation models can play a vital role. Models can facilitate the testing of various management options at numerous levels in a short time, which could not be realized in the same time by conventional field experimentation. Hence, the ***third paper*** *presents the first step of the adaptation of the CROPGRO model to Chinese cabbage. CROPGRO was selected as it successfully simulates the growth of various other vegetable crops under different climate, soil and management conditions.*

Adaptation of CROPGRO to Chinese cabbage I. Estimation of cardinal temperatures

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Abstract

Chinese cabbage (*Brassica rapa* ssp. *pekinensis*) is a popular vegetable of East Asia. However, its production is often characterized by unbalanced fertilization and irrigation. To improve Chinese cabbage production systems with respect to management under different environments, process-oriented simulation models constitute a powerful and inexpensive tool. Up to now, no cropping system model includes Chinese cabbage. Therefore, the generic CROPGRO model, which already simulates several vegetable crops, was selected for adaptation to Chinese cabbage. The first and most crucial step was the determination of temperature response. Plant growth data was available from a series of greenhouse and open field experiments in Germany and in China. By correlating mean relative growth rate to temperature, as determined in two greenhouse experiments, the minimum growth temperature was identified at 0 °C. Maximum temperature was defined according to published sources at 34 °C. Next, leaf appearance rate was used for defining the phenology model in CROPGRO. The non-linear temperature function of the phenology model was then applied to the daily average temperature values of four field experiments, testing a wide range of temperatures and maximum leaf appearance rates. By minimizing the sum of squared errors between simulated and observed values, the lower and upper optimum temperatures were identified at 14 °C and 24 °C respectively. Applying the model to three independent data sets affirmed the findings. Estimated cardinal temperatures are reliable and can be used to simulate growth and development of Chinese cabbage under a diverse range of temperatures.

Keywords: *CROPGRO, Chinese cabbage, model, cardinal temperatures*

Introduction

Degrading land and water resources along with economic and market pressure are increasing the demand for information in the agricultural sector. Computer simulation models provide a powerful and inexpensive tool that can support a judicious management of natural resources. Models cannot only help to describe and understand complex systems, but facilitate the testing of hypothesis and the comparison of various management options.

Chinese cabbage (*Brassica rapa* ssp. *pekinensis* syn. *Brassica campestris* ssp. *pekinensis*) is a traditional field vegetable of East Asia (Elers und Wiebe, 1984). It is assumed that Chinese cabbage developed as an interspecies cross of bok choy (*Brassica rapa* var. *chinensis*) and field mustard (*Brassica rapa* var. *rapa*) (Vogel, 1996). In terms of production amount Chinese cabbage is the most important vegetable in China (Chen, 2003; Zhang et al., 2006). Since the middle of the last century it is cultivated throughout the temperate regions of the world. The traditional production season is autumn, but spring and also summer production are of increasing importance for fresh year-round market supply. The cold tolerant leafy vegetable is popular due to a short growth period with high biomass accumulation, its versatile usages, and a good storability (Daly and Tomkins, 1995). The later makes it an essential source of Vitamin C in many rural regions of East Asia during winter months. Originally, it is a biennial plant, but for commercial production the vegetative plant tissue is harvested before the generative phase initiates. Chinese cabbage is an open field crop, with negligible production under protected cultivation. Direct seeding is possible for autumn production, but the use of transplants is dominant.

In China production of Chinese cabbage is often characterized by unbalanced fertilization and irrigation. Chen (2003) surveyed an average input of more than 600 kg nitrogen per hectare and year in Chinese cabbage production in the Beijing region, with maximum values exceeding 1500 kg per hectare. This not only leads to health hazardous nitrogen levels in marketed Chinese cabbage (Zhong et al., 2002), but also to severe environmental degradation. In combination with excessive flood irrigation, nutrients are washed below the rooting zone and into ground water. In addition to the environmental pollution, this also results in suboptimal economics for the producers. In this context crop models generate important information that can help to overcome unbalanced input management. Models are employed throughout world to adapt cropping systems and improve resource use efficiency in various types of crops and farming systems. To this day, no cropping systems model includes Chinese cabbage.

The accurate simulation of Chinese cabbage growth and development would help to predict its yield potential under varying input levels, management strategies, and changing climatic conditions and could help to adapt Chinese cabbage cropping systems e.g. in the context of nitrogen fertilization and irrigation. Thus, the objective of this study was to adapt the generic CROPGRO model for simulation of Chinese cabbage. The first and most crucial step for model adaptation is the determination and quantification of temperature response of Chinese cabbage. Parameterization was based on the findings of growth experiments under semi-controlled (greenhouse) and field conditions, and completed with information from published sources.

Model description

CROPGRO is a generic model that simulates the soil-plant-atmosphere system. It was originally developed for legumes, building on SOYGRO (Wilkerson et. al., 1983), BEANGRO (Hoogenboom et al., 1994) and PNUTGRO (Boote et al., 1987). It was selected for simulation of Chinese cabbage, as it proved successful to simulate various types of crops, including not only legumes like chickpea (*Cicer arietum* L.; Singh and Virmani, 1994) and velvet bean (*Mucuna pruriens*; Hartkamp et al., 2002), but also forage crops like *Brachiaria decumbens* (Giraldo et al., 2001) or vegetables like tomato (*Lycopersicon esculentum* L.; Scholberg et al., 1997). Furthermore it is part of the Decision Support System of Agrotechnology Transfer (DSSAT), which simulates a total of 28 crops (Jones, et al. 2003). The different crop models can be linked to analyze rotations and consecutive cropping seasons (Thornton et al. 1997, Singh et al. 1999), which is of special importance in vegetable production systems. Additionally the user friendly interface of DSSAT allows easy access to the model and ensures a growing number of researchers all over the world developing new modules, refining existing ones and applying the models in their specific research work. An adaptation of CROPGRO to Chinese cabbage promises a significant impact and was therefore chosen over the development of a stand-alone model that might run the risk of ending up in the drawer.

Due to the relatively close morphological and phenological relationship with white cabbage (*Brassica oleracea* convar. *capitata* L.) the existing cabbage model (Hoogenboom et al., 2003) was selected as a starting point for the adaptation of CROPGRO to Chinese cabbage. CROPGRO is a process-oriented model that simulates plant growth and development on a daily basis. It comprises a crop carbon balance, crop soil water balance and crop soil nitrogen balance. The model requires daily weather data, including minimum and maximum air temperature, precipitation and solar radiation. Furthermore, soil physical and chemical parameters and crop management information are needed. Differences in crops' characteristics are represented through parameters and coefficients, which are organized in three separate files. The parameters describing species specific traits, like photosynthesis and respiration characteristics, as well as plant composition and phenological parameters are listed in the species (SPE) file. To define ecotype differences within one species, thermal time requirements to reach a certain development stage and plant growth parameters are set in the ecotype (ECO) file. Finally cultivar specific traits, like the maximum size of leaves, specific leaf area and leaf photosynthesis rate are defined in the cultivar (CUL) file. On the output side, the model generates predictions of dry matter production of all plant parts, leaf area index, and canopy development on a daily basis. Additionally water and nitrogen stress and biomass senescence are determined (Hartkamp, 2002). For a more detailed description of the CROPGRO model Boote et al. (1998) is recommended.

Cardinal temperatures

All biochemical processes are highly temperature dependent. Under conditions of sufficient solar radiation, where water and nutrients are non-limiting, crop growth is mainly a function of temperature. The ability to explain plant response to temperature is a basic prerequisite for crop growth modeling. Various concepts exist to describe temperature response. Models range from simple approaches assuming a linear relationship between development rate and temperature to more complex approaches. Dumur et al. (1990) tested weibull, logit and probit functions on their data to explain the response of germination rates to temperature in faba bean. Soltani et al. (2006) compared segmented functions, beta-functions and dent-like functions for estimating seedling emergence in chickpea. The latter, which is also referred to as linear three-segmented spline function (Piper et al., 1996), represents the temperature function of the phenology model in CROPGRO.

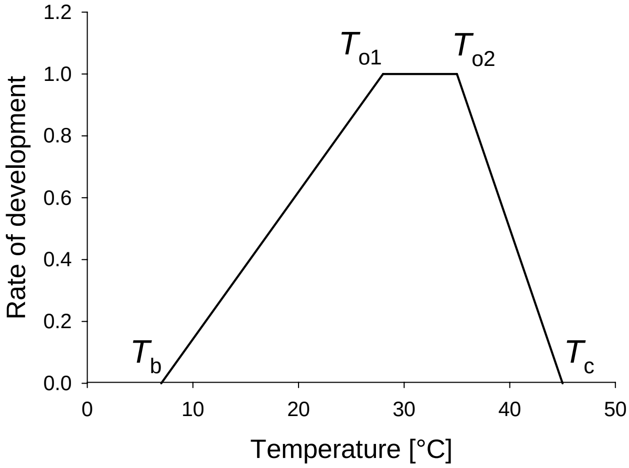

Fig. 1. Relation between rate of development and temperature for main stem leaf number progression used in the soybean species file.

The three linear segments are defined by four critical points. The cardinal temperatures of the model are the base, the lower and upper optimum and the ceiling temperature (Fig. 1). Below the base temperature (T_b) development rate is zero. Between base and lower optimum temperature (T_{o1}) development increases linearly. Between lower and upper optimum temperature (T_{o2}) development is constantly at maximum rate. Above the upper optimum temperature development decreases linearly towards ceiling temperature (T_c). The temperature function reads as:

$$\begin{aligned} &f(T) = \frac{T - T_b}{T_{o1} - T_b}, \text{ if } T_b < T < T_{o1}; \\ &f(T) = \frac{T_c - T}{T_c - T_{o2}}, \text{ if } T_{o2} < T < T_c; \\ &f(T) = 1, \text{ if } T_{o1} \le T \le T_{o2}; \\ &f(T) = 0, \text{ if } T \le T_b \text{ or } T \ge T_c; \end{aligned} \qquad [1]$$

Most crops represented in CROPGRO produce generative harvest organs, and thus undergo a phenological change from vegetative to generative phase. As crops show different sensitivity to temperature in the different phases of their life cycle (Piper, 1996), CROPGRO assumes different cardinal temperatures before and after flower formation. Cabbage solely uses the same cardinal temperatures for vegetative and early reproductive phase (Table 1). One has to be aware that for the existing cabbage model as well as for the newly developed Chinese cabbage model the terminology of CROPGRO has to be “translated” to fit the simulation of leafy vegetables. The cabbage head is presented in the model by “pod” and is therefore considered to be a generative organ. The stem, which is considered as vegetative organ in CROPGRO is still considered as such for cabbage and Chinese cabbage, even though it is part of the economic tissue which is actually marketed as part of the head. Thus only the leaves of the cabbage head account as pod in CROPGRO.

Table 1. Critical temperatures during vegetative and reproductive phase of some vegetable and leguminous crops as defined in CROPGRO.

Crop	**Development phase**	**Temperature**			
		T_b	**To_1**	**To_2**	**T_c**
		°C			
Bell pepper	Vegetative	5.5	21	28	55
	Early reproductive	10	28	28	55
Cabbage	Vegetative	0	18	28	45
	Early reproductive	0	18	28	45
Chickpea	Vegetative	0	20	32	55
	Early reproductive	0	25	25	50
Faba bean	Vegetative	0	27	30	40
	Early reproductive	0	22	26	45
Groundnut	Vegetative	11	28	30	55
	Early reproductive	11	28	28	55
Soybean	Vegetative	7	28	35	45
	Early reproductive	6	26	30	45
Tomato	Vegetative	10	28	28	55
	Early reproductive	10	28	28	55

To determine cardinal temperatures the concept of required growing degree days (GDD) to reach the generative growth stage has been used for various leguminous crops (Piper et al., 1996; Grimm et al., 1994; Soltani et al., 2006). However to quantify temperature response during vegetative stages as required for Chinese cabbage, the leaf appearance rate (Haun, 1973) or mean relative growth rate (Krug, 2008) are adequate parameters. The time interval between initiations of successive leaves, referred to as plastochron interval in dicots and phyllochron interval in monocots (Baker and Reddy, 2001), is also used to determine vegetative or V-stage in CROPGRO-Soybean (Hoogenboom et al., 1999). To determine cardinal temperatures in Chinese cabbage the current study makes use of both parameters - relative growth rate and plastochron interval - following a stepwise approach. In greenhouse experiments the effect of temperature on mean relative daily growth rate is explained by polynomial regression. In the next step the derived estimations of optimum, minimum and maximum temperatures were tested on the data of field experiments to ensure their validity under open field conditions. This was realized testing of appropriate temperature values on the non-linear cardinal temperature function (eqn.1) to predict the plastochron intervals observed in the field experiments.

Materials and Methods

Greenhouse experiments

To determine the effect of temperature on growth and development of Chinese cabbage two experiments were conducted in the ‘Klimatron’ at the horticulture research station of Hohenheim University, Germany (48°42’42 N, 9°11’57 E). Seasonal effects were accounted for by running two nearly identical greenhouse experiments in autumn 2007 (GH-Exp.1) and spring 2008 (GH-Exp.2). Four temperature regimes were applied; two greenhouse chambers with semi-controlled environments, one ambient greenhouse chamber (two sides of the greenhouse chamber are open) and one open field treatment. The temperature in the two greenhouse chambers was controlled by active warming and passive cooling. A temperature difference of 4K between treatment 1, 2 and 3 was intended. The development of the daily average temperatures of the four temperature treatments for the different greenhouse experiments is shown in Fig. 2. Three cultivars were tested in both experiments. The Chinese cultivar “Beijing No.3” and the German cultivar “Kasumi” were grown in both experiments. The Chinese cultivars “Qiulu 75” and “Spring Sun” were additionally grown in GH-Exp.1 and GH-Exp. 2 respectively. The experiments were arranged as split-plot design with three replications. Temperature treatment constituted the main-plot and cultivar the sub-plot. Each greenhouse chamber had an effective area of 32 m^2, with nine sub-plots of 3.25 m^2 each. The open field treatment was carried out in three sub-plots of 12 m^2 each. All plants were cultivated in 30 x 40 cm spacing. The substrate in the greenhouse chambers was a cocopeat-sand mixture (62%-38%) of three meters depth. The soil in the open field treatment was a loess-derived luvisol (WRB). In all treatments fertilization and irrigation were applied ensuring non-limiting conditions. In the greenhouse chambers fertigation (compound fertilizer, 15-5-25) was applied through drip-irrigation, whereas 160 kg ha^{-1} slow-release nitrogen fertilizer (ENTEC) was incorporated before planting in the open field plots.

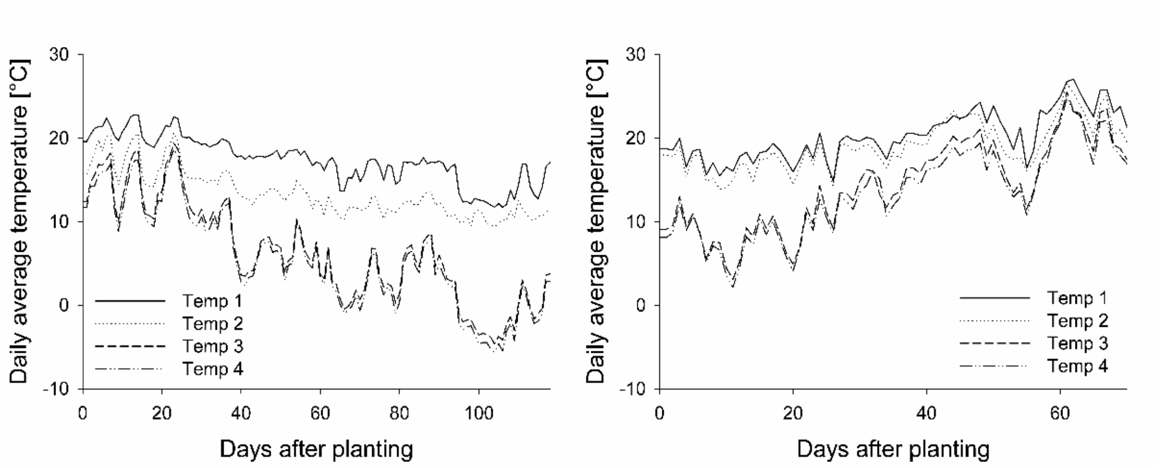

Fig. 2. Development of the daily average temperatures of the four temperature treatments during GH-Exp.1 (left) and GH-Exp.2 (right).

In both experiments transplants were used. Seeds were sown in nutrient enriched peat soil in multipot-plates and kept under controlled conditions in a 22/18 day/night temperature regime. Seedlings were transplanted at four to six leaves stage, which is common transplanting size for Chinese cabbage. Climate data for each treatment was measured one meter above ground and data was collected by an automated system in 12 minutes intervals. Incoming photosynthetically active radiation (PAR) was measured using PAR quantum sensors (UMS, Munich, Germany). For determination of air temperature thermistor temperature sensors (RAM, Herrsching, Germany) were used.

Plant samples were taken destructively in seven to 20 days intervals in both experiments. At the day of transplanting 20 seedlings of each cultivar were randomly selected to determine the starting values of all plant parameters (Table 2). In the subsequent measurements five plants per treatment and replication were randomly selected and destructively analyzed. Plant height and diameter, number of leaves (minimum length 3 cm, minimum width 2 cm) and fresh and dry weight of all above ground plant parts (leaves, stem, head) were measured. Single plant leaf, stem and head dry matter was calculated from dry matter to fresh matter ratio determined for each replicate. Homogenized plant samples were vacuum freeze dried, starting at -30°C with a daily increase by 10 K. Leaf area was determined destructively using a LI-3100 Area Meter (LI-COR, Lincoln, Nebraska, USA). For each factor combination and replication five and four plants were sampled in the greenhouse and open field treatments respectively.

Table 2. Mean plant characteristics at the onset of the experimental treatments. The leaf area comprises leaf, midrib and stalk area. The values in brackets are standard errors of mean.

Experiment	**Cultivar**	**Start of Experiment**			
		Date	**Number of leaves**	**Leaf area per plant (cm^2)**	**Dry weight per plant (g)**
1	Beijjng No.3	10/08/07	3.65 (0.57)	31.2 (6.4)	0.111 (0.024)
	Kasumi		4.05 (0.50)	36.2 (10.9)	0.105 (0.028)
	Qiulu 75		3.20 (0.40)	33.3 (9.7)	0.113 (0.037)
2	Beijjng No.3	04/28/08	6.10 (0.94)	60.6 (17.0)	0.248 (0.074)
	Kasumi		5.35 (1.19)	50.1 (12.2)	0.228 (0.055)
	Spring Sun		7.00 (0.71)	71.2 (15)	0.250 (0.062)

Field experiments

Four field experiments were conducted as part of this study. Due to its relatively short life cycle Chinese cabbage can be cultivated up to three times per year. This resulted in a total of nine data sets being available for model development and testing (Table 3). The experiments were included in a larger study on Chinese cabbage cropping systems. However, the generated field data were suitable for model development and testing. In all experiments Chinese cabbage was strip intercropped with maize or sweet corn to determine interspecific effects between the two crops. However, very large strips, of up to twenty rows of Chinese cabbage were planted between the maize strips. This ensured that a sufficient number of plants were grown under pure monocropping conditions without any interspecific competition. Effects of the neighboring maize on Chinese cabbage growth and development were observed maximally until the third row of Chinese cabbage. Thus, all plants starting from row 4 were grown under monocropping conditions and were available for the current study (Fig. 3).

Table 3. Overview of field experiments available for model development and testing.

Experiment	**Set**	**Year**	**Location**	**Cultivar**	**Planting method**	**Start of experiment**	**Season**
1	1	2008	Uni Hohenheim	Kasumi	Transplanting	07/25/2008	Summer
2	1	2008	Ihinger Hof	Yuki	Transplanting	08/31/2008	Autumn
3	1	2009	Ihinger Hof	Spring Sun	Transplanting	04/16/2009	Spring
	2	2009	Ihinger Hof	Kasumi	Transplanting	06/19/2009	Summer
	3	2009	Ihinger Hof	Beijjng No.3	Transplanting	08/20/2009	Autumn
4	1	2008	Quzhou	Spring Sun	Transplanting	04/15/2008	Spring
	2	2008	Quzhou	Beijjng No.3	Direct sowing	08/07/2008	Autumn
	1	2009	Quzhou	Spring Sun	Transplanting	04/16/2009	Spring
	2	2009	Quzhou	Beijjng No.3	Direct sowing	08/13/2009	Autumn

The first experiment (Exp.1) was conducted at the research station for horticulture of Hohenheim University (48°42’43” N, 9°11’56“ E, 389 m.s.l.), southwest Germany in late summer 2008. The soil was a loess-derived luvisol (WRB). Average yearly rainfall is 697 mm with an average temperature of 8.8 °C. One set of Chinese cabbage (cv. Kasumi) was planted end of July. The second and third experiment (Exp.2 and Exp.3) were performed approximately 20 km west of Exp.1 at Hohenheim University’s research station Ihinger Hof (48º44’39” N, 8º55’10” E, 484 m.s.l.) in 2008 and 2009. The average rainfall per year is 690 mm with an average temperature of 7.9 °C. The soil was a keuper with loess layers. In Exp.2 one set of Chinese cabbage (cv. Yuki) was planted end of August. In Exp.3 three consecutive sets of Chinese cabbage were planted. The cultivars “Spring Sun”, “Kasumi” and “Beijing No.3” were planted in April, June and August respectively. For all plantings transplants were used, which were obtained from a local vegetable seedling producer. Before planting 160 kg N ha^{-1} were applied as Calcium Ammonium Nitrate for every set of Chinese cabbage in all three experiments. Due to sufficient precipitation over the entire growing season additional irrigation was only applied directly after transplanting for one to three times in case natural precipitation did not occur in the first two weeks after planting. Soil water and nitrogen as well as plant nitrogen status were checked at the beginning and end of every set. The first three experiments were designed in four nonrandomized complete blocks. Randomization was not possible, as the intercropping system required alternating strips.

The fourth experiment (Exp.4) was conducted at the Quzhou experimental station of the China Agricultural University (36°52’21” N, 115°01’05“ E, 36 m.s.l.) in Hebei province, China in 2008 and 2009. Average annual rainfall is 416 mm with an average temperature of 14.3°C. The soil is a calcaric fluvisol (WRB). In both years, one set of spring and one set of autumn Chinese cabbage were grown. In both years the cultivars “Spring Sun” and “Beijing No.3” were planted in spring and autumn respectively. For spring planting transplants were used, which were produced by a local vegetable seedling producer. For the autumn plantings seeds were directly sown into the field. As rainfall concentrates on the summer months, additional irrigation is necessary to enable crop production in early and late season. Two irrigation strategies were applied: “Farmer’s practice” and “Farmer’s practice -20%” (-30% in 2009). However, for model calibration only data from the 100% irrigation treatments were used. The design was a completely randomized block design.

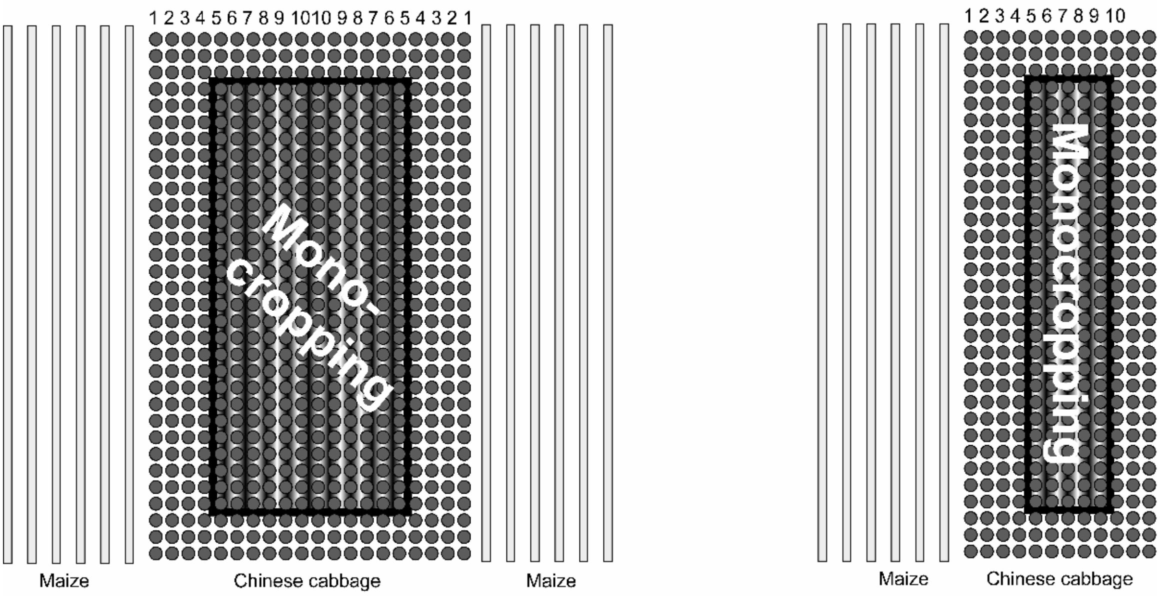

Fig. 3. Layout of a single replication of Exp.1 to Exp.3 (left) and Exp.4 (right). In Exp.1 to Exp.3 maize was planted east and west of Chinese cabbage; in Exp.4 maize was planted only in the west. The monocropped plants were available for model development and testing.

In all experiments, daily maximum and minimum temperature, precipitation and solar radiation were measured at standard weather stations located at most 300 meters from the experimental sites. An overview of monthly air temperatures during the growth periods of the four field experiments is given in Table 4.

Plant sampling measures conducted in the field experiments are for the most part identical to the ones of the greenhouse experiments explained above. However, dry matter was not determined by vacuum freeze drying, but by oven drying at 90°C for at least 48 h until constant weight was reached. Additionally to the destructive measurements which were conducted in two to four weeks intervals, phenological stage, leaf number as well as plant height and diameter were determined on a weekly basis. In Exp.1, Exp.2 and Exp.4 three plants of every single row were measured per destructive measurement. In Exp.3 only plants of rows 1, 2, 3, 5, 7 and 9 were examined. For the final harvest of each set of Chinese cabbage the sample size was doubled, examining six plants of every row.

Table 4. Minimum, mean and maximum monthly air temperatures during the growth periods of the four field experiments in Germany and China.

				Temperature [°C]		
Experiment No.	**Location**	**Year**	**Month**	**Min.**	**Mean**	**Max.**
				°C		
1	Uni Hohenheim	2008	July	13.8	19.0	24.2
			August	13.3	18.3	23.3
			September	8.9	13.1	17.4
			October	5.9	10.1	14.2
2	Ihinger Hof	2008	August	11.8	16.8	22.5
			September	7.4	11.7	16.4
			October	5.2	9.0	13.6
			November	0.8	4.4	8.4
3	Ihinger Hof	2009	April	5.4	11.6	17.0
			May	8.6	14.7	19.9
			June	10.1	15.9	20.2
			July	12.7	17.8	23.1
			August	12.6	18.5	24.6
			September	9.6	14.4	19.6
			October	4.7	8.5	12.8
			November	3.5	7.0	10.7
4	Quzhou	2008	April	10.5	15.9	21.3
			May	15.9	21.6	27.2
			June	19.7	24.6	29.4
			July	21.9	25.9	29.9
			August	21.1	25.2	29.3
			September	15.6	20.7	25.8
			October	9.1	15.6	22.0
			November	0.9	7.8	14.7
		2009	April	9.5	15.7	21.9
			May	15.5	21.1	26.7
			June	20.5	26.9	33.3
			July	21.9	26.1	30.2
			August	20.2	24.4	28.6
			September	15.2	20.0	24.8
			October	9.6	16.5	23.4
			November	-3.2	1.5	6.1

Analysis

Greenhouse Experiments

Data were first subjected to analysis of variance using the general linear model (GLM) procedure in the Statistical Analysis System (SAS Institute, 1989). Means of treatments were compared using least significant difference at 5% probability. To quantify the response of plant growth to temperature the relative growth rate (*RGR*) of total above ground biomass was selected for the greenhouse experiments. To determine *RGR* the following equation is generally used:

$$W_2 = W_1 \, e^{RGR(t_2 - t_1)} \qquad [2]$$

where W_1 and W_2 are the plant dry matters at two points in time t_1 and t_2. Solving eqn. [2] for *RGR* yields the equation often referred to as the classical growth analysis approach (Hunt, 1982).

$$RGR = \frac{\ln(W_2) - \ln(W_1)}{t_2 - t_1} \qquad [3]$$

In the current study, as in most plant growth experiments destructive harvesting is required to determine plant parameters. As a result the data obtained at two points in time (t_1 and t_2) is generated from different individuals of the same batch (Evans, 1972). Instead of substituting W_1 and W_2 with sample means $\overline{W_1}$ and $\overline{W_2}$ to estimate *RGR*, the approach of Hoffmann and Poorter (2002) was employed. They recommend calculating mean relative growth rate (*MRGR*) from the means of the natural logarithm-transformed single plant weights:

$$MRGR = \frac{\overline{\ln(W_2)} - \overline{\ln(W_1)}}{t_2 - t_1} \qquad [4]$$

which helps to avoid bias. Applied to the data of the greenhouse experiments the *MRGR* of total above ground biomass was used. According to Goudriaan and Van Laar (1994) exponential growth ceases above a biomass of 100 g m^{-1}, due to increasing intraspecific competition. Therefore data was excluded from analysis as soon as average dry matter per treatment and replicate exceeded 100 g m^{-1}. The *MRGR* was then calculated for each time span between two consecutive measurements using eqn. [4].
Finally estimated *MRGR* given in g g^{-1} d^{-1} was correlated to temperature. The temperature values measured in 12 minutes intervals were used to determine daily average temperature (*DAT*) for each treatment:

$$DAT = \left(\sum_{00:12}^{24:00} T \right) / 60 \qquad [5]$$

The average temperature since the previous measurement (*ATPM*) was then calculated for the respective growth periods:

$$ATPM = \frac{\sum_{t_1}^{t_2} DAT}{t_2 - t_1} \qquad [6]$$

The information on temperature response of Chinese cabbage derived from the correlation of *MRGR* and temperature in the greenhouse experiments specified the value range for fitting of the nonlinear model of cardinal temperatures in eqn. [1] which was then applied to the data of the field experiments.

Field Experiments

Leaf appearance rate is assumed to be unchanging over time under constant temperatures in CROPGRO, as it is also reported in literature for various crops (Hesketh, 1973, Sié, 1998, Sinclair, 1984). This allows the estimation of cardinal temperatures via temperature response of mean leaf appearance rate (*MLAR*):

$$MLAR = \frac{\overline{n_{l2}} - \overline{n_{l1}}}{t_2 - t_1} \qquad [7]$$

where $\overline{n_{l1}}$ and $\overline{n_{l2}}$ are the means of number of leaves at two consecutive measurements t_1 and t_2. The cardinal temperature function of eqn. [1] was then applied to the mean daily temperatures measured in Exp.1, Exp.2 and both autumn Chinese cabbage sets of Exp.4, which were later also used for model calibration. The cardinal temperatures, as well as the maximum rate of leaf appearance ($LAR_{\max}$):

$$LAR_{\max} = \frac{MLAR}{f(T)} \qquad [8]$$

were then estimated by a least squares fit minimizing the sum of mean squared errors between predicted n_{lpi} and observed number of leaves n_{loi}. This was realized by first calculating the sum of squared errors (*SSE*) for every single experiment (Wallach and Goffinet, 1989):

$$SSE = n \sum_{i=1}^{n_i} \frac{ERR2_i}{\sum_{i=1}^{n_i} n_{loi}}$$

where [9]

$$ERR2_i = (n_{\mathrm{loi}} - (f(T)LAR_{\max})_i)^2$$

is the squared difference between the *i*th observed number of leaves and the corresponding model prediction. Later the sums of squared errors were weighted similar to the approach of Young (1979) over the four data sets:

$$SSE_{total} = SSE_{Exp1} + SSE_{Exp2} + SSE_{Exp4a} + SSE_{Exp4b} \quad [10]$$

In the final step the determined cardinal temperatures and leaf appearance rate were tested on the observed leaf appearance rates of the three sets of Chinese cabbage of Exp.3.

Results and discussion

Greenhouse experiments

In both experiments no significant differences between cultivars in total above ground biomass production was observed except for the last measurements. The differences detected can mainly be attributed to the fact that cultivar "Beijing No.3" switched to generative phase before the end of both experiments, whereas the other cultivars maintained in the vegetative growth stage. In GH-Exp.1 dry matter production gradually decreased from "Temp 1" to "Temp 4" (Fig.4 left). A strong correlation between temperature and growth could be observed. Production was increasing slightly exponentially except for "Temp 4" where average temperatures below 0 °C occurred frequently during the last weeks of the experiment. In GH-Exp.2 biomass increase was most rapid in the coolest environment "Temp 4" (Fig.4 right). It became obvious that the temperatures in the other treatments were above optimum.

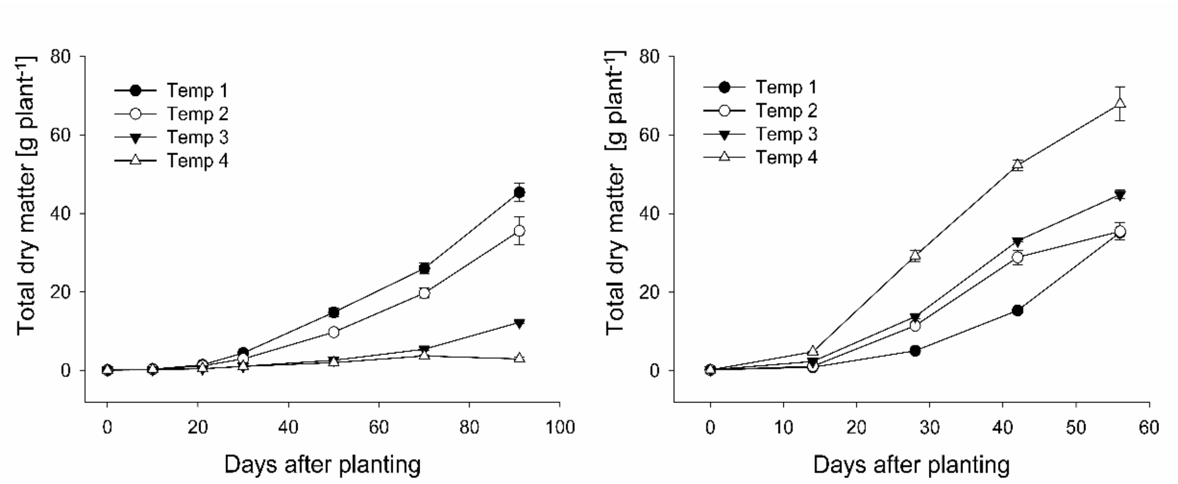

Fig. 4. Total above ground dry matter production of the four temperature treatments of GH-Exp.1 (left) and GH-Exp.2 (right). Error bars indicate twice the standard error of the mean over the three cultivars.

To quantify the temperature response of Chinese cabbage the mean relative growth rates were plotted against average temperatures (Fig. 5). This was done for every consecutive measurement for each replication of cultivar x temperature treatment combination. As described above, only data from cultivar x temperature treatment combinations were used, which had an average dry matter below 100 grams per square meter. Temperature response is described by polynomial regression. A second order polynomial (eqn. [11]) was fitted to the data points, following the approach of Baker and Reddy (2001) who estimated cardinal temperatures in muskmelon. Polynomials are also recommended by Schabenberger and Pierce (2002) to be a valuable exploratory tool for identifying suitable nonlinear models.

$$y = 0.0004x^2 + 0.0137x + 0.002 \qquad [11]$$

An estimate of the optimum growth temperature T_{opt} was then determined by calculating the vertex point of the function. Estimated T_{opt} was 18.4 °C. Base temperature (T_{b}) and ceiling temperature (T_{c}) were determined by the polynomials intersection with the *x*-axis. T_{b} was determined at -0.1 °C and T_{c} at 37.0 °C. The results obtained from the polynomial fit give a good hint on the range of minimum, optimum and maximum temperatures. However, due to the extrapolation of the polynomial regression, the reliability of T_{c} is fairly low. An R^2 of 0.7 mainly results from the big number of data points in connection with random variation. It however calls for a further testing of the acquired cardinal temperature values.

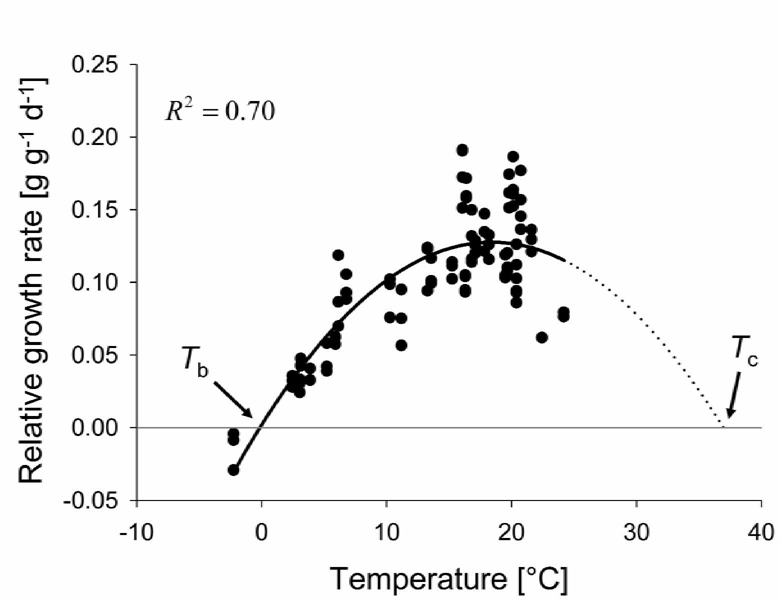

Fig. 5. Relation between mean relative growth rate of total above ground dry matter and average temperature of each cultivar and temperature treatment combination in the greenhouse experiments.

Moreover Chinese cabbage is cultivated in open field for the greater part, and the adaptation of CROPGRO is intended to enable simulation of such production systems. Being aware that crops show different physiological reactions under controlled and open field conditions, as detected for various crops (Hurd, 1977; Krug and Fink, 1990; Patterson, et al., 1977; Santos Filho, et al., 2009), temperature response determined solely from protected environments might be insufficient. Therefore growth data obtained from open field experiments was included in the current study to accurately estimate cardinal temperatures.

Field experiments

Based on the three cardinal temperatures ($T_{b,}$ $T_{c,}$ T_{opt}) determined in the greenhouse experiments, the nonlinear model (eqn. [1]) was tested on the data of the field experiments. However, extreme temperatures below 0°C and above 30 °C hardly occurred during the growth periods of the selected field experiments. Therefore T_b was fixed at 0 °C, as the results of the analysis of the greenhouse experiments (T_b = -0.1 °C) suggested. A minimum growth temperature of 0 °C has also been selected for CROPGRO’s cabbage, chickpea and faba bean models and is a generally accepted base temperature for plant growth of temperate climate crops (Yan and Hunt, 1999). The experiments by Huang et al. (1995) on heat tolerance of Chinese cabbage showed furthermore that growth and development are inhibited above temperatures of 34 °C. Therefore the ceiling temperature (T_c) was set at 34 °C. Fixing T_b and T_c had the additional advantage of reducing the number of degrees of freedom. T_{o1} and T_{o2}

and the maximum leaf appearance rate (LAR_{max}) were then determined by applying integer temperature values in the range of 10 °C to 20 °C for T_{o1} and in the range of 16 °C to 32 °C for T_{o2}. LAR_{max} was tested in the range of 0.85 leaves per day to 1.19 leaves per day, which was determined by visual data inspection to be a reasonable range.

The best prediction of leaf appearance rate over the four data sets of Exp.1, Exp.2 and the two autumn sets of Exp.4 resulted in a parameter setting of T_{o1} of 14 °C and T_{o2} of 24 °C and maximum leaf appearance rate of 0.96 leaves day^{-1}. At this setting the *SSE* was minimized to 0.0959. Leaf appearance rates between the first and last measurement of each experiment were slightly overestimated for “Uni Hohenheim” (Exp.1) and “Quzhou 2009” (Exp.4b), and slightly underestimated for “Ihinger Hof 2008” (Exp.2) and “Quzhou 2008” (Exp.4a) (Fig. 6).

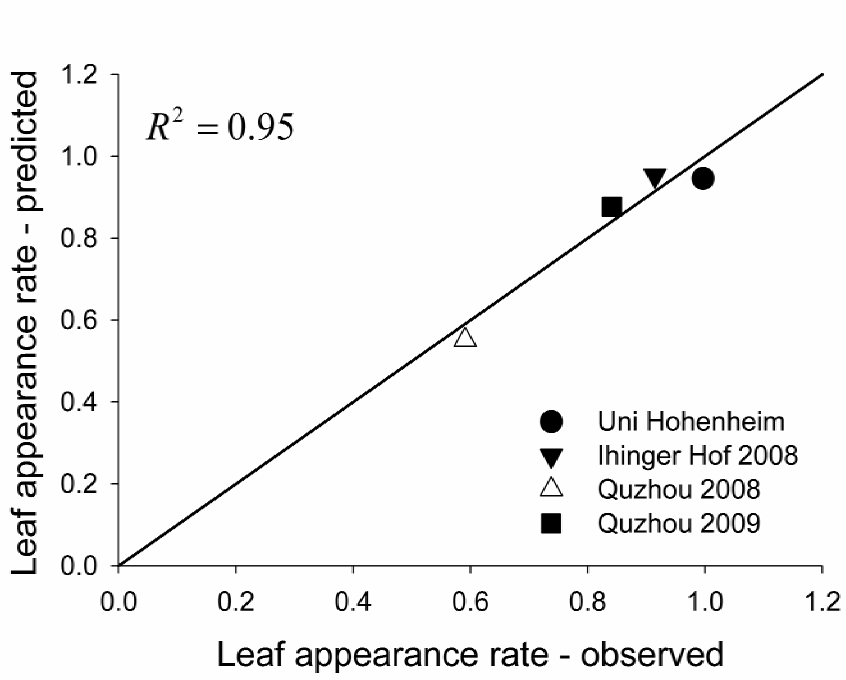

Fig. 6. Predicted vs. observed mean leaf appearance rates of Chinese cabbage of Exp.1, Exp.2 and the two autumn sets of Exp.4 used for model calibration. The solid line is a 1:1 line.

The lower and upper optimum temperatures T_{o1} and T_{o2} obtained from the field experiment analysis are consistent with the optimum temperature of 18.4 °C determined from the greenhouse data analysis. The comparison with the defined cardinal temperatures of other CROPGRO crops showed that Chinese cabbage has the lowest temperature values. T_{o1} and T_{o2} are even slightly lower compared to those defined in CROPGRO-cabbage with of 18 °C and 28 °C (Hoogenboom et al., 2003). However, the obtained values are reasonable taking into consideration that Chinese cabbage is a cool climate crop, which is mainly cultivated in early and late season. Shattuck (1986) even recommends an optimum temperature range of

13 °C to 15 °C for production in Southern Ontario. The temperature range is also in line with the optimum temperatures identified for optimum head formation of 16 °C to 18 °C (Lee, 1984; Guttormsen and Moe, 1985).

The maximum leaf appearance rate of 0.96 leaves per day as determined for Chinese cabbage is far above the one defined in the ecotype file of CROPGRO-cabbage with 0.38 leaves per thermal day (Hoogenboom et al., 2003). In CROPGRO most crops' leaf appearance rates are defined between 0.3 and 0.4 leaves per thermal day. Only tomato and chickpea feature a higher leaf appearance rate of 0.52 and 0.6 leaves day^{-1} respectively. The comparably higher leaf appearance rate might be explained by the comparably short stem of Chinese cabbage. It uses less assimilated carbon that might then be available for further leaf addition. In literature leaf appearance rates are reported at 0.15 to 0.2 leaves day^{-1} for rice (Sié et al., 1998), 0.3 leaves day^{-1} for soybean (Baker, et al., 1989) and 0.7 to 0.8 leaves day^{-1} for muskmelon (Baker and Reddy, 2001). Fleisher et al. (2006) identified a maximum leaf appearance for potato of 0.96 leaves day^{-1} at an optimum temperature of 27.2 °C.

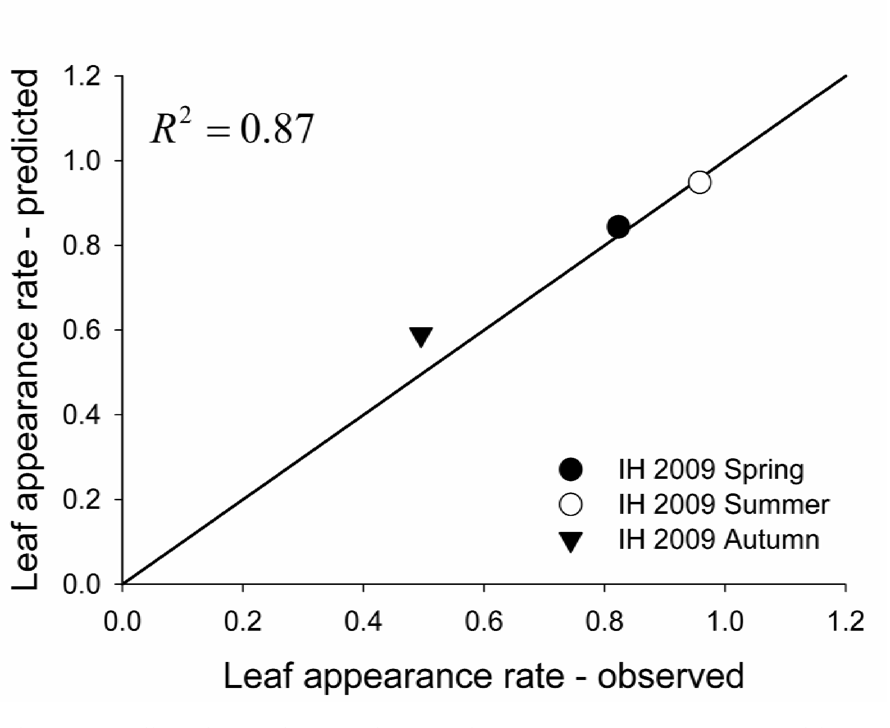

Fig. 7. Predicted vs. observed mean leaf appearance rates of Chinese cabbage of the three sets of Exp.3 used for model testing. The solid line is a 1:1 line.

Testing the cardinal temperature model on the independent data of Exp.3 showed satisfying accuracy (Fig.7). The leaf appearance rate, determined from transplanting to last measurement was very well predicted for the spring and summer set. Infestation of cabbage stem flea beetle (*Psylliodes chrysocephala*) slowed down plant growth in the beginning of the autumn set. The pest pressure resulted in a slight overestimation of leaf appearance rate in the autumn set.

Overall, the determined cardinal temperatures and maximum leaf appearance rate for Chinese cabbage proved sufficiently reliable and will determine the phenology model for the newly developed CROPGRO-Chinese cabbage model, which is described in the companion paper (Feike et al., 2010).

Conclusions

The results of the two analyses indicated that Chinese cabbage has relatively low cardinal temperatures compared to cabbage and other crops simulated in CROPGRO. Differences between cultivars in temperature response were small. Response of relative growth rate, as determined from the data of the greenhouse experiments, showed that growth ceases at temperatures just below 0 °C. Maximum growth was determined at 18.4°C. By applying the non-linear temperature function to the data of the field experiments, the cardinal temperatures, as required for the phenology model of CROPGRO were estimated. The four cardinal temperatures were identified at T_b of 0 °C, T_{o1} of 14 °C, T_{o2} of 24 °C, and T_c of 34 °C, at a maximum leaf appearance rate of 0.96 leaves day^{-1}. Both cardinal temperatures and leaf appearance rate differed greatly from the ones of cabbage, which are a T_b of 0 °C, T_{o1} of 18 °C, T_{o2} of 28 °C, and T_c of 45 °C, at a maximum leaf appearance rate of only 0.38 leaves day^{-1}. Testing the model on three independent data sets affirmed the results. The estimated cardinal temperatures are reliable and can be used to define the phenology model of Chinese cabbage in CROPGRO to simulate growth and development under a diverse range of temperatures.

Acknowledgements

We want to thank the German Research Foundation (DFG, GRK 1070) and the Ministry of Education of P.R. China (special fund for agriculture profession (200803030) & innovative group grant of NSFC (No.30821003)) for their financial support.

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8 Adaptation of CROPGRO to Chinese cabbage II. Model development and testing

Publication IV

Feike, T., S. Graeff-Hönninger, Q. Chen, and W. Claupein. 2010. Adaptation of CROPGRO to Chinese cabbage II. Model development and testing. Agronomy Journal (submitted).

The first and most crucial step for integration of a new crop into CROPGRO was presented in the third paper. After the accurate determination of the temperature response of Chinese cabbage and fixation of cardinal temperatures, model development was pursued in the ***fourth paper****. The generic structure of CROPGRO allows the adaptation of the model based on changes in parameter settings. The source code of the model maintains untouched. Crop growth parameters were identified based on the results of the greenhouse and field experiments. Additional information could be collected from published sources. The process of adaptation and changes performed in the genotype, ecotype and cultivar files are described. In the next step the performance and validity of the model is tested on up to six independent data sets.*

Adaptation of CROPGRO to Chinese cabbage
II. Model development and testing

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Abstract

The rapid increase of vegetable production aggravates the severe resource degradation caused by unsustainable agricultural production in China. The integration of Chinese cabbage, the number one vegetable, into the generic CROPGRO model allows testing of different management scenarios at various input levels over a wide range of environments. CROPGRO is part of the DSSAT shell, which simulates and is able to connect models of 28 different crops. The generated information can help to improve resource use efficiency, while maintaining high yield levels. The existing CROPGRO-cabbage model was adapted based on published sources, and field data obtained at two locations in Germany and China in 2008 and 2009. Major changes concentrated on leaf growth and photosynthesis parameters, as well as on plant tissue composition. Parameters of capital importance (e.g. head dry matter, leaf area index, specific leaf area) were predicted well over up to six independent data sets. Sensitivity analyses were conducted to predict the potential yield level at the Chinese location using actual weather data from 2001 to 2009. Increasing fertilization from 100 to 200 kg N ha^{-1} did not result in a higher yield. In most years one irrigation application was sufficient to ensure a high yield level. Furthermore, the latest possible planting date was identified to be end of August. The newly developed model proved to be a reliable decision support. However, to further improve the model's predictive capacity, adaptation of the transplanting option, parameterization of major pest damages, and the development of a vernalisation sub-module are recommended.

Keywords: *CROPGRO, Chinese cabbage, model development, sensitivity analysis*

Introduction

Heading Chinese cabbage (*Brassica campestris* ssp. *pekinensis*) is a major vegetable of East Asia. In China it is ranking first in terms of production amount (Chen, 2003). Since the middle of the last decade it is cultivated all over the temperate zones of the world. Chinese cabbage can be cultivated year round, but main production focuses on early and late season. During those seasons its production does not have to compete with the production of other vegetable crops, which demand higher growing temperatures.

In many regions of China, unsustainable agricultural practices endanger the production base for future generations. Unbalanced fertilization and irrigation are the main reasons for leaching of nutrients, ground and surface water pollution (Li et al., 2009) and depleting water resources (Jia et al., 2002). The negative trends are further aggravating, since the production of vegetables has more than doubled in the last twenty years, while cereal production stagnated (FAOSTAT, 2008). Vegetables generally demand higher inputs compared to cereal production. Therefore the optimization of China's vegetable production systems with regard to amount and timing of fertilization and irrigation should be given highest priority.

Crop simulation models are particularly feasible to improve cropping systems. Traditional agronomic research collects data at specific points in time and space, with the conclusions drawn having limited validity. Employing a modeling approach, the crops behavior can be tested under various environmental conditions and management strategies (Jones et al., 2003). The CROPGRO model already simulates various vegetables like tomato, bell pepper and cabbage (Hoogenboom et al., 2003). CROPGRO is part of the Decision Support System for Agrotechnology Transfer (DSSAT), which simulates 28 crops. It successfully proved to simulate various management options, including fertilization strategies (Rinaldi et al. 2007), irrigation management (Dogan et al., 2006) and crop rotations (Singh et al., 1999). The ever growing user community of DSSAT ensures a steady improvement of the model and testing of modeling approaches in various fields of agronomy. Modeling Chinese cabbage in CROPGRO is promising to have a strong impact on improvement of Chinese cabbage cropping systems in China and other parts of the globe. Hence, the objective of the current study was to adapt the existing cabbage model to Chinese cabbage. After model development the performance of the model was evaluated at two locations over two years. Additionally sensitivity analysis was employed to test different irrigation and fertilization strategies and identify the latest reasonable sowing date for autumn Chinese cabbage at the Chinese location.

Materials and methods

Model development

Species, ecotype and cultivar files of cabbage (*Brassica oleracea* convar. *capitata* L.) were initially used to parameterize CROPGRO for Chinese cabbage. The cardinal temperatures were defined at a base temperature (T_b) of 0 °C, a lower optimum temperature (T_{o1}) of 14 °C, an upper optimum temperature (T_{o2}) of 24 °C and a ceiling temperature (T_c) of 34 °C, as determined in the companion paper (Feike et al., 2010). Data on plant tissue composition including percentage of lipids, lignins, proteins and minerals were compiled from published sources (Lima, 2009; Pokluda, 2008; USDA, 2009; Wills, 1984) and included in the species and cultivar files (see Table 1).

The settings defined for the cabbage cultivar “Tastie” were used for adaptation of the cultivar and ecotype files of the Chinese cabbage cultivars “Beijing No.3” and “Spring Sun” (Table 2). The data of field experiments, described in detail in the companion paper (Feike et al., 2010) was used for parameterization and model testing. In total nine sets of Chinese cabbage were available. The experiments were conducted at three locations, two in Germany and one in China in 2008 and 2009 (Table 3).

Table 1. Tissue composition values (concentrations in g g^{-1} tissue dry weight) of cabbage as defined in CROPGRO and values for Chinese cabbage as reported in the literature (Lima, 2009; Pokluda, 2008; USDA, 2009; Wills, 1984). Seed and shell tissue parameters are "translated" to head tissue in Chinese cabbage.

Compounds	**Tissue**	**Actual tissue**	**CROPGRO coefficient**	**Cabbage**	**Chinese cabbage**	**Values reported in literature on Chinese**
Proteins	Leaf	Outer leaves	PROLFG	0.24	0.25	0.240-0.275
	Stem	Stem	PROSTG	0.11	0.115	0.115-0.229
	Shell	Head	PROSHG	0.15	0.214	0.214 [†]
	Seed	Head	SDPROG	0.18	0.214	
	Seed: minimum[§]	Head	PROMIN	0.02	Same	
	Seed: maximum[§]	Head	PROMAX	0.04	Same	
Lipids	Leaf	Outer leaves	PLIPLF	0.024	0.02	0.018-0.024
	Stem	Stem	PLIPST	0.017	0.014	0.001-0.019
	Shell	Head	PLIPSH	0.024	0.036	0.036[†]
	Seed	Head	SDLIP	0.024	0.036	
Lignins	Leaf	Outer leaves	PLIGLF	0.111	0.1	0.093–0.109 [‡]
	Stem	Stem	PLIGST	0.076	0.093	
	Shell	Head	PLIGSH	0.111	0.1	
	Seed	Head	PLIGSD	0.111	0.1	
Minerals	Leaf	Outer leaves	PMINLF	0.043	Same	0.093 [‡,¶]
	Stem	Stem	PMINST	0.03	Same	
	Shell	Head	PMINSH	0.043	0.065	0.065[†]
	Seed	Head	PMINSD	0.043	0.065	
Carbohydrate-cellulose	Leaf	Outer leaves	PCARLF	0.502	0.6	0.458-0.807
	Stem	Stem	PCARST	0.675	0.743	0.743-0.887
	Shell	Head	PCARSH	0.626	0.6	0.458-0.807
	Seed	Head	PCARSD	0.606	0.6	
Organic acids	Leaf	Outer leaves	POALF	0.036	0.044	0.044[‡]
	Stem	Stem	POAST	0.024	Same	
	Shell	Head	POASH	0.036	0.044	
	Seed	Head	POASD	0.036	0.044	

[†] Range values reported in the literature for "shredded heads".

[‡] Range values reported in the literature for "homogenized plant" including head, outer leaf and stalk tissue.

[§] Minimum and maximum values of seed protein content used in CROPGRO to account for variability in nitrogen and protein content as a function of environmental conditions.

[¶] Minerals in ash.

Table 2. Cultivar specific parameters for the cabbage cultivar "Tastie" and the two Chinese cabbage cultivars "Beijing No.3" and "Spring Sun" used for calibrating CROPGRO.

Description of variable	**Parameter**	**Units**	**Cabbage**	**Chinese cabbage**	**Chinese cabbage**
Cultivar unique code	VAR#	None	9900001	CC00001	CC00002
Cultivar name	VRName	None	"Tastie"	"Beijing No.3"	"Spring Sun"
Code for the ecotype to which this cultivar belongs	ECO#	None	CB0401	CC0401	CC0402
Time between plant emergence and flower appearance (initiation of head formation) (R1)	EM-FL	Photothermal days	26	27	24
Time between first seed (head formation) (R5) and physiological maturity (R7)	SD-PM	Photothermal days	55	50	50
Time between head formation and end of leaf expansion	SD-LF	Photothermal days	42	12	40
Maximum leaf photosynthesis rate at 30°C, 350 vpm CO_2 and high light	LFMAX	mg $CO_2 m^{-2} s^{-1}$	1.03	4.2	2.8
Specific leaf area of cultivar under standard growth conditions	SLAVR	$cm^2\ g^{-1}$	220	220	350
Maximum size of full leaf	SIZLF	cm^2	50	500	500
Maximum fraction of daily growth that is partitioned to head	XFRT		0.6	0.45	0.5
Time required for cultivar to reach final pod load (head weight) under optimal conditions	PODUR	Photothermal days	40	40	90
Fraction protein in head	SDPRO	g(protein)/g(head)	0.18	0.214	0.214
Fraction oil in head	SDLIP	g(oil)/g(head)	0.02	0.036	0.036

Table 3. Experimental locations, years and seasons providing data for model development and testing.

Location	Country	Longitude degree (°)	Latitude degree (°)	Elevation (m.s.l.)	Year	Growing season	Start of experiment	Mean temperature (°C)	Accumulated rainfall (mm)	Accumulated irrigation (mm)	Cultivar	Planting method	Measurements[†]
Hohenheim	Germany	48.42	9.11	389	2008	Summer	07/25/2008	17.4	331	30	Kasumi	Transplanting	LSD, YCF
Ihinger Hof	Germany	48.44	8.55	484	2008	Autumn	08/31/2008	9.9	170	30	Yuki	Transplanting	LSD, YCF
Ihinger Hof	Germany	48.44	8.55	484	2009	Spring	04/16/2009	13.1	173	17.5	Spring Sun	Transplanting	LSD, YCD, PS, SLA, HI
Ihinger Hof	Germany	48.44	8.55	484	2009	Summer	06/19/2009	17.5	228	17.5	Kasumi	Transplanting	YCD, HI
Ihinger Hof	Germany	48.44	8.55	484	2009	Autumn	08/20/2009	11.6	124	50	Beijjng No.3	Transplanting	LSD, YCD, PS, SLA, LAI, HI
Quzhou	China	36.52	115.01	36	2008	Spring	04/15/2008	20.6	142	170	Spring Sun	Transplanting	YCD, HI
Quzhou	China	36.52	115.01	36	2008	Autumn	08/07/2008	18	115	28.6	Beijjng No.3	Direct sowing	LSD, YCD, PS, SLA, LAI, HI
Quzhou	China	36.52	115.01	36	2009	Spring	04/16/2009	19.8	73	108	Spring Sun	Transplanting	YCD, HI
Quzhou	China	36.52	115.01	36	2009	Autumn	08/13/2009	18.8	128	165.7	Beijjng No.3	Direct sowing	LSD, YCD, PS, SLA, LAI, HI

[†] Key to measurements: LSD: number of leaves; YCF: yield component fresh matter; YCD: Yield component dry matter; PS: plant size; SLA: specific leaf area; LAI: leaf area index; HI: harvest index.

Measurements of plant characteristics, growth and development, including biomass accumulation, leaf area index, specific leaf area, leaf number, and plant size, were conducted on a weekly to monthly basis in the respective experiments. Plant nitrogen content was additionally determined in the "Ihinger Hof" experiment in 2009. The model was first calibrated for head development based on the time series data, as the accurate simulation of the development of the economic tissue was considered most important. Subsequently the model was calibrated for total above ground biomass, specific leaf area, and leaf area index, minimizing the error between the observed and predicted values. The plotting tool GBuild, which is part of the DSSAT v.4.5 shell was used to visualize simulated vs. observed data during development and validation phase, and to calculate the validation statistics. Additionally to the root mean square error (RMSE) the index of agreement (d) (Willmott, 1981), which is a more reasonable tool when comparing time course data, was used to determine the validity of the model. The model was developed based on the 2008 autumn set of the Quzhou experiment, which was directly sown using cultivar "Beijing No.3". After the adjustment of cardinal temperatures and tissue composition values, the daily canopy assimilation rate PHTMAX was increased from 61 to 92 g CH_2O $m^{-2}day^{-1}$ to account for the more vigorous growth and higher biomass accumulation of Chinese cabbage compared to white cabbage. Additionally leaf growth, canopy development and other parameters were adjusted. A list of the major changes from cabbage to Chinese cabbage in the species file is presented in Table 4. Finally the model was tested using the field data of the remaining Chinese cabbage data sets.

Table 4. Major adaptations to Chinese cabbage in the CROPGRO species file.

Process	**Coefficient value**	**Source of data**
Daily canopy assimilation rate (PHTMAX)	92 g CH_2O $m^{-2}day^{-1}$	Calibration with trial data
Specific leaf area of the standard reference cultivar at peak early vegetative phase (SLAREF)	400 cm^2 g^{-1}	Derived from trial data
Leaf area for the leaf at the 5th node position (SIZREF)	550 cm^2	Derived from trial data
Maximum specific leaf area under low light (SLAMAX)	550cm^2g^{-1}	Derived from trial data
Minimum specific leaf area under high light (SLAMIN)	30 cm^2g^{-1}	Derived from trial data
Curvature of the daily response of specific leaf area to incoming solar radiation (SLAPAR)	-.015	Calibration with trial data

Sensitivity analysis

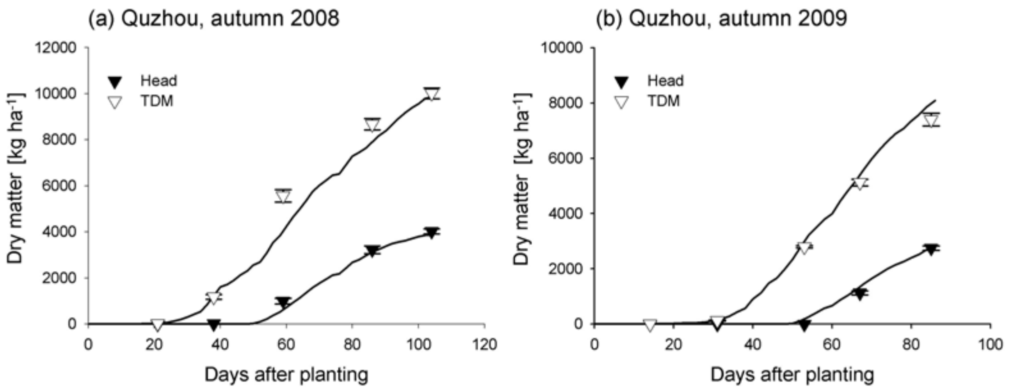
Sensitivity analysis was conducted testing four irrigation and four fertilization strategies and their respective combinations. Analysis was run, using soil and weather data of Quzhou experimental station. Daily minimum and maximum air temperature, precipitation and solar radiation were available for 2001 to 2009. Initial soil conditions were defined at 50 % available soil water and a nitrogen content of 75 kg ha^{-1}, which are reasonable values in intensive vegetable rotations in Asia (Neeteson, 1995; Nyvall, 2002). The 8 Aug. was selected as sowing date, similar to the actual sowing dates of the field experiments of 2008 and 2009. The irrigation strategies were constituted of zero irrigation, one application, two applications and three applications at day zero, day 15 and day 30 after planting, respectively. For each application 20 mm were applied. Fertilization was applied before sowing for all treatments, comprising a zero treatment, 100, 200 and 300 kg ha^{-1}.

To asses the possibility of late sowing of autumn Chinese cabbage in southern Hebei province, six different sowing dates were tested on cultivar “Beijing No.3” over the nine years of weather data of Quzhou. Sowing dates were delayed weekly starting 8 Aug., with the12 Sept. being the last sowing date.

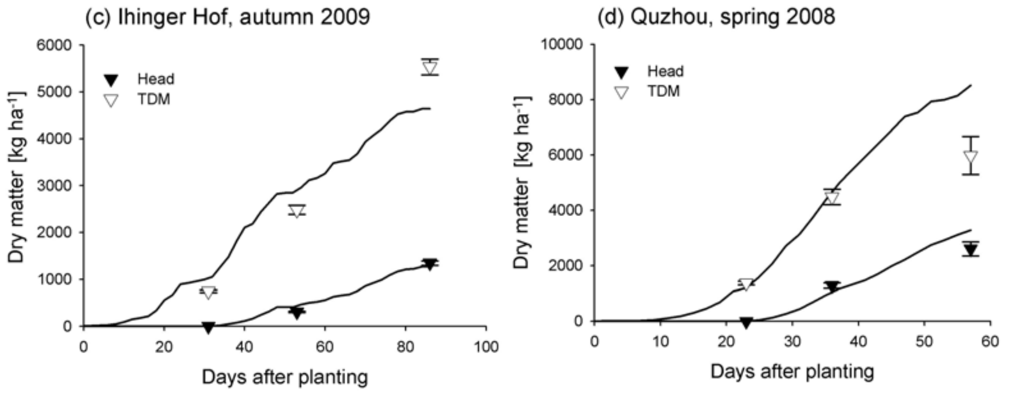
Results and discussion

Head and total above ground dry matter (TDM)

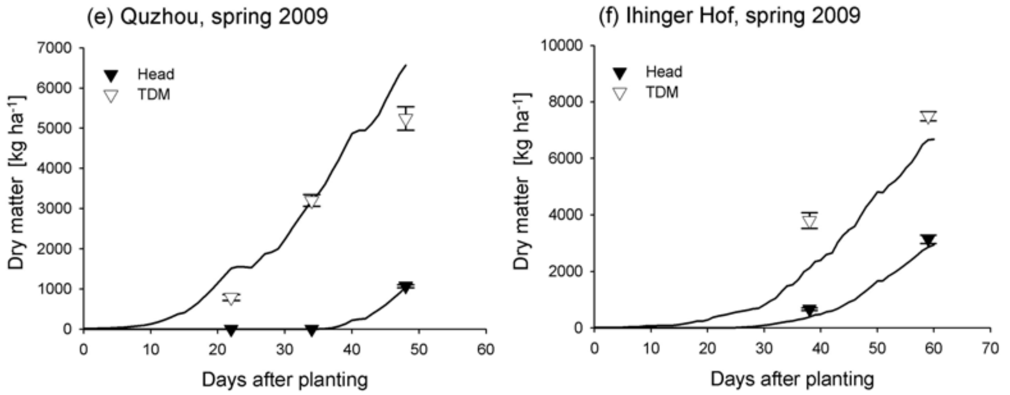
Head dry matter was simulated very well over all datasets (Fig. 1). Both, development and final head dry matter showed a high correlation with most experiments’ indexes of agreement (d) above 0.98. Only in both spring sets of the Quzhou experiment, final head weight was slightly overestimated. Overestimation was even stronger for the total above ground dry matter (TDM), which is the sum of leaf, stem and head dry matter. The major reason was that in both years leaf tip burn and head rot disease occurred towards the end of the spring experiments in Quzhou. The parameterization of major pest damages of Chinese cabbage and incorporation into DSSAT can further improve model prediction. At the Ihinger Hof experiment TDM was somewhat overestimated in both sets. We assume that the soil’s mineralization potential was under predicted, which resulted in nitrogen stress and reduced biomass accumulation.


(a) Quzhou, autumn 2008

(b) Quzhou, autumn 2009


(c) Ihinger Hof, autumn 2009

(d) Quzhou, spring 2008


(e) Quzhou, spring 2009

(f) Ihinger Hof, spring 2009

Fig. 1. Simulated (lines) and observed (data points) development of head dry matter (▼) and total above ground dry matter (TDM) (▽) over six independent data sets. Vertical bars are twice the standard error of the mean.

Leaf area index and specific leaf area

Leaf area index (LAI) represents the main parameter influencing biomass accumulation as it determines interception of solar radiation and influences water, gas and energy exchange (de Jesus et al., 2001). During model development the focus was rather on correct simulation of LAI development over time than on the final LAI value. An imprecise prediction of LAI during early growth stage would create a stronger error on yield formation, compared to an inaccurate prediction just before harvest. In both years final LAI of the Quzhou experiments was slightly overestimated (Fig 2 (a) and (b). As the field data showed a decline of leaf area towards the end of the growing season, it is assumed that leaf senescence is predicted too low by the model.

The reference values for leaf area (SIZREF) and specific leaf area (SLAREF) were set to 550 cm^2 and 400 $cm^2\ g^{-1}$, respectively, according to the observed field data. The simulated specific leaf area (SLA) was slightly higher than the observed (Fig. 3), except the measurement of the Quzhou 2009 autumn set just before head formation. However, the simulation lines followed the observed data. The slight overestimation of SLA, which means that leaves are assumed to be thinner than they actually are, does automatically lead to a slight underestimation of leaf dry matter, given a correct simulation of leaf area.

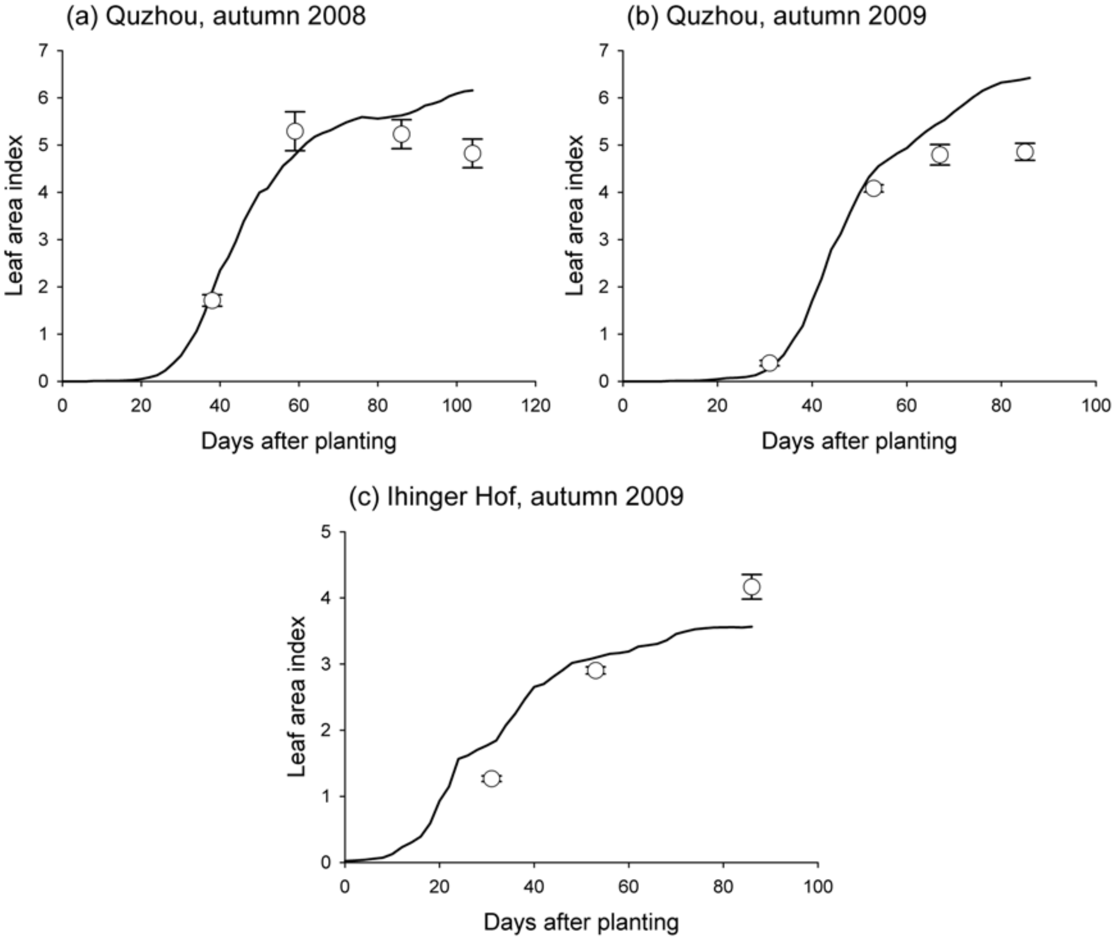


Fig. 2. Simulated (lines) and observed (data points) development of leaf area index of the autumn Chinese cabbage sets of Quzhou and Ihinger Hof. Vertical bars are twice the standard error of the mean.

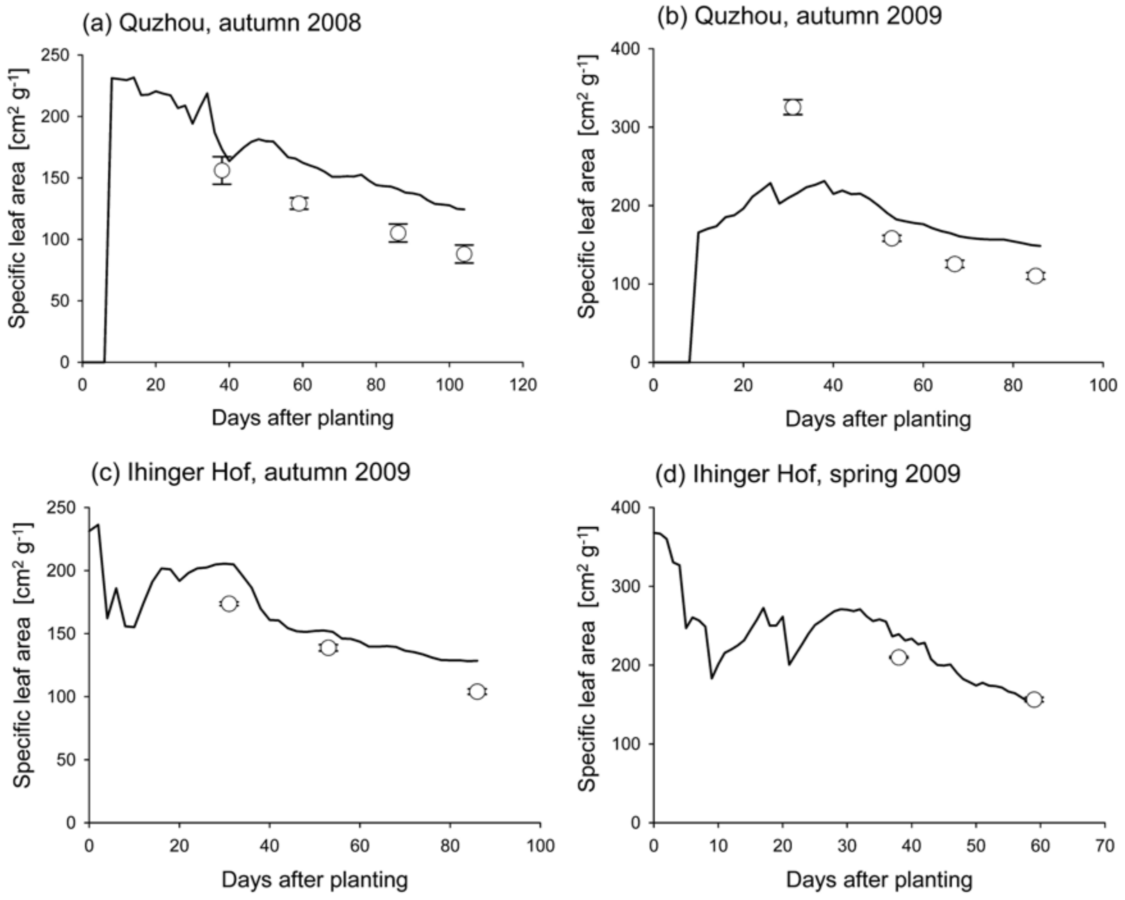


Fig. 3. Simulated (lines) and observed (data points) development of specific leaf area of the autumn Chinese cabbage sets of Quzhou and spring and autumn sets of Ihinger Hof. Vertical bars are twice the standard error of the mean.

Leaf and stem dry matter

Six datasets were available for calibration and testing of leaf and stem dry matter development. In general predicted development followed the trend of observed data (Fig. 4). However, stem dry matter was strongly overestimated in most data sets. At the same time, leaf dry matter was underestimated. As mentioned above, total above ground dry matter was predicted well. Therefore underestimation of leaf and overestimation of stem dry matter compensated one another. This can be explained by the fact that the petiole of Chinese cabbage was completely attributed to leaf matter during field measurements. It seems that the model allocated at least part of the petiole to stem dry matter, which makes sense, considering that the petiole is hardly photosynthetically active.

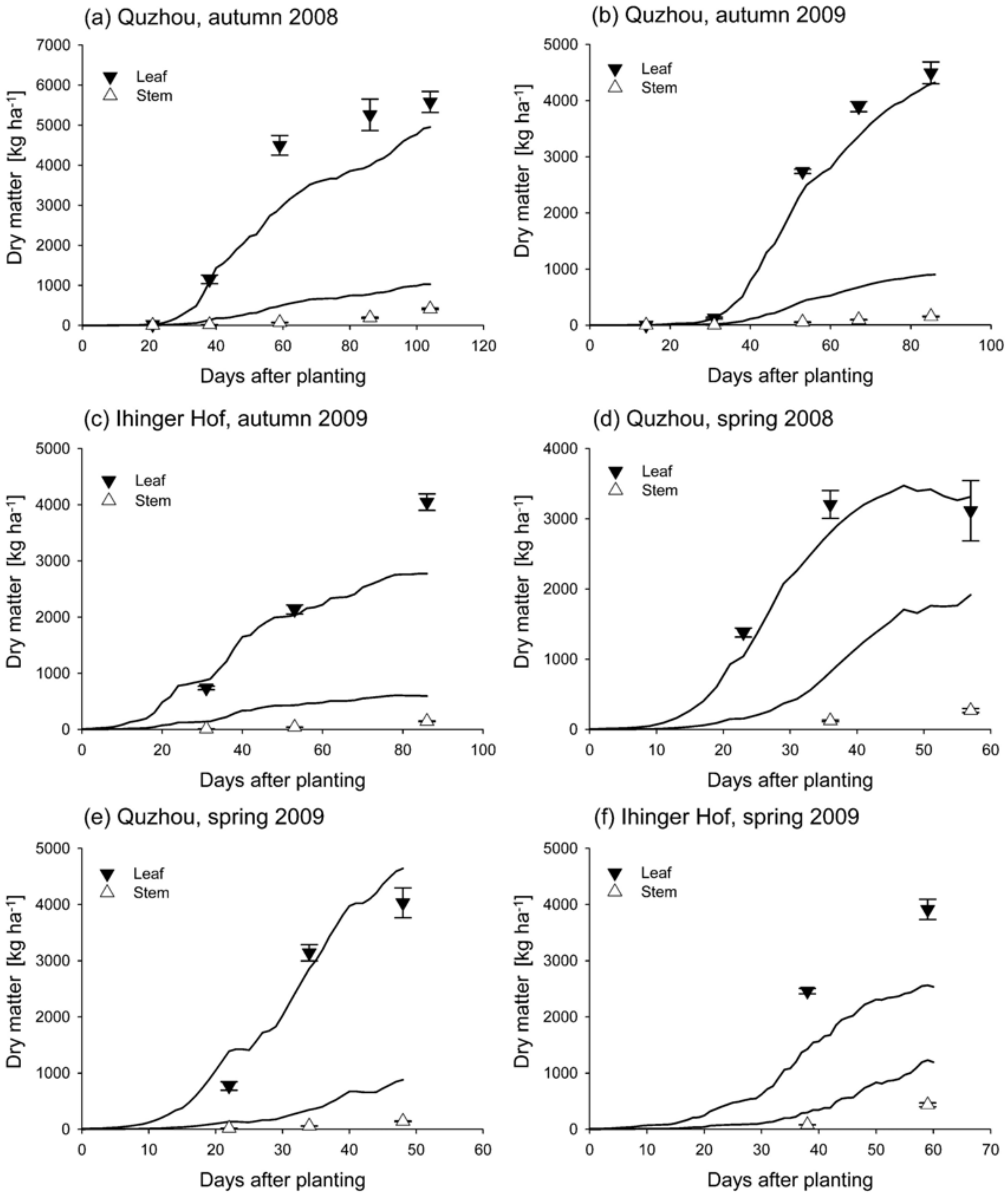


Fig. 4. Simulated (lines) and observed (data points) development of leaf dry matter (▼) and stem dry matter (▽) over six independent data sets. Vertical bars are twice the standard error of the mean.

Number of leaves

Leaf number developments were predicted satisfactory for the two directly sown autumn sets of Quzhou. Again, leaf senescence seemed to be calculated too low, which resulted in an overestimation of final number of leaves. Predictions of leaf number of the transplanted Chinese cabbage of the Ihinger Hof autumn 2009 experiment revealed a major limitation of the transplanting options in DSSAT 4.5. Simulated and observed values follow a very similar slope (Fig. 5 (c)). However, initial leaf number at the day of transplanting was heavily overestimated. Seedlings were transplanted at five leaf stage, but the model calculated the seedlings to have developed approximately 12 leaves by that time. The model assumes an unimpeded and continuous growth process from sowing until harvest, ignoring any disturbance caused by the transplanting process. However, in practice Chinese cabbage seedlings, same as seedlings of other leafy vegetables are mostly pre-grown in multipot-plates. The volume of the growth medium available per seedling is limited, what might slow down plant growth towards the end of the pre-growing period (McKee, 1981). Additionally transplants have to be packed, stored and transported, what causes further stress to the plants. Finally seedlings might suffer transplanting shock, caused by root damage and change in microclimate and soil physical and chemical properties (Salam et al., 2001). Until now, the crop management data tool XBuild, which is embedded in the DSSAT 4.5 shell, offers various parameterization options for transplants, such as pre-growing temperature, initial sprout length or planting material dry weight. By enabling the definition of leaf number of transplants, the accuracy of the Chinese cabbage model could be further improved.

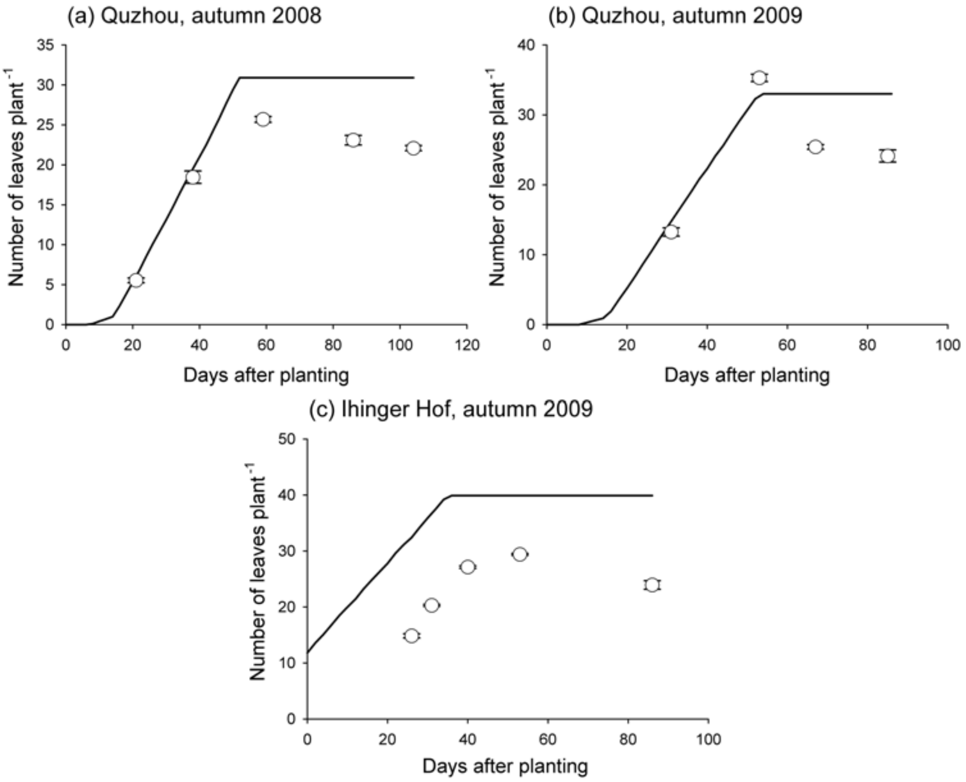


Fig. 5. Simulated (lines) and observed (data points) development of leaf number of the autumn Chinese cabbage sets of Quzhou and Ihinger Hof. Vertical bars are twice the standard error of the mean.

Canopy height and width

In CROPGRO development of plant height and width are calculated based on the plants' number of leaves. As a result the above described overestimation of transplants' leaf number, automatically leads to an overestimation of plant size and width of transplanted Chinese cabbage (Fig. 6 (c)). However, for the directly sown Chinese cabbage of the Quzhou experiment (Fig. 6 (a) and (b)) simulated and observed values are close to each other. The model restricts plant width not to exceed inter-row spacing, which was 60 cm for the Quzhou experiments. Nevertheless, in the field plants' leaves do not stop expansion at row boarders, but slightly overlap the neighboring plants. Hence, observed values of plant width were regularly above 60 cm.

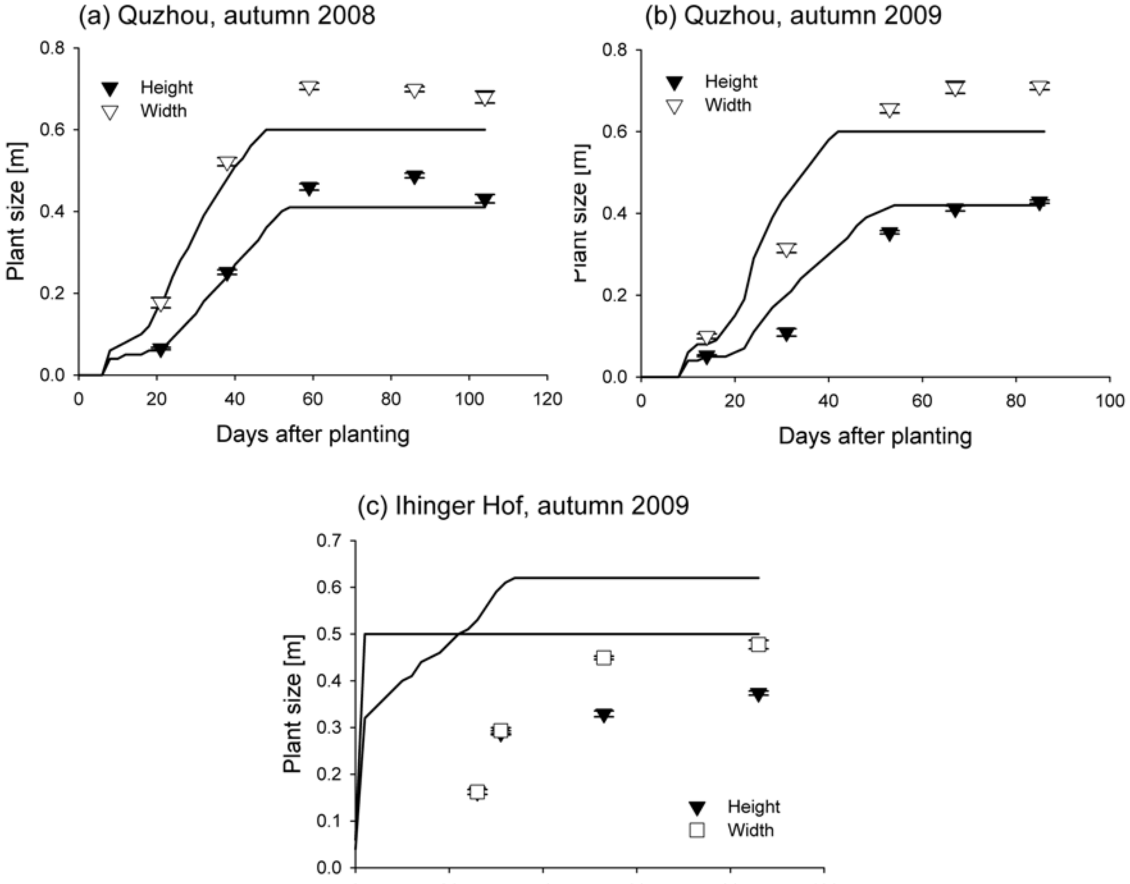


Fig. 6. Simulated (lines) and observed (data points) development of plant size of the autumn Chinese cabbage sets of Quzhou and Ihinger Hof. Vertical bars are twice the standard error of the mean.

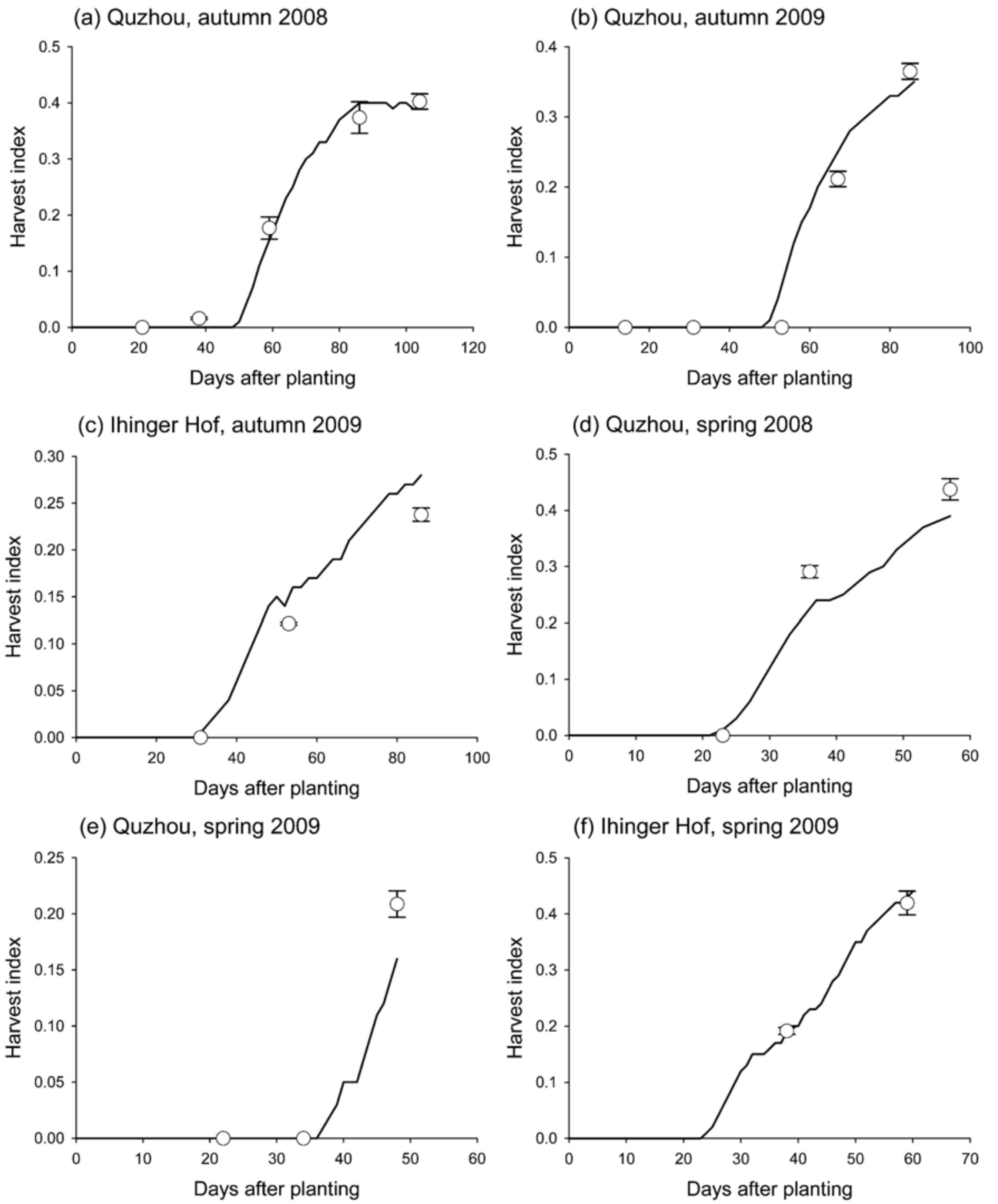


Fig. 7. Simulated (lines) and observed (data points) development of harvest index of the autumn and spring Chinese cabbage sets of Quzhou and Ihinger Hof. Vertical bars are twice the standard error of the mean.

Harvest index

Simulated harvest index fit the observed data very well (Fig. 7). Only in the spring sets of Quzhou final harvest index was slightly underestimated. A small discrepancy in timing of head formation could be seen in the developments of harvest index of the two autumn sets of Quzhou (Fig. 7 (a) and (b)). Head formation is defined as the time when "the two youngest leaves do not unfold completely" (Meier, 2001). This phenological criterion is much more difficult to be determined in the field, compared to e.g. flowering in soybean or silking in maize. Different researchers might show variations in perception of a leaf being “completely unfolded” or “still folded”. Hence, our focus was not too much on timing of head formation, but all the more on development and final values of harvest index and pod weight, which were both simulated very well.

To further improve the model, the parameterization of a pest sub-module for Chinese cabbage, as well as the extension of the transplanting option to enable the definition of number of leaves of seedlings is suggested. Beyond that, the integration of a new sub-module that computes vernalisation of Chinese cabbage and enables the prediction of flowering is recommended. Flowering leads to premature bolting and unmarketable cabbage heads. As cold temperatures during early growth induce vernalisation (Pressmann and Shaked, 1988), the problem mainly occurs in spring production. With advances in plant breeding (Zhang et al., 2006; Ajisaka et al., 2001), and the development of late bolting varieties the problem might decrease. However, it is still a major issue for Chinese cabbage producers all over the globe. Various research groups have concentrated on the phenomena (Elers and Wiebe, 1984; Hernandez et al., 2004; Moe and Guttormsen, 1985; Yui and Hida, 2002), of which some developed simple mathematical models (Krug and Kahlen, 2008; Matsui et al., 1978; Mori et al., 1979) that might serve as a base for development of a vernalisation sub-module in DSSAT. Vernalisation sensitivity is highly depending on the cultivar (Zhang et al., 2006). Therefore sensitivity will have to be defined in the ecotype (ECO) or cultivar (CUL) file of the Chinese cabbage model.

Sensitivity analysis of the validated model

Potential yield under varying irrigation and fertilization

To overcome persistent overuse of fertilizer and irrigation water in Chinese cabbage production, the prediction of yields under varying input levels can generate viable information. It could be shown that under the existing soil and climatic conditions of Quzhou experimental station, the application of 200 kg N ha^{-1} does not create higher yields in average over nine years. The highest average yield of 3656 kg head dry matter ha^{-1} was realized with an application of 100 kg N ha^{-1} and three irrigation applications. The reduction of irrigation to two and even one application only caused slight yield losses which resulted in 3355 and 3231 kg ha^{-1} head dry matter respectively. However, the reduction to zero irrigation and zero fertilization reduced the yields significantly. The reasons for the drastic yield losses are illustrated by the accumulated water and nitrogen stress factors. The highest water stress factor was observed for the zero irrigation and 300 kg N ha^{-1} combination. This is very reasonable as high nitrogen application rates evoke excessive leaf formation, which results in high transpiration rates and a depletion of soil moisture. Accumulated nitrogen stress is highest in the zero N treatments. Fairly small variations could be observed between the 100 and the 300 kg N ha^{-1} treatment. The results prove that a reduction of nitrogen application rates below 200 kg N ha^{-1} is highly recommendable for the Quzhou conditions. Irrigation application can be reduced to one time, with only small yield reduction in most years.

Table 5. Simulated (mean, S.D., 10th and 90th percentile) head dry matter, accumulated water stress factor and accumulated nitrogen stress factor for cultivar "Beijing No.3" at Quzhou experimental station, using actual weather data from 2001 to 2009.

Irrigation	Fertilization	Head dry matter [kg ha^{-1}]				Accumulated water stress factor				Accumulated nitrogen stress factor			
		Mean	S.D.	10th	90th	Mean	S.D.	10th	90th	Mean	S.D.	10th	90th
none	none	2057	680	1153	2861	0.24	0.32	0	0.51	15	3	11.2	18.2
none	100 kg	2827	1022	1465	4021	1.76	2.24	0.13	4.73	10.5	5.5	3.6	16.8
none	200 kg	2743	883	1477	3667	1.82	2.32	0.13	4.83	9.2	6.6	0.7	16.7
none	300 kg	2693	837	1477	3496	1.83	2.36	0.13	4.95	9	6.6	0.5	16.6
1 x 20 mm	none	2309	526	1735	2940	0.26	0.37	0	0.81	14.3	2.9	11.1	17.4
1 x 20 mm	100 kg	3231	828	2159	4050	1.78	2.16	0.08	3.95	8.9	5	3.2	14.4
1 x 20 mm	200 kg	3144	715	2176	3727	1.77	2.11	0.08	3.84	7.3	6	0.2	13.7
1 x 20 mm	300 kg	3084	692	2189	3796	1.76	2.09	0.08	3.83	7	6	0.1	13.5
2 x 20 mm	none	2466	462	1978	2959	0.28	0.32	0	0.56	14.1	2.7	11.3	16.8
2 x 20 mm	100 kg	3481	764	2606	4100	1.58	2.13	0.08	5.08	7.8	4.8	3.1	13.2
2 x 20 mm	200 kg	3355	671	2638	3953	1.54	2.15	0.08	4.96	5.7	5.8	0.2	12.2
2 x 20 mm	300 kg	3281	660	2650	3877	1.53	2.16	0.08	4.88	5.2	5.8	0.1	11.7
3 x 20 mm	none	2546	398	2116	2890	0.34	0.49	0	0.79	13.9	2.5	11.5	16.6
3 x 20 mm	100 kg	3656	675	2932	4141	1.4	2.19	0.08	3.93	6.9	4.3	3.2	11
3 x 20 mm	200 kg	3493	604	2935	4206	1.35	2.23	0.01	3.76	4.3	5.3	0.1	9.6
3 x 20 mm	300 kg	3378	604	2900	4158	1.32	2.22	0.01	3.62	3.9	5.3	0.1	9.1

Effect of late sowing on yield potential

Testing of late sowing dates was undertaken, to evaluate the possibility of cultivating Chinese cabbage in sequence after summer crops like spring maize, bush bean or other vegetables. The fertilizer and irrigation levels were set to 100 kg N ha^{-1} and one irrigation application. This combination proved to be most reasonable, following the results of the sensitivity analysis above. The best sowing date was 15 Aug., with an average yield of 3319 kg ha^{-1}. However, planting between 8 Aug. and 22 Aug. did not cause strong yield variations. From 29 Aug. onwards average yield declined steadily. Beginning of September represented the critical time, with average yields falling to 1265 kg N ha^{-1} for the 12 Sept. plantings. The analysis generated useful and logical estimates from an agronomic standpoint, which will be helpful in further testing of cropping sequences with Chinese cabbage in DSSAT. However, data of both sensitivity analyses has to be tested in the field.

Table 6. Simulated head dry matter (Mean, S.D., 10th and 90th percentile) of cultivar “Beijing No.3” at Quzhou experimental station for different sowing dates, using actual weather data from 2001 to 2009.

	Head dry matter [kg ha^{-1}]			
Sowing date	Mean	S.D.	10th	90th
08 Aug.	3218	833	2159	4050
15 Aug.	3319	732	2462	4091
22 Aug.	3107	677	2363	4027
29 Aug.	2772	742	2013	3787
05 Sep.	2424	713	1671	3112
12 Sep.	1265	780	318	2213

Conclusions

Major model changes from CROPGRO-cabbage to simulate Chinese cabbage concentrated on plant tissue composition, photosynthesis rate, and leaf growth parameters. Chinese cabbage is characterized by a more vigorous growth, higher leaf appearance rate and a greater maximum leaf size of up to 500 cm^2 leaf^{-1}. Parameterization and model development proved successful, as growth and development of Chinese cabbage were simulated close to the observed data. The most important parameters: head weight, leaf area index and specific leaf area were simulated well over different locations, years and seasons. Simulation of leaf number and plant size were only satisfactory for the two directly sown Chinese cabbage sets. After an extension of the transplanting option in DSSAT, to enable the definition of leaf number of seedlings (which is not possible up to now), prediction of leaf number and plant size of transplanted Chinese cabbage should be improved greatly. In summary, CROPGRO generates accurate predictions of the crucial parameters. Hence, we conclude that CROPGRO can be used to estimate potential yield of Chinese cabbage under different environments and management strategies.

Sensitivity analysis confirmed the reliability of the model, producing reasonable results, which are logical from an agronomic point of view. At the Chinese location the simulation over nine years of actual weather data, recommended that increasing fertilization from 100 to 200 kg N ha^{-1} did not lead to significant yield increases. In most years a single irrigation application proved sufficient to ensure a high yield level. However, the highest average yield was realized with three irrigation applications. Furthermore, testing of late sowing dates suggests that Chinese cabbage planting has to be accomplished until end of August to generate a satisfactory yield.

For the necessary further improvement of CROPGRO-Chinese cabbage we see bright prospects. The popularity of DSSAT combined with the skills, knowledge and field data of the numerous research groups working with Chinese cabbage in East Asia and worldwide can greatly contribute to e.g. parameterize major pest damages of Chinese cabbage, develop a vernalisation sub-module to predict premature bolting, or improve predictions for soil nutrient management.

Acknowledgements

We want to thank the German Research Foundation (DFG, GRK 1070) and the Ministry of Education of P.R. China (special fund for agriculture profession (200803030) & innovative group grant of NSFC (No.30821003)) for their financial support.

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9 Light competition in Chinese cabbage/maize strip intercropping systems

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Publication V

Feike, T., S. Munz, S. Graeff-Hönninger, Q. Chen, J. Pfenning, G. Zühlke, and W. Claupein. 2010. Light competition in Chinese cabbage/maize strip intercropping systems. GI-Edition - Lecture Notes in Informatics (LNI) “Precision Agriculture Reloaded – Informationsgestützte Landwirtschaft”, pp. 65-68 (published).

http://subs.emis.de/LNI/Proceedings/Proceedings158/57.pdf

The CROPGRO model proved to reliably simulate growth and development of Chinese cabbage, described in the fourth article. The conducted sensitivity analysis demonstrated the potential applications of the model. The identification of viable input levels of nitrogen fertilizer and irrigation, or the testing of crop performance at different sowing dates generated agronomically logical and expressive results. As the CROPGRO model was initially developed to simulate crop growth under monocropping conditions, ways have to be found how to simulate the altered resource availabilities of intercropping systems. The by far most prominent change in growth factor availability in the selected Chinese cabbage – maize strip system regards solar radiation. Hence, the ***fifth article*** *covers the identification and quantification of the availability of photosynthetically active radiation at various locations within the Chinese cabbage strip.*

Abstract

With working force moving out of agriculture and steadily increasing use of machinery, traditional intercropping systems are practiced less and less in China. If intercropping is to have a future, new high yielding intercropping systems that can easily be mechanized have to be developed. The advantage of intercropping over monocropping lies within a potentially higher resource capture. In this respect, competition for solar radiation plays a key role, for optimizing the design of intercropping systems. A strip intercropping experiment with Chinese cabbage and maize was conducted at the "Ihinger Hof" research station of Hohenheim University in Southwest Germany in 2009. Wide strips of Chinese cabbage were planted between wide strips of maize. To determine the reduction in incoming radiation in the Chinese cabbage strips caused by the shading of the higher maize plants photosynthetically active radiation (PAR) was measured regularly. The center of the strips served as the reference (monocropping situation), as the shading by maize was negligible. Measurements were conducted in certain distance from the neighboring maize using a handheld PAR-meter. Simultaneous and continuous measurements and thus the direct quantification of differences in total daily incoming radiation at different locations in the Chinese cabbage strips was not possible. By polynomial regression of the timeline data measured over the course of the day for every location within the strip, the differences in incoming radiation could be determined as the integrals of the polynomials. A significant reduction in incoming PAR was identified for the first three rows of Chinese cabbage next to maize; with the lowest values of 70% and 56% in row 1 west and row 1 east respectively. As yields in these rows close to maize was significantly lower than in the center of the strips, it is assumed that radiation was the limiting growth factor.

10 Production potential of strip intercropped Chinese cabbage in the North China Plain

Publication VI

Feike, T., Q. Chen, S. Graeff-Hönninger, Y. Pan and W. Claupein. 2010. Production potential of strip intercropped Chinese cabbage in the North China Plain. Agronomy Journal (submitted).

The fifth article described the methodology and results of the determination of total daily available radiation in Chinese cabbage strips. In ***article six*** *the methodology is extended, which enables the prediction of light availability in strips of any theoretical width. This allows the testing of performance of strip intercropped Chinese cabbage in CROPGRO by adjusting the availability of solar radiation through the "environmental modifications" option. Finally, crop growth and yield formation are simulated for 12 locations and five soil texture groups of the NCP. By linking the results to a GIS, the production potential of strip intercropped Chinese cabbage is determined and illustrated over the entire NCP.*

Production potential of strip intercropped Chinese cabbage in the North China Plain

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Abstract

The management of competition is the key factor for optimizing intercropping systems. To determine resource availability and yield response in strip intercropping, field experiments with Chinese cabbage (*Brassica rapa* ssp. *pekinensis*) and maize (*Zea mays* L.), two major crops of the North China Plain were conducted in China and Germany in 2008 and 2009. The results showed that plant response is very much depending on the locally available radiation. In Germany significant yield reduction in autumn production of Chinese cabbage occurred due to the shading by the neighboring maize, whereas in China with incoming radiation being nearly twice as high, a similar degree of shading did not cause significant losses. Based on the quantified share of available radiation in the Chinese cabbage strip depending on the distance to the maize, available radiation in two theoretical systems, a three and a six row system was estimated. The CROPGRO model, which was calibrated and validated based on the field experiment data, was then employed to simulate growth and development of Chinese cabbage over the entire North China Plain. Performance under monocropping and strip intercropping conditions was simulated at 12 locations, over up to 30 years of weather data and tested for five soil texture classes. Yield decline of up to 18 % was determined for the three row system, while the plants grown in the six row system even overyielded the monocropped plants at some locations and soil types. The study asserts the importance of an adjustment of intercropping systems to local conditions.

Keywords: *Chinese cabbage, CROPGRO, North China Plain, intercropping, modelling, GIS*

Introduction

Sustainable farming has finally become a major issue in China's agricultural policy. The severe environmental degradation many parts of the country have experienced during the last decades urges the development of production systems that preserve natural resources while at the same time maintain high yield levels. In the North China Plain (Fig. 1), which is one of the major agricultural regions of China, environmental problems are aggravating. Since the beginning of the 1990s a strong increase in vegetable production could be observed (CSY, 2008). On one side the production of high value vegetable crops can help reducing the ever widening rural-urban income gap. On the other side vegetables demand high inputs of irrigation and agrochemicals, which contribute further to resource depletion and pollution (Chen, 2003).

An alternative production system for vegetables that has strong potential to reduce the severe resource degradation is intercropping. The simultaneous cultivation of two or more crops in the same field is a traditional production system in the North China Plain (Knörzer, 2009). Farmers intercrop various vegetables with cereals, cotton or other vegetables (Feike, 2010). Due to an often improved resource use efficiency and increased agro-biodiversity, inputs can be reduced and degradation caused by agricultural production can be minimized (Tsubo et al., 2001; Walker and Ogindo, 2003; Vandermeer, 1989). However, the already small share of intercropping among all cropping systems in the region is most likely to reduce further. The majority of the systems are row intercropping systems which demand a huge input of manual labour. Field preparation, sowing, plant protection and harvest have to be conducted by hand. In the past cheap labour had been inexhaustibly available in rural China, while land constituted the limiting production factor. Nowadays, with more and more people moving out of agriculture (CSY, 2008), labour intensive systems are loosing ground. Furthermore, use of agricultural machinery has increased tremendously since the beginning of the 1990s (HSY, 2008), which has a huge impact on the management and basically the design of cropping systems.

Therefore the potentially sustainable intercropping systems have to be adapted to fit the demands of modern agriculture. To enable mechanization of the majority of management measures in the system, the conversion into strip intercropping is a viable option. In this way, the beneficiaries of intercropping can be maintained, while the demand for manual labour is drastically reduced (Sullivan, 2003).

From an agronomic point of view the key to a successful intercropping system with high land use efficiency lies in the management of a tolerable degree of competition. To understand, describe and optimise such complex interactions between two different species, crop simulation models have demonstrated to be powerful tools (Baumann et al., 2002; Brisson et al., 2004; Kiniry et al., 1992). For the current study, the generic CROPGRO model was used. Chinese cabbage (*Brassica rapa* ssp. *pekinensis*) and maize (*Zea mays* L.) were selected as companion crops due to various reasons. First of all, the two crops differ strongly in their morphological, physiological and phenological development. Chinese cabbage is a small dicot C3 plant with planophile leaves; maize a tall monocot C4 plant with erectophile leaves. Hence, significant effects through interspecies interactions were ensured. Second, maize and Chinese cabbage constitute the number one cereal and vegetable crops of the North China Plain (CSY, 2008; Chen, 2003), with great agronomic and economic importance. And third, relay intercropping of spring maize and Chinese cabbage in rows is common practice in autumn season. Farmers plant seedlings of Chinese cabbage in between the rows of the fully developed spring maize, beginning of August. When maize is harvested approximately one month later, the Chinese cabbage crop is already established.

Furthermore, studying strip intercropping of maize and autumn Chinese cabbage offers one big advantage from the modeller's point of view: The general feature of intercropping, its complexity of below and above ground interactions is significantly reduced in the presented case. Below ground competition of the sufficiently irrigated and fertilized Chinese cabbage crop is negligible. Mechanical seedbed preparation will destroy eventually existing roots of the neighbouring maize in the upper soil layer, which will be the main rooting zone of Chinese cabbage for the time of coexistence. On the other hand a strong above ground competition for light occurs. The taller maize crop reduces the incoming solar radiation in Chinese cabbage significantly, all the more the closer the Chinese cabbage is located to the maize. Therefore cause and effect can be clearly identified and quantified.

In this paper we examine the production potential of monocropped and strip intercropped autumn Chinese cabbage in the North China Plain using the CROPGRO model linked to a GIS. The paper concentrates on the yield potential of the high value crop Chinese cabbage, as its yield will have a stronger effect on the economics and thus the success of the system. Maize purely serves as a partner in the field experiments and simulation, but its growth and yield potential are not part of the study. The specific objectives of the study were to (i) quantify the reduction in incoming radiation in Chinese cabbage depending on the distance to the neighbouring maize crop, (ii) determine plant response under reduced radiation, and (iii) identify the spatial and temporal variability of monocropped and strip intercropped Chinese cabbage yields due to climatic and soil differences over the entire North China Plain.

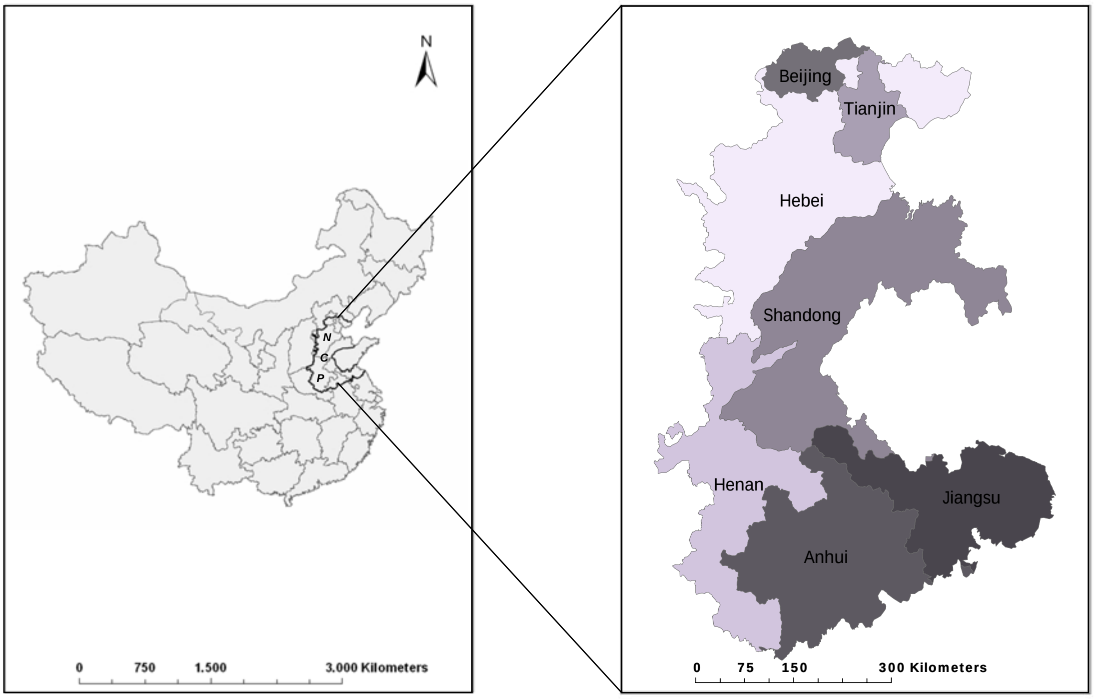


Fig. 1. The location of the North China Plain (NCP) in mainland China (left) and the location of the provinces within the NCP (right).

Materials and Methods

Field experiments

Data of two field experiments was used in this study. The first experiment (Exp.1) was conducted at the Quzhou experimental station of the China Agricultural University in 2008 and 2009. It is located in the southern part of Hebei province in the center of the North China Plain (36°52’21” N, 115°01’05“ E, 36 m.s.l.). Average annual rainfall is 416 mm with an average temperature of 14.3 °C. The soil is a calcaric fluvisol (WRB). In both years two sets of Chinese cabbage were cultivated in spring and autumn respectively. For all plantings compound fertilizer (15-5-15) was applied at a rate of 800 kg ha^{-1} before planting and 400 kg ha^{-1} just before canopy closure. Two irrigation treatments were applied: “farmer’s practice” and a reduced treatment. However, only data of the 100% irrigation treatment is used in the current study. The design was a completely randomized block design with four replications.

The second experiment (Exp. 2) was conducted in Southwest Germany at the “Ihinger Hof” experimental station of University of Hohenheim (48º44’39” N, 8º55’10” E, 484 m.s.l.) in 2009. The average yearly rainfall is 690 mm at an average temperature of 7.9 °C. The soil was a keuper with loess layers. Three sets of Chinese cabbage were cultivated in spring, summer and autumn, respectively. For every set 160 kg N ha^{-1} were applied as Calcium Ammonium

Nitrate before planting. Irrigation was applied in the first weeks according to demand. Four replications were available. Due to the alternating strips of Chinese cabbage and maize randomization was not possible.

In both experiments strips of Chinese cabbage were grown in north-south orientation next to strips of maize. In Exp. 1 maize was only grown east of Chinese cabbage, whereas in Exp. 2 maize was grown east and west (Fig. 2). The Chinese cabbage strips were designed with 12 and 20 rows in Exp.1 and Exp.2 respectively. The large number of rows ensured a sufficient number of plants, which were not in the least influenced by the neighboring maize. Significant effects on growth and development could only be identified from the first to the third row next to maize (Müller et al., 2009). Therefore row 4 and above accounted as monocropping. For the presented study only data of the autumn sets of Chinese cabbage were used. For all three sets of autumn Chinese cabbage cultivar "Beijing No.3" was planted next to the maize cultivars "Xian Yu 335" and "Companero" in Exp.1 and Exp.2, respectively. An overview of cultivation details is given in Table 1.

Table 1. Cultivation details of the autumn Chinese cabbage (CC) sets and the strip intercropped spring maize (SM) for the three experiment data sets.

Cultivation details	**Quzhou 2008**	**Quzhou 2009**	**Ihinger Hof 2009**
Planting method	direct sowing	direct sowing	transplants
Sowing/planting date CC	08/08/2008	08/13/2009	08/20/2009
Harvest date SM	09/16/2008	09/15/2009	10/12/2009
Harvest date CC	11/20/2008	11/07/2009	11/15/2009
Duration of coexistence [d]	39	33	53
Duration sole CC [d]	65	53	34
Total growth period CC [d]	104	86	87
Avg. radiation coexistence [MJ m^{-2} d^{-1}]	16.8	13.4	9.2
Avg. radiation sole [MJ m^{-2} d^{-1}]	10.1	12.2	4.0
Avg. plant height SM [cm]	273	254	244
Crop density SM [plants m^{-2}]	8.4	8.4	8.6
Crop density CC [plants m^{-2}]	4.2	4.2	4
Row spacing SM [cm]	60	60	75
Row spacing CC [cm]	60	60	50

Plant growth and development was examined in two to four weeks intervals in the respective experiments. Various plant parameters were measured including leaf area index, and dry matters of all plant parts; however for the prediction of yield potential presented in the current paper, we concentrate on Chinese cabbage head dry matter data. In both experiments, daily maximum and minimum temperature, precipitation and solar radiation were measured at standard weather stations located less then 200 meters from the experimental sites.

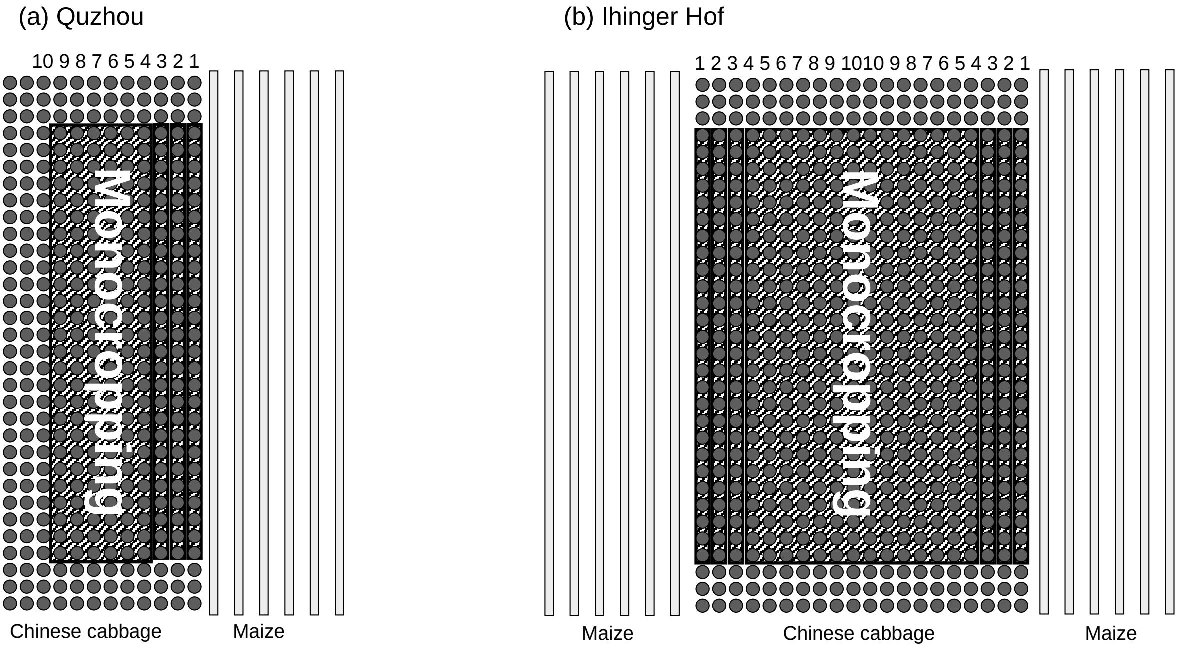


Fig. 2. Bird-eyes view of one replication of Exp.1 (a) and Exp.2 (b). Rows of Chinese cabbage are numbered consecutively starting with the rows next to maize.

Quantifying light competition

As stated above solar radiation was the main growth factor differing between the Chinese cabbage in monocropping and intercropping (close to the maize and in the middle of the strips). To determine the effect of shading by the maize crop and quantify the availability of photosynthetically active radiation (PAR) in the different rows of Chinese cabbage, AccuPar LP-80 Ceptometers (Decagon, Pullman, USA) were used in both experiments. To enable the estimation of total daily available radiation depending on the location in the strip, fast consecutive measurements were conducted with the handheld device in certain distance (row 1, row 2, row 3, etc) from the maize crop. The measurements were repeated in one to three hour intervals over the course of the day, to account for the changing position of the sun. To quantify the share of available solar radiation for each row, polynomials of degree four were fit to the measured PAR data points over the course of the day (Fig. 3).

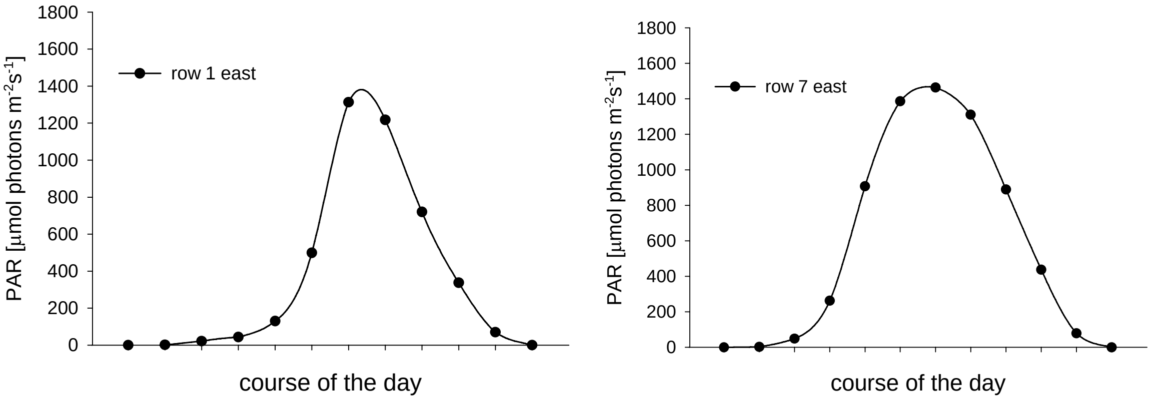
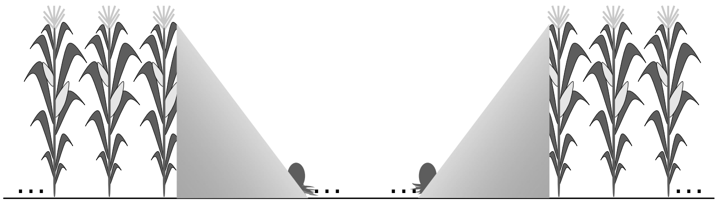


Fig. 3. Measured solar radiation values of the first row at the east side of the Chinese cabbage strip (left) and row 7 east (right). Row 1 east is shaded during the morning time, while row 7 does not suffer any shading during the course of the day.

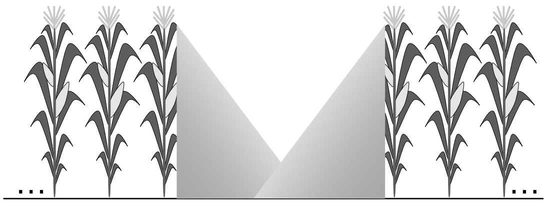
$$\int_{sunrise}^{sunset} f(x)dx = F(sunset) - F(sunrise) \qquad [1]$$

The integral of each polynomial (eqn.1), which is the area under the curves, represents the amount of daily available PAR. By dividing the integral of every single row by the integral of the data measured at the center of the sunlit strip, the share of available PAR was estimated for each row. In Exp.2 each row existed twice, once on the eastern and once on the western part of the strip. Therefore mean values were calculated to obtain a single value for every treatment.

(a) Experiment design



(b) Six-row system



(c) Three-row system

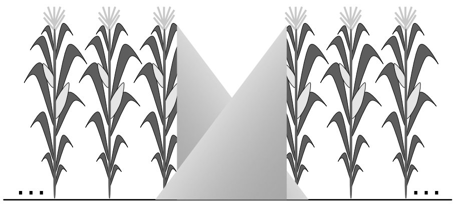


Fig. 4. Schematic description of the shading effects in the conducted experiments (a) and two theoretical strip intercropping systems (b and c).

In the next step the share of incoming radiation was estimated for two theoretical strip systems: a six-row and a three-row system. Applying a row spacing of 0.6 m, as used in Exp.1, three rows and six rows result in strip widths of 1.8 and 3.6 m, respectively, which represents common machinery working widths in field grown vegetables in China. In the theoretical systems the amount of incoming radiation decreases with decreasing strip width (Fig. 4). To estimate the potentially available radiation in such systems, the measured data of the field experiments were used. The applied method is illustrated in Fig. 5. To i.e. estimate the potentially incoming radiation in the most eastern row of a three-row system, we assume that the plants in that row are exposed to the conditions of "row 1 east" during morning time. In the afternoon, shading occurs from the west side of the strip, so that the plants are exposed to the light conditions of "row 3 west". After identifying the intersection of the two polynomials, the potentially available radiation can be determined for the specific row. The integral of the eastern row from sunrise to the two polynomials' intersection represents availability of sunlight during morning time, and the integral of the western row from the intersection point to sunset represents availability of sunlight in the afternoon. In this way the share of available PAR can be estimated for every single row in a three and six row system by dividing the calculated integrals by the integral of the sunlit row in the middle of the strip.

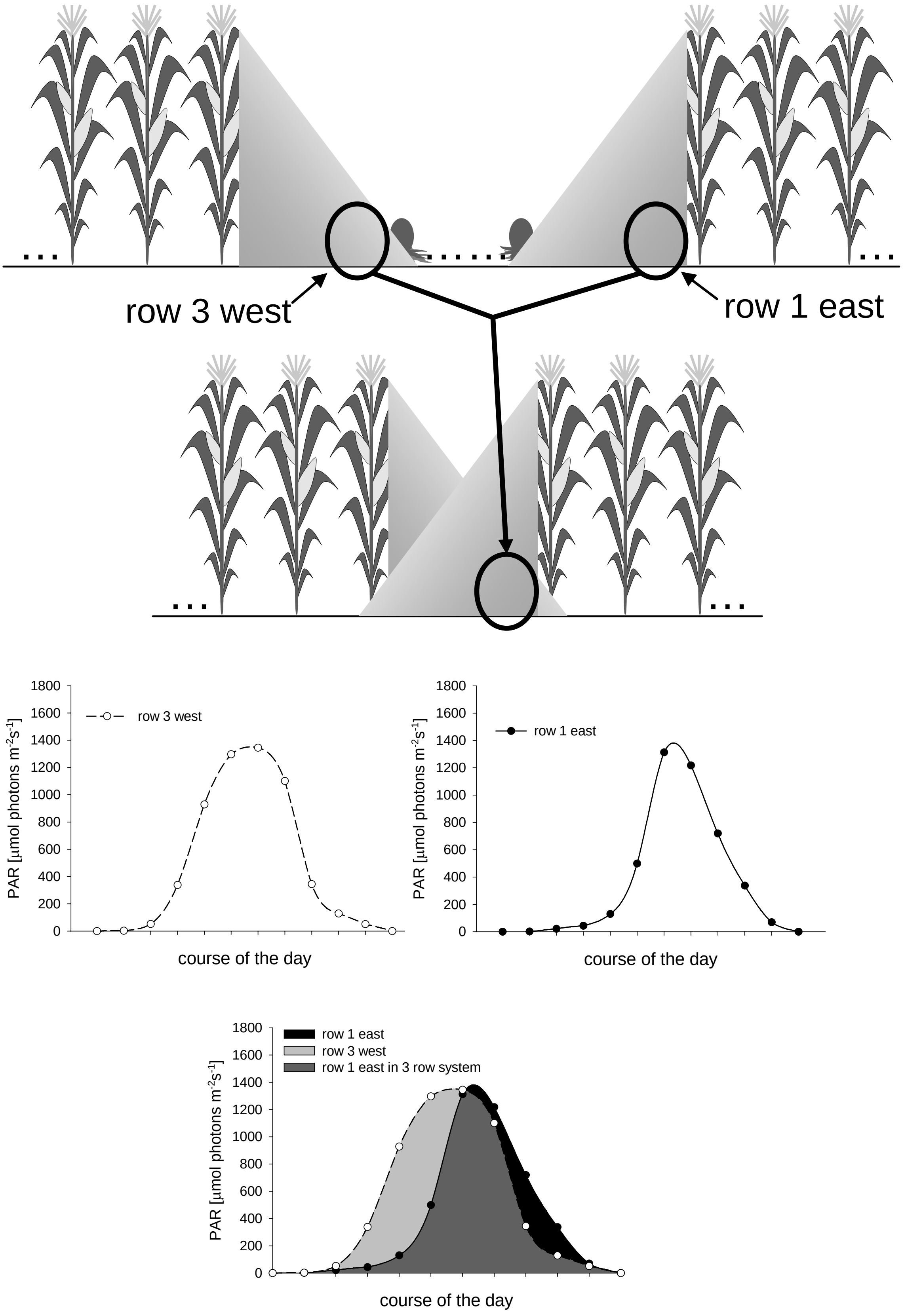


Fig. 5. Schematic (top) and graphical (bottom) description of the potentially available photosynthetically active radiation (PAR) in the most eastern row of a three-row system. The dark grey area in the bottom graph represents the available PAR in the most eastern row of the theoretical three strip system.

For Exp.1 shading information was only available for the morning time, as maize was only cultivated west of the Chinese cabbage strip. By mirror-inverting the measured solar conditions of the morning hours of each row, the solar conditions of the afternoon hours were generated. For the calculation of daily available PAR in the theoretical systems, the integrals were then calculated from sunrise to zenith position and from zenith to sunset for the respective rows. For the prediction of the yield potential of the three- and six-row systems, the mean radiation values over the two experiment years of Exp.1 were used.

Model description

The CROPGRO model is a generic model that simulates the soil-plant-atmosphere system in a daily time step. It simulates various leguminous crops like soybean (*Glycine max*; Boote et al., 1998), velvet bean (*Mucuna pruriens*; Hartkamp et al., 2002), and chickpea (*Cicer arietum* L.; Singh and Virmani, 1994), but has also been extended to the forage crop *Brachiaria decumbens* (Giraldo et al., 2001) and various vegetables including tomato (*Lycopersicon esculentum* L.; Scholberg et al., 1997) and Chinese cabbage (Feike et al., 2010). The model simulates daily growth and development depending on the climatic and soil conditions, as well as management practices. To describe differences between crops and cultivars, the plant growth parameters are specified in the species (SPE), ecotype (ECO) and cultivar (CUL) files. To finally run the model, a minimum dataset is required, that involves information on the grown cultivar, row spacing, planting density and date, as well as amount and timing of irrigation and fertilization. Additionally the environmental conditions have to be defined including information on soil texture and daily ambient temperature, precipitation and radiation. For a detailed description of CROPGRO Boote et al. (1998) is recommended. In the current study the settings of the Chinese cabbage cultivar “Beijing No.3”, as described in Feike et al. (2010) are used without any modification.

Simulations

The CROPGRO Chinese cabbage model was tested under monocropping and strip intercropping conditions comparing predicted and observed yields. The validated model was then used to simulate potential production of Chinese cabbage under monocropping and strip intercropping conditions in the NCP. In general model settings were kept as used for the simulation of the field experiments. Cultivar “Beijing No.3” was planted at a density of 4.2 plants m^{-2} at a row spacing of 0.6 m. Due to the climatic conditions across the NCP, planting dates of Chinese cabbage were delayed from south to north (Anonymous, 2004; Wang, 2010), varying from 8 Aug. in the north to 26 Aug. in the south. A similar shift occurs regarding maturity and harvest of spring maize (Wu et al., 1989), where main harvest occurs 1 Sept. in the south and 16 Sept. in the north (Fig. 6).

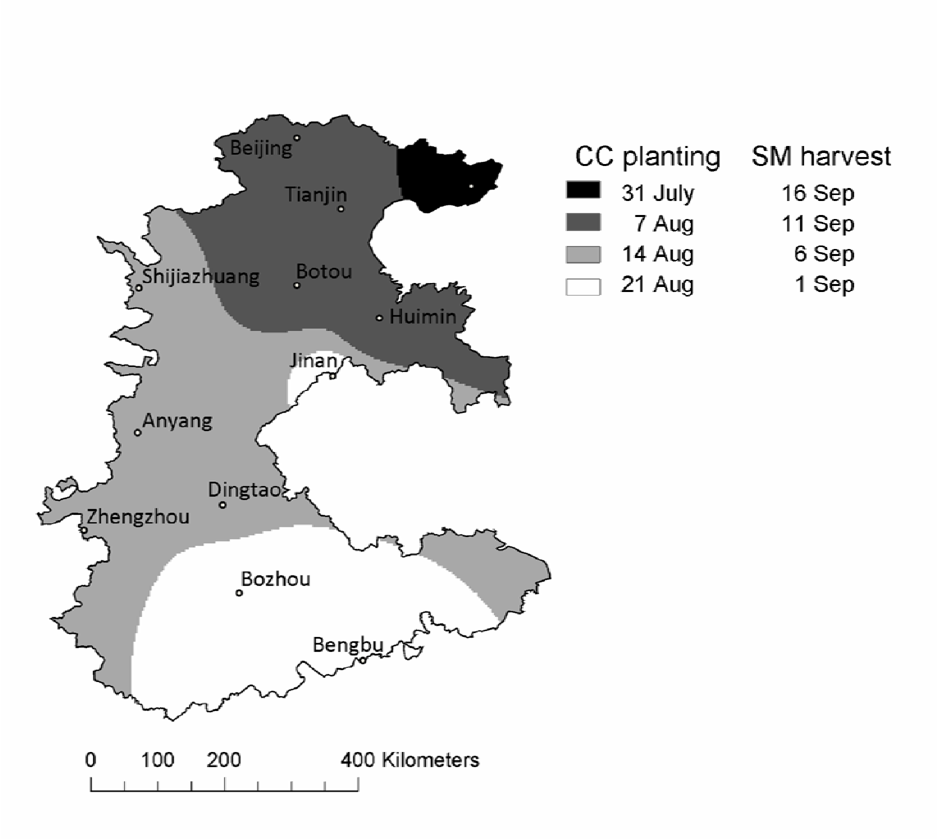


Fig. 6. Sowing date variation of Chinese cabbage (CC) and harvest date variation of spring maize (SM) across the North China Plain.

In the entire NCP rainfall concentrates in the summer months and becomes scarce towards the end of the year, which requires additional irrigation in the production of autumn Chinese cabbage. Therefore 20 mm of irrigation were applied three times: directly after planting, after two weeks, and after four weeks. Before planting 150 kg N ha^{-1} were fertilized and another 50 kg were applied before canopy closure three weeks later. As the Chinese cabbage model is not yet able to consider vernalisation and undesired premature bolting (Feike et al., 2010), harvest date was fixed at 75 days in all cases, to ensure the harvest of marketable heads.

Data on soil texture was obtained from Binder et al. (2008), who compiled the original data of Böning-Zilkens (2004) and the Chinese Academy of Sciences (1994). The soil texture classes sand, sandy loam, loam, silt loam and silt constitute the prevailing soil classes in the NCP. Physical properties are presented in Table 2. By inclusion of the five soil types, variations in potential yields caused by soil variations over the NCP were accounted for.

Table 2. Physical properties of the different soil texture classes used in the analysis (Source: Böning-Zilkens, 2004; Chinese Academy of Science, 1997; adapted and modified by Binder et al. 2008).

Soil texture	**Profile depth**	**Particle size distribution** Clay	Silt	Sand	**Bulk density**	**LL**	**DUL**	**SAT**
	cm	%			g cm^{-3}	m^3 m^{-3}		
Sand	0-20	6.2	1.4	92.4	1.47	0.06	0.14	0.42
	20-40	7.2	2.9	89.9	1.41	0.07	0.14	0.44
	40-60	7.0	2.5	90.5	1.44	0.07	0.14	0.43
	60-80	5.7	0.6	93.7	1.52	0.06	0.13	0.40
	80-100	5.7	0.6	93.7	1.52	0.06	0.13	0.40
	Avg.	6.4	1.6	92.0	1.47	0.06	0.14	0.42
Sandy loam	0-20	12.9	23.2	63.9	1.39	0.10	0.21	0.45
	20-40	12.6	23.5	63.9	1.41	0.10	0.21	0.44
	40-60	12.4	23.8	63.8	1.42	0.10	0.20	0.44
	60-80	12.1	24.0	63.9	1.43	0.10	0.20	0.43
	80-100	12.0	24.1	63.9	1.43	0.10	0.20	0.43
	Avg.	12.4	23.7	63.9	1.42	0.10	0.20	0.44
Loam	0-20	10.9	48.0	41.1	1.40	0.10	0.25	0.49
	20-40	10.6	48.1	41.3	1.45	0.10	0.25	0.49
	40-60	10.3	48.3	41.4	1.49	0.09	0.25	0.49
	60-80	10.1	47.8	42.1	1.50	0.09	0.24	0.49
	80-100	9.6	46.1	44.3	1.49	0.09	0.24	0.48
	Avg.	10.3	47.7	42.0	1.47	0.09	0.24	0.48
Silt loam	0-20	15.9	57.2	26.9	1.34	0.14	0.25	0.51
	20-40	16.8	58.7	24.5	1.43	0.13	0.23	0.40
	40-60	17.7	60.1	22.2	1.51	0.14	0.24	0.38
	60-80	13.6	55.6	30.8	1.42	0.10	0.23	0.36
	80-100	12.9	59.8	27.3	1.47	0.10	0.27	0.42
	Avg.	15.4	58.3	26.3	1.43	0.12	0.24	0.41
Silt	0-20	15.5	80.0	4.5	1.33	0.11	0.30	0.47
	20-40	10.4	86.0	3.6	1.35	0.10	0.30	0.46
	40-60	8.8	88.0	3.2	1.35	0.10	0.31	0.46
	60-80	7.9	89.0	3.1	1.35	0.10	0.31	0.46
	80-100	12.2	84.6	3.2	1.37	0.10	0.30	0.46
	Avg.	11.0	85.5	3.5	1.35	0.10	0.30	0.46

Long term weather data of 12 climate stations (Table 3) distributed over the entire NCP were available from the China Meteorological Administration (2007). For most sites data was available for 30 years, only for two sites available data comprised ten and eleven years respectively. The daily weather records included minimum and maximum temperature, amount of precipitation and sunshine hours. Sunshine duration was converted to amount of daily solar radiation (MJ m^2 d^{-1}) using the Angström equation applying recommended default coefficients of 0.25 and 0.5 (Allen et al., 1998). Yearly average data of the 12 weather stations is presented in Table 4.

Table 3. Location, province, longitude, latitude, altitude and years of available data of the 12 weather stations used in the analysis.

Location	Province	Longitude	Latitude	Altitude	Years
Beijing	Beijing	116°35'13"	40°4'27"	31	1976-2005
Laoting	Hebei	118°54'0"	39°26'0"	11	1976-2005
Tianjin	Tianjin	117°10'0"	39°6'0"	3	1976-2005
Botou	Hebei	116°33'0	38°5'0"	13	1996-2005
Shijiazhuang	Hebei	114°25'0"	38°2'0"	81	1976-2005
Huimin	Shandong	117°32'0"	37°30'0"	12	1976-2005
Jinan	Shandong	116°58'48"	36°40'48"	170	1976-2005
Anyang	Henan	114°24'0"	36°3'0"	63	1976-2005
Dingtao	Shandong	115°34'0"	35°4'0"	51	1995-2005
Zhengzhou	Henan	113°39'0"	34°43'12"	110	1976-2005
Bozhou	Anhui	115°46'0"	33°53'0"	38	1976-2005
Bengbu	Anhui	117°23'0"	32°55'0"	19	1976-2005

Table 4. Average climate data of weather stations used in the analysis. Variances are given in brackets.

Location	Average precipitation	Average maximum temperature	Average minimum temperature	Average solar radiation
	mm	°C	°C	MJ m^{-2} d^{-1}
Beijing	555 (151)	18.1 (0.7)	7.6 (0.8)	15.5 (0.5)
Laoting	589 (167)	16.6 (0.6)	6.1 (1.0)	15.5 (0.5)
Tianjin	542 (139)	18.2 (0.6)	8.4 (0.5)	15.0 (0.7)
Botou	477 (152)	19.3 (0.5)	8.7 (0.3)	15.8 (0.9)
Shijiazhuang	518 (159)	19.4 (0.6)	8.9 (0.9)	14.9 (0.9)
Huimin	543 (153)	18.8 (0.6)	7.8 (0.8)	15.8 (0.5)
Jinan	683 (187)	19.7 (0.6)	10.6 (0.6)	15.6 (0.7)
Anyang	539 (151)	19.8 (0.6)	9.3 (0.8)	14.8 (0.7)
Dingtao	680 (254)	19.7 (0.6)	9.6 (0.4)	15.1 (0.6)
Zhengzhou	630 (155)	20.3 (0.6)	9.6 (0.7)	14.8 (0.8)
Bozhou	798 (210)	20.4 (0.7)	10.4 (0.8)	15.2 (0.8)
Bengbu	906(228)	20.6 (0.7)	11.7(0.6)	14.9 (0.7)
Average	641 (181)	19.2 (0.7)	9.1 (0.7)	15.3 (0.7)

For the simulation of the two strip intercropping systems, the generated estimates of share of incoming radiation were used to adapt the daily radiation values via the "environmental modifications" option in CROPGRO. Potential yield was simulated for every single row of the three and six row strips separately. Keeping all other management options constant the performance of the monocropping, and two strip intercropping systems was tested over the five soil texture classes at the 12 locations. Inverse distance weighting (Shepard, 1968) was then used to interpolate the point data over the entire NCP. Weighted averages are taken from the observed values, with the weight of the single point data decreasing as distance increases (Fisher et al., 1987).

Results and Discussion

Field experiments and model testing

The PAR measurements revealed a significant reduction in incoming solar radiation in the Chinese cabbage rows next to the maize (Table 5). In all three experiment sets the ratio of total daily available PAR was reduced to around 60 % compared to the monocropping situation in the centre of the strips. From row 4 onwards, the reduction was marginal.

Table 5. Share of total daily available photosynthetically active radiation (PAR) in the Chinese cabbage strips next to maize over the three experiment sets.

	Quzhou		**Ihinger Hof**
Treatment	**2008**	**2009**	**2009**
Row 1	0.62	0.58	0.61
Row 2	0.78	0.74	0.80
Row 3	0.91	0.86	0.90
Row 4	0.99	0.98	0.98
Row 5	0.99	0.99	0.99
monocr.	1.00	1.00	1.00

The results were used to modify the climate data underlying the model runs, as described above. The reduction in radiation did not lead to significant yield reductions in the first row of Exp. 1, all the more in Exp. 2 at the German site both in the field and in the model (Fig. 7). Two main reasons where identified for the differences in yield reduction. First, the duration of coexistence of Chinese cabbage and maize of 53 days was much longer in Exp. 2 compared to Exp. 1, where coexistence was 39 and 33 days in 2008 and 2009 respectively (Table 1). Second, the average incoming solar radiation was much lower at the German site compared to the Chinese site. At the Ihinger Hof the measured solar radiation for the time of coexistence was 9.2 MJ m^{-2} d^{-1}, whereas in Quzhou it was 16.8 and 13.4 MJ m^{-2} d^{-1} in 2008 and 2009 respectively. It becomes obvious that the observed reduction of incoming radiation during the first weeks of Chinese cabbage growth did hardly have a yield reducing effect under high radiation conditions as found in North China in August. On the other hand, the low radiation conditions at the German site, which is located approximately 1400 km north of the Chinese site, does not allow production of Chinese cabbage in intercropping without drastic yield reduction.

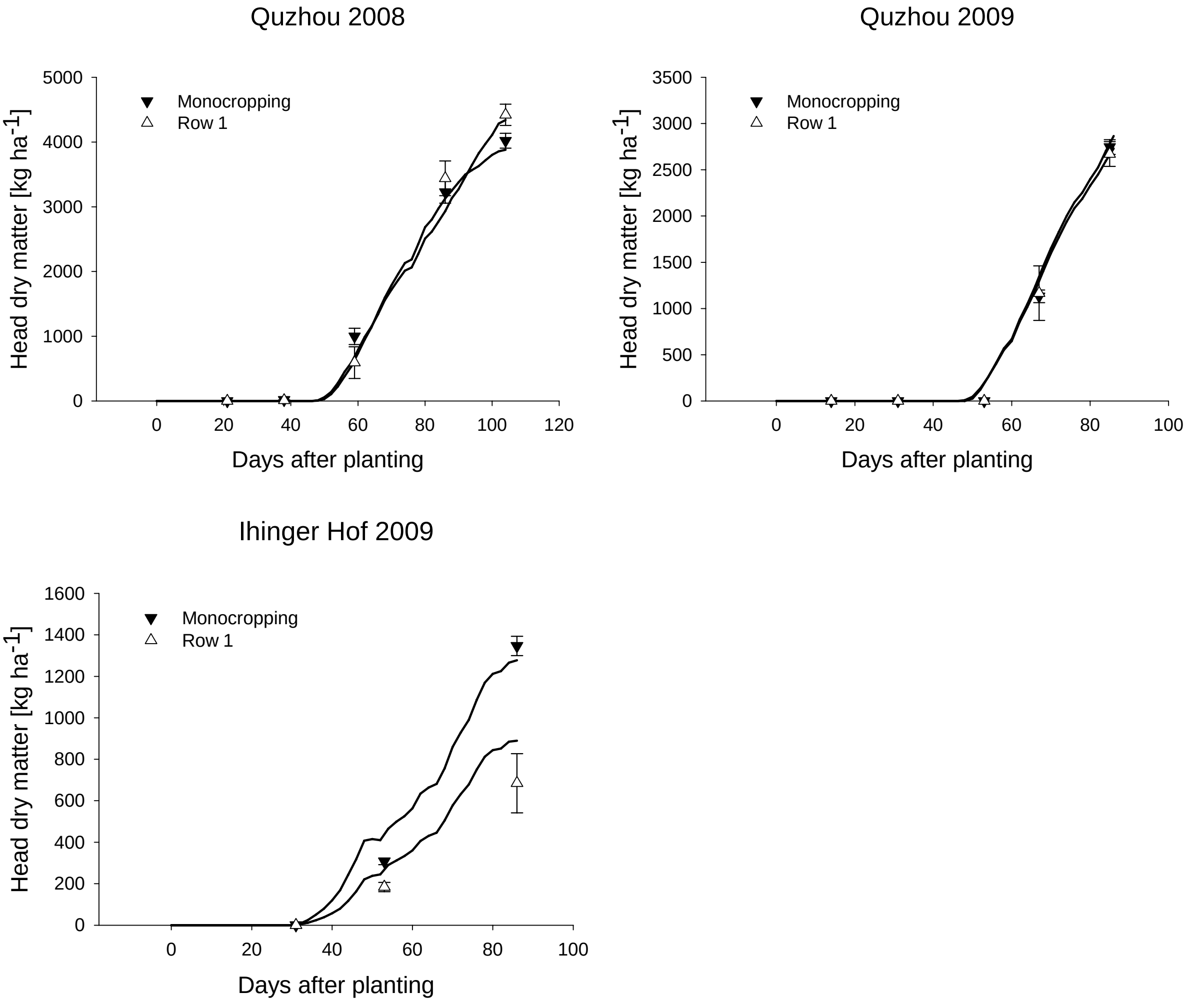


Fig. 7. Simulated (lines) and observed (symbols) values of head dry matter in Exp. 1 (top) and Exp. 2 (bottom). Error bars indicate twice the standard error of means.

The results of model testing at the Chinese site proved the validity of the model (Table 6). In 2008 the average root mean square errors between simulated and observed yield data were 140 kg ha^{-1} for the monocropping treatment and 81 kg ha^{-1} for row 1. In 2009 average errors were 38 kg ha^{-1} for monocropping and 72 kg ha^{-1} for row 1. The model shows a viable reaction to reduced radiation under the conditions of the NCP and can therefore be considered to generate reliable data for predicting the yield potential of Chinese cabbage under the reduced radiation conditions of strip intercropping.

Table 6. Average observed and simulated yields and root mean square errors between simulated and observed values of Exp. 1 in 2008 and 2009.

		Head dry matter, kg ha^{-1}			
Year	**Location**	**Observed**	**Simulated**	**Percentage**	**RMSE**
2008	Monocropping	4020	3880	-3.48%	140
	Row 1	4420	4339	-1.83%	81
	Row 2	4331	4464	+3.07%	133
	Row 3	3938	3843	-2.41%	95
2009	Monocropping	2746	2784	+1.38%	38
	Row 1	2591	2663	+2.78%	72
	Row 2	2873	2782	-3.17%	91
	Row 3	2925	2879	-1.57%	46

Therefore the share of incoming radiation in the theoretical three and six row systems could be calculated as described above. The share was calculated for every row based on the data of the two experiment years of Exp.1 (Table 7). For final parameter setting in the "environmental modifications" setting of CROPGRO, the average values of the two years were used. The three row system constitutes of two times row 1 (east and west) and one row 2 in the middle. In the six row system row 1 to row 3 occur two times, on the east and the west side of the strip. The share of incoming radiation varied from 0.51 in the two first rows of the three row system, to 0.85 in the two middle rows of the six row system. For graphical display in the maps below, the average yield potential was average for the three and six row system respectively and entered as a single value.

Table 7. Calculated share of available solar radiation (compared to monocropping) in the theoretical three row and six row Chinese cabbage strip systems based on the measured radiation data of 2008 and 2009.

Strip system	**Row**	**2008**	**2009**	**Average ratio**
Three rows	1	0.54	0.47	0.51
Three rows	2	0.55	0.48	0.52
Three rows	1	0.65	0.61	0.63
Six rows	2	0.77	0.73	0.75
Six rows	3	0.88	0.83	0.85

Simulation of production potential

During the growth period of autumn Chinese cabbage (August – November) a gradual decline of average temperature can be observed in the NCP from south to north. The variation ranges from just above 15 °C in the north to around 20 °C in the most southern tip of the NCP (Fig.

8). A similar tendency can be observed for the accumulated precipitation which is higher in the south, compared to the north. The location “Huimin” features by far the lowest values with below 100 mm over the entire growth period. Regarding average daily radiation, differences are small, with lower values reported for the western part of the NCP. However, a negative correlation between rainfall and radiation can be observed, as the number of cloudy days is reduced when precipitation is low. Thus “Huimin” also represents the place with the highest incoming radiation over the growth period.

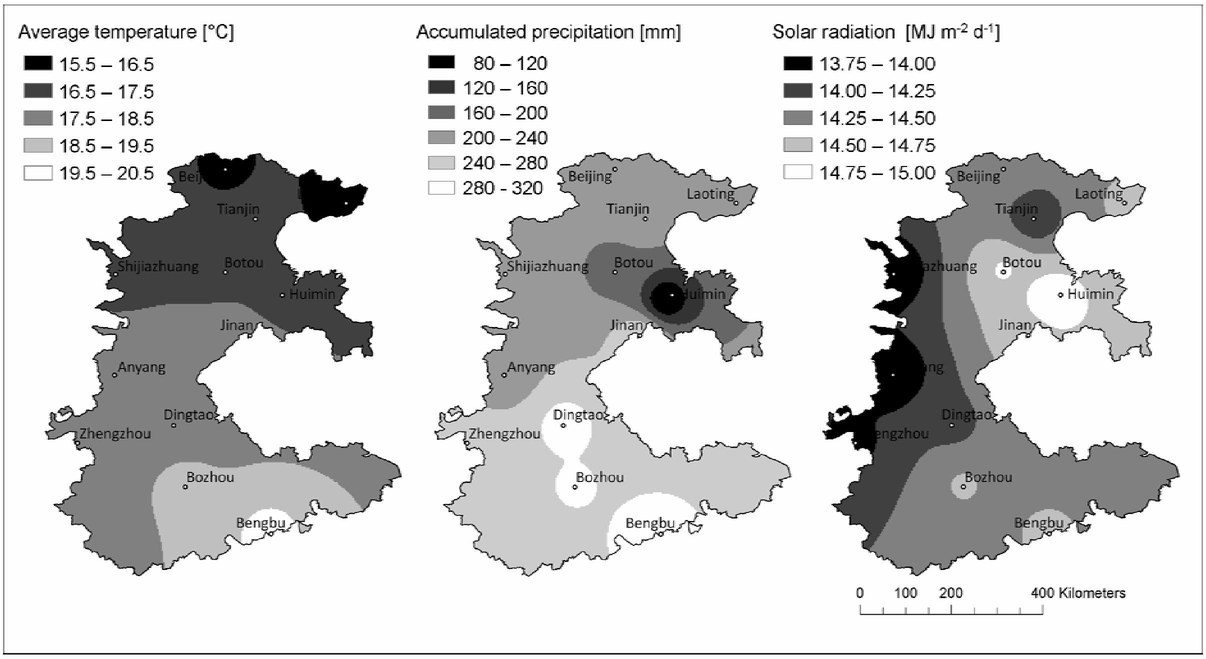


Fig. 8. Average temperature, accumulated precipitation and average solar radiation over the growing season of autumn Chinese cabbage (August – November) over the North China Plain.

According to the simulation analysis, yields of monocropped Chinese cabbage varied between 2800 kg ha^{-1} on sandy soils around Anyang and Huimin and 5100 kg ha^{-1} on silty soils around Bejing, Laoting and Huimin (Fig. 9). The low yield potential on the sand soils can mainly be attributed to water stress, as the water limited location Huimin has a very high yield potential on soils with a higher water holding capacity. In general soil texture has a stronger effect on yield potential in the north of the NCP compared to the south, most probably a result of higher precipitation in the south. Average yield potential over all locations was 3000 kg ha^{-1} on sand, 3200 kg ha^{-1} on sandy loam, 4700 kg ha^{-1} on loam, 3900 kg ha^{-1} on silt loam and 4800 kg ha^{-1} on silt (Table 8).

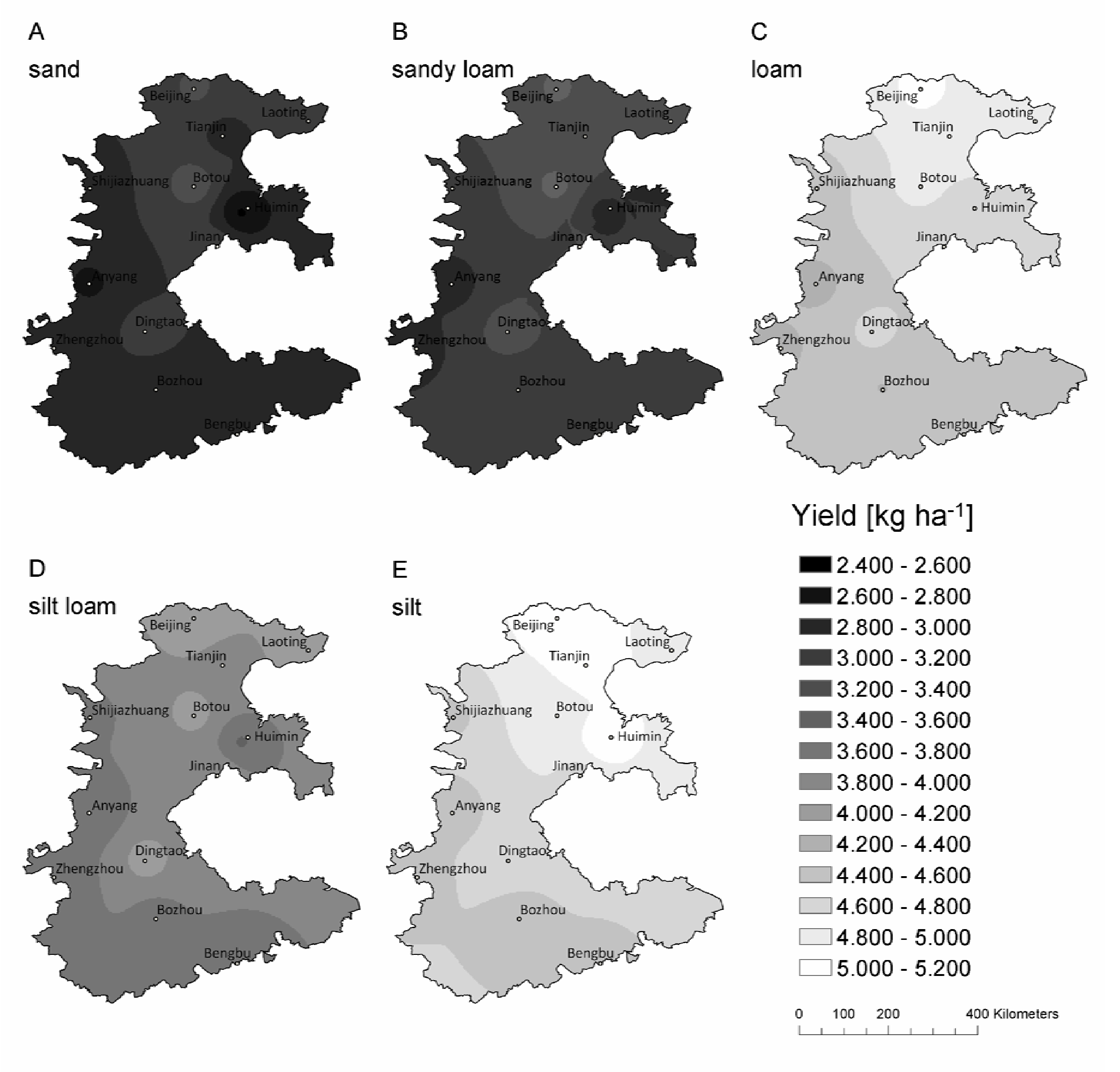


Fig. 9. Simulated yield potential of monocropped Chinese cabbage over the five soil texture classes for the entire North China Plain.

Under the reduced radiation conditions of the three row strip system, yields are generally lower, compared to monocropping (Fig. 10). Over all soil types, yields are lowest in the western part of the NCP around Anyang and Zhengzhou, which are characterized by lowest radiation values. This confirms the view that the yield potential can be reduced by light competition in strip intercropping systems under low light conditions. In general lower yield variations are observed in the three row system compared to monocropping over the soil texture classes.

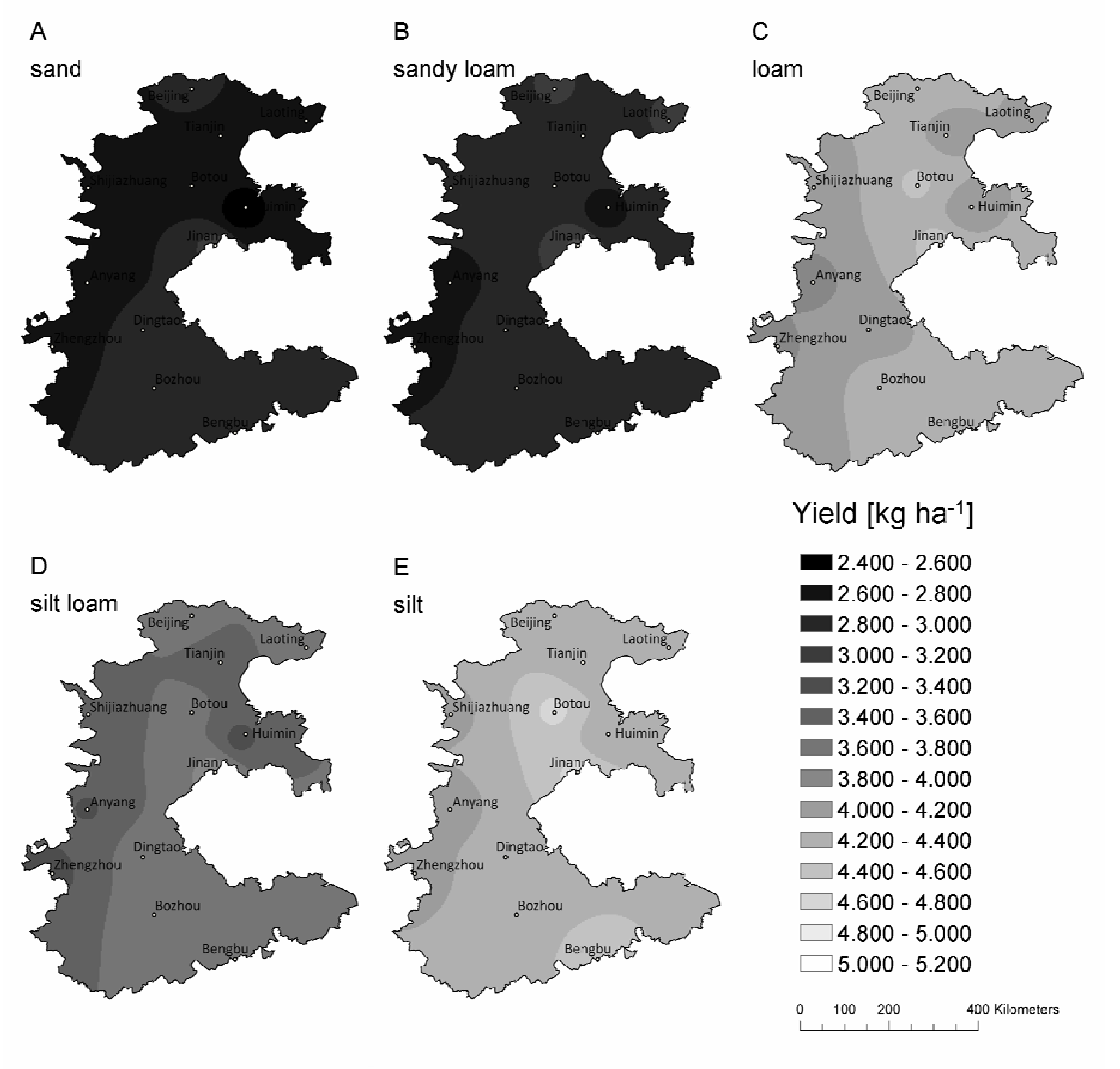


Fig. 10. Simulated yield potential of Chinese cabbage grown in a three row strip intercropping system over the five soil texture classes for the entire North China Plain.

In the six row systems similar trends occur as in the three row system (Fig. 11). Overall a yield reduction compared to monocropping is observed. With higher yield levels in the north compared to south and south west. On sand soils again Huimin produces least yield of around 2500 kg ha^{-1} with Beijing, Laoting and Jinan reaching a yield level above 3000 kg ha^{-1}. The highest yield level is reached around Botou with above 5000 kg ha^{-1} on the silt soil.

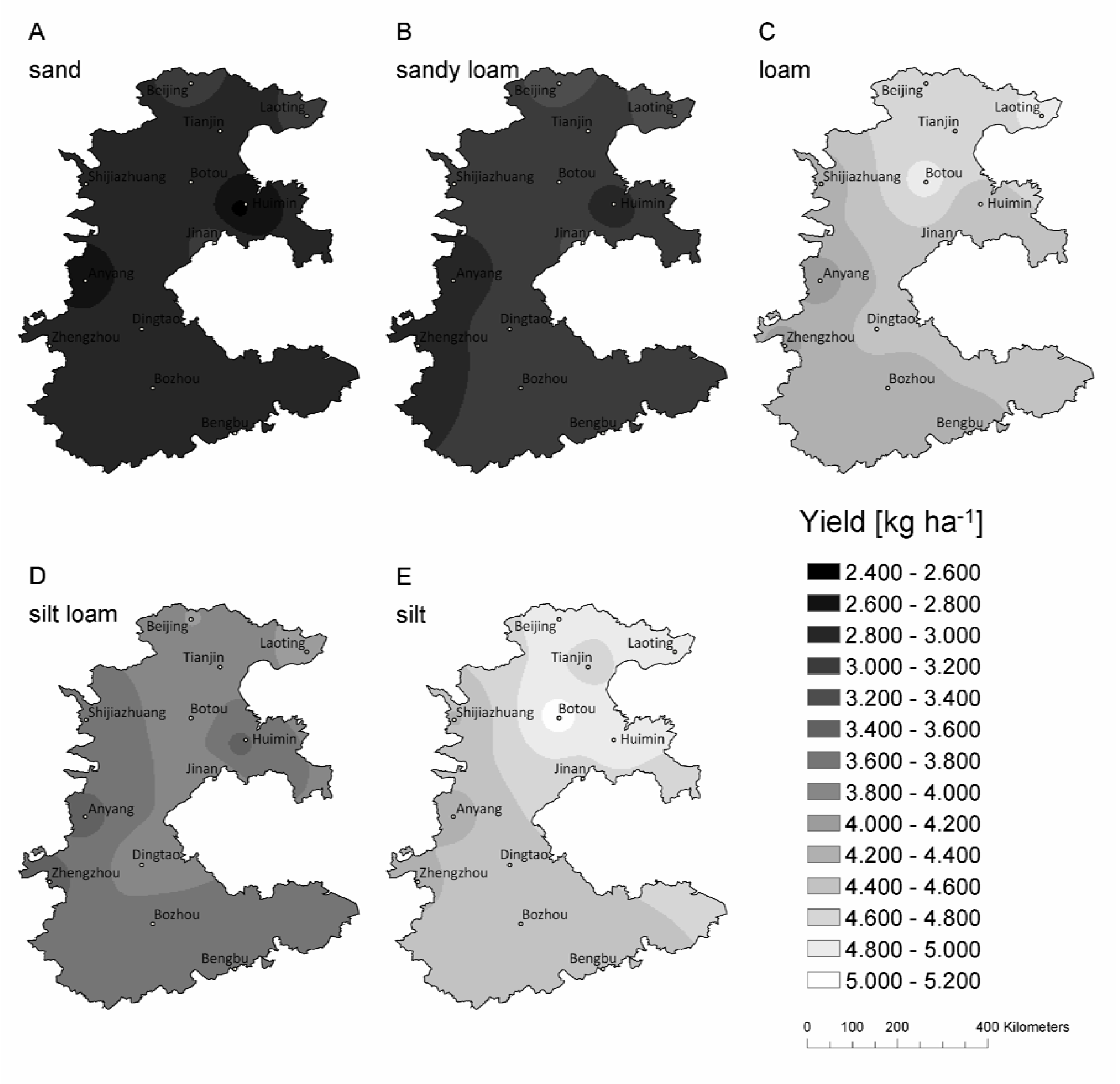


Fig. 11. Simulated yield potential of Chinese cabbage grown in a six row strip intercropping system over the five soil texture classes for the entire North China Plain.

Comparing the production potential of monocropping to the strip intercropping systems, an overall yield decline can be observed (Table 8). Over all locations yield decline is much higher in the three row system, compared to the six row system. Yield declines are highest on the highly productive soil textures loam and silt, reaching values of above 15 % in the three row system. In the six row system yield declines are marginal with maximum values just above 5 %, and even slight yield increases compared to monocropping being observed.

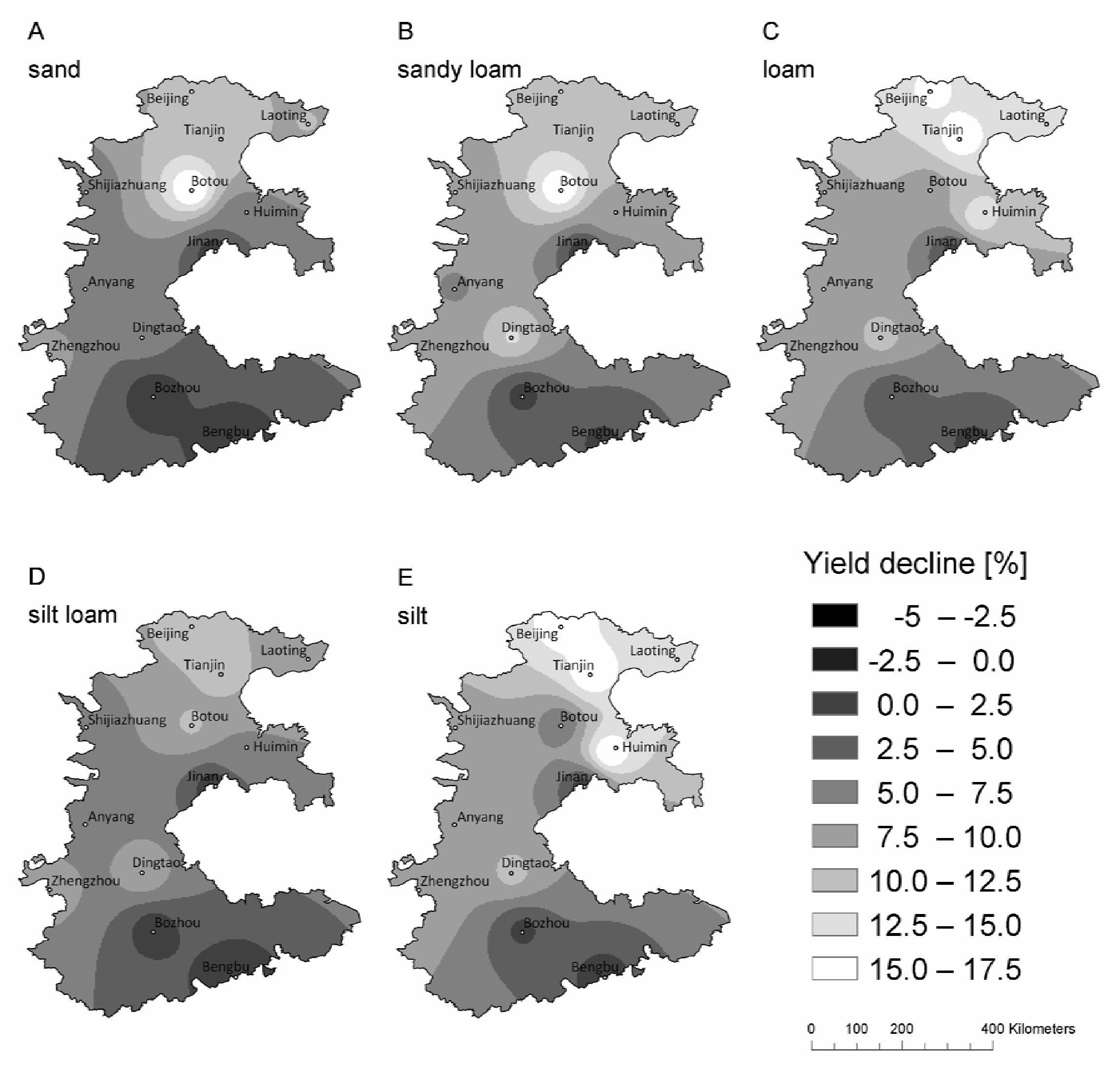


Fig. 12. Yield decline of Chinese cabbage grown in a three row strip intercropping system compared to monocropping over the five soil texture classes for the entire North China Plain.

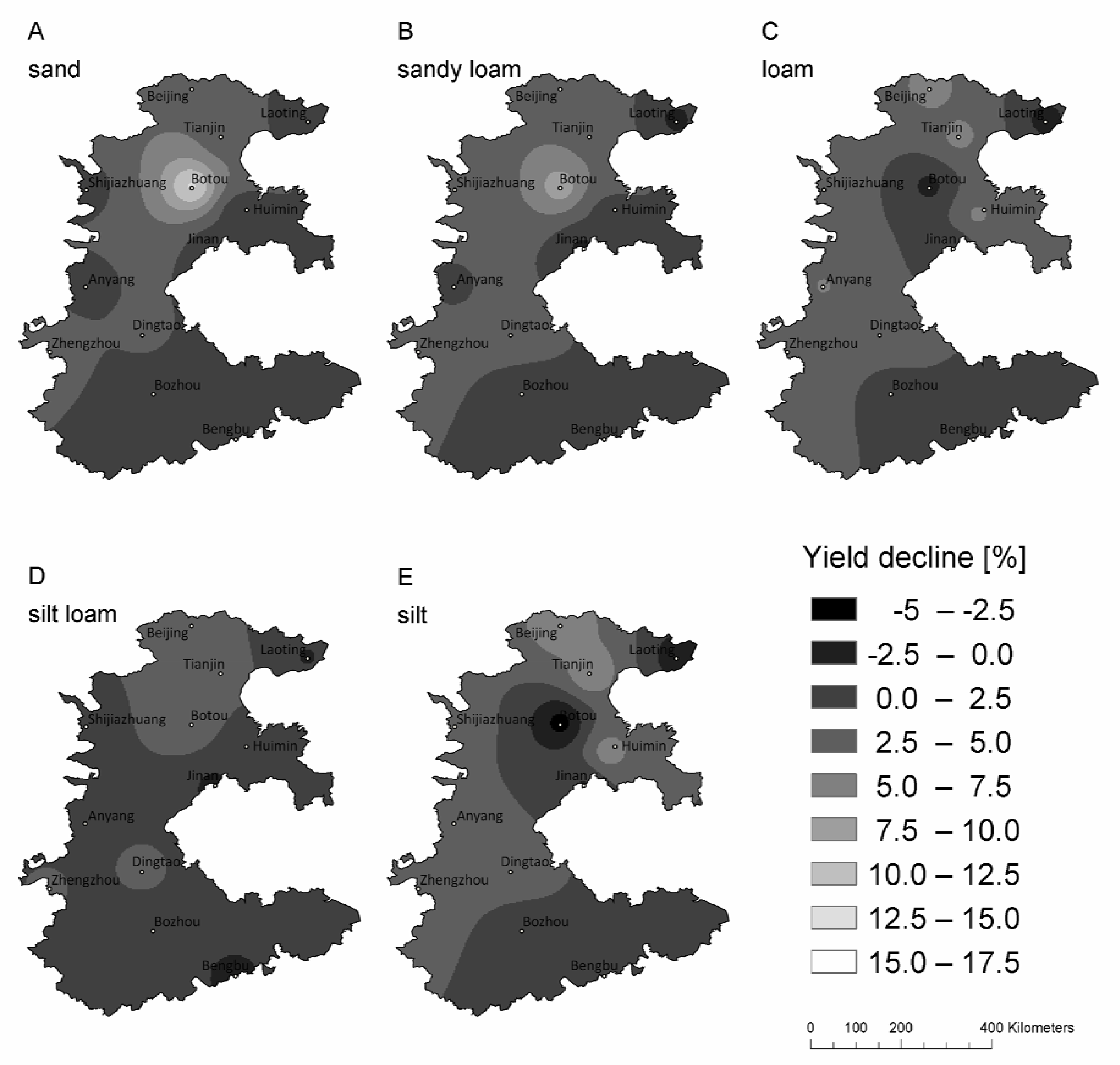


Fig. 13. Yield decline of Chinese cabbage grown in a six row strip intercropping system compared to monocropping over the five soil texture classes for the entire North China Plain.

Looking at the spatial distribution of yield declines over the NCP (Fig. 12 and Fig. 13), one can see that in the three row system yield declines are stronger in the north compared to the south. Furthermore the locations which are most productive under "good" soil conditions in monocropping (Beijing and Huimin) are the ones suffering highest losses in the three row systems. Under the "poorer" conditions, losses are smaller. This is confirms the view, that intercropping can be especially suitable under marginal conditions (Sullivan, 2003).

The slight reduction in incoming radiation as specified for the six row system shows even yield advantages over monocropping at some locations and soil types. Slight yield increases were observed at the locations Botou and Laoting for the productive soil types loam and silt. In the south yield variations were lower compared to the north over all soil textures.

Table 8. Average yields of Chinese cabbage grown in monocropping, three row and six row strip intercropping and potential yield decline for the two intercropping systems compared to monocropping tested for the five soil texture classes over the entire NCP. The numbers in brackets are the 10th and 90th percentile.

	Yield			**Yield decline**	
Soil texture	**Monocropping**	**Three row strip**	**Six row strip**	**Three row strip**	**Six row strip**
	kg ha^{-1}			%	
Sand	3000 (2800 – 3200)	2800 (2600 – 2900)	2900 (2700 – 3100)	6.9 (0.9 – 11.2)	2.7 (0.2 – 4.1)
Sandy loam	3200 (2900 – 3400)	2900 (2700 – 3000)	3100 (2900 – 3300)	8.2 (1.8 – 12.5)	2.9 (0.0 – 4.8)
Loam	4700 (4400 – 4900)	4200 (4000 – 4500)	4500 (4200 – 4800)	9.2 (2.3 – 15.1)	3.0 (-0.1 – 5.4)
Silt loam	3900 (3600 – 4100)	3600 (3300 – 3800)	3800 (3600 – 4000)	6.7 (0.9 – 10.9)	1.8 (-0.2 – 3.4)
Silt	4800 (4500 – 5100)	4400 (4100 – 4700)	4700 (4400 – 5000)	9.3 (1.6 – 16.9)	2.8 (-0.6 – 6.3)

Conclusions

The paper presents an approach to predict the production potential of Chinese cabbage under monocropping and strip intercropping conditions in the North China Plain. By quantifying the reduction in incoming radiation caused through shading by the neighbouring maize strip, plant response could be explained and simulated in the CROPGRO model. Accurate estimation of share of available radiation in two theoretical strip intercropping systems enabled the prediction of yield using the validated model. Finally, yield variations caused by climatic differences over time and space were simulated for the different production systems over the entire North China Plain. The simulations showed that yield variations are caused by differences in soil textures were much stronger, compared to variations caused by the different climatic conditions over the NCP. The production in a strip intercropping system, which consists of three rows of Chinese cabbage (1.8 m strip width) next to maize, caused yield reductions of up to 18 %. In the six row strips yield decline was generally smaller, for some locations and soil types even slightly higher compared to the monocropped plants. The results further indicate that the use of Chinese cabbage cultivars that are more tolerant to shading might be useful.

Acknowledgements

We want to thank the German Research Foundation (DFG, GRK 1070) and the Ministry of Education of P.R. China (special fund for agriculture profession (200803030) & innovative group grant of NSFC (No.30821003)) for their financial support.

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The results of the sixth article identified a yield potential of monocropped Chinese cabbage between 2800 kg ha^{-1} *and 5100 kg ha*$^{-1}$ *depending on location and soil texture. The reduction in incoming radiation was determined to be up to 50 % for a Chinese cabbage strip of 1.8 m, when strip intercropped with maize. The reduction of radiation resulted in a yield decrease of up to 20 % compared to monocropped Chinese cabbage. However, when increasing strip width to 3.6 m yield decrease was much smaller and at some locations and soil types yield was even higher compared to monocropping. Thus, the significance of designing intercropping systems according to the local soil and climatic conditions was asserted.*

11 General Discussion

The general discussion deals with the overall goals and outcomes of the study. Each of the six articles of the thesis can be read independently and is discussed independently at its end. The papers are therefore not discussed one by own again, but the conducted research is reflected focusing on the future of intercropping in China, the character of competition in intercropping, and the overall productivity of the examined system, presenting the yields of maize in the field experiments, which had not been part of the six publications. The importance of integrating farmers' knowledge into the frame of a decision support system is discussed, considering potentials and limitations of crop models to foster the development of sustainable agricultural production systems in the NCP.

Even though its share in the national GDP is continuously declining, agriculture still plays a vital role in China. Around 40 % of the population generates its main income from agricultural activities (CSY, 2008). Additionally food security is a major issue in China. The country has one of the lowest arable land per capita ratios of the world (Wen et al., 1992). A major question of China's future remains: How to feed the ever growing population on declining land resources? In the last decades rural farming communities have experienced a rapid development and immense production increases. However, researchers and politicians realize that new ways have to be found to maintain and increase yield levels (Lu, 2002).

Actual importance of intercropping

Intercropping became a hot topic of agricultural research in China in the last decades (e.g. Gao et al., 2009; Li et al., 2004; Zhang and Li, 2003). Special emphasis was put on the determination of below ground competition in various grain-grain and grain-legume systems. However, one crucial question remained: what is the actual situation of intercropping in the North China Plain and how will it develop in the future? Referring to the existing literature, one third of China's grain is produced in intercropping systems (Tong, 1994). Other sources state the high importance of intercropping in China (Zhang and Li, 2003; Li et al., 2001), referring to sources written in Chinese. When traveling through the North China Plain, however, hardly any intercropping systems can be found along the major railways and roads. It obviously is extremely difficult to assess the share of intercropping among all cropping systems on whatever level. No statistical service (FAOSTAT, 2009; CSY, 2009; DESTATIS, 2009) collects and provides this data. According to our estimations, published in the second article, intercropping makes up less than 5 % of all cropping systems in the NCP.

Intercropping exists, and is sometimes even prominent on local level. A fact that strongly contributes to intercropping being hardly detected is that it is practiced much more in remote parts, compared to the urban centers of the NCP.

The scientific excellence of the intercropping research in China is beyond question; however it seems that researchers slightly lost sight of the realities farmers are facing in rapidly changing rural China. This disconnectedness is a common problem in sustainability research (von Wirén-Lehr, 2001; Knowler and Bradshaw, 2007). Yearly increasing numbers of publications on intercropping face a situation where less and less farmers practice the examined systems. If there is to be a future for intercropping in China, it is a major task of the researchers not only to provide scientific evidence, but also connect with farmers to bring research into practice (Dohan, 2002). A strong interest from agronomic research in certain attributes of agricultural production systems does not prevent them from becoming extinct, as the example of rubber-rice-agroforestry systems in Sumatra shows (Feintrenie and Levang, 2009).

To make intercropping fit the demands of modern agriculture two possible ways of adjustment were identified. Apart from converting the traditional row intercropping systems to strip intercropping systems, which was the topic of article V and VI, the development of machinery that enables mechanization of the traditional systems is possible. The latter was realized in Japan. The "National Agricultural Research Center for the Tohoku Region" in northern Japan developed a seeding machine (Fig. 14) that enables mechanized sowing of soybean into wheat and wheat into soybean in the traditional wheat-soybean relay intercropping system (Amaha, 2006).

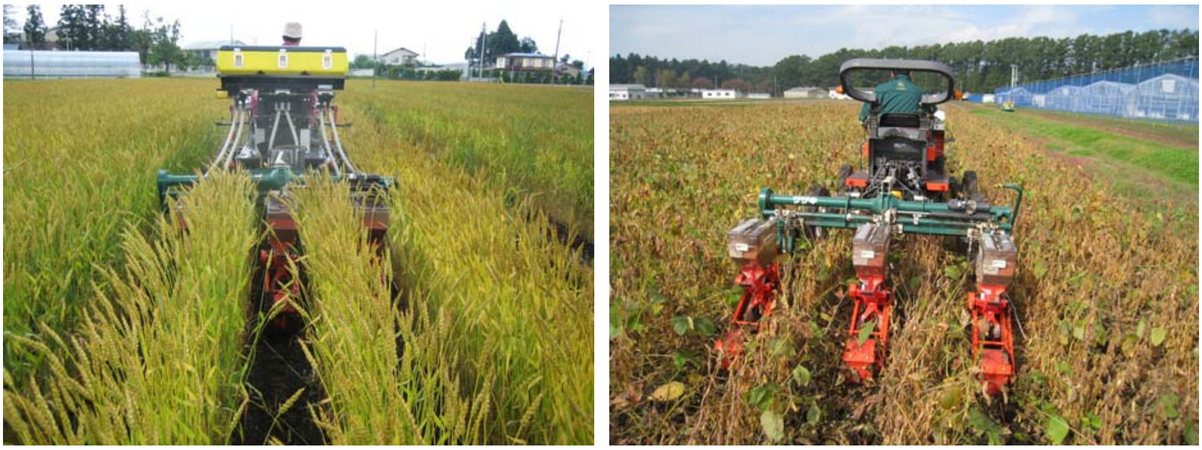

Fig. 14. Mechanized sowing of soybean into wheat (left) and wheat into soybean (right) in northern Japan using the "interseeder". (Photos: Kouchi Amaha)

The high clearance tractor works well under experimental conditions. The machine allows the production of the two crops in one season, which would not be possible otherwise. Land equivalent ratio is very high, as yields of both crops are only slightly lower compared to their monocropping equivalents (Amaha, 2006). However, the high purchase price and relatively low sowing capacity hindered a real commercial success. Nevertheless, for the Chinese conditions the development of similar machinery seems very promising to enable the mechanization of several common intercropping systems, like the winter wheat – maize system.

The character of competition

The complexity involved in intercropping systems creates great challenges to agronomic research. Numerous publications deal with various aspects of intercropping. Competition for resources is a major topic throughout the publications. Most researchers try to separate the involved effects and focus on singular aspects of competition. Nutrient availability and facilitation is an often investigated feature, with a strong focus on cereal – legume systems. Elmore and Jackobs (1986) identified the interactions between sorghum intercropped with nitrogen-fixing and non-nitrogen-fixing soybean varieties. Ghosh et al. (2006 & 2009) studied nutrient competition and management in legume-legume and cereal-legume systems, similar to others (e.g. Hauggaard-Nielsen et al., 2001; Jensen, 1996; Li et al., 1999). Regarding below ground interactions, competition for soil water plays an additional role (Yadaf and Yadaf, 2001; Willey, 1990). Suppression of weeds through directed management of intercrops is another feature of interest (e.g. Itulya et al., 1998; Liebmann and Dyck, 1993; Rana and Pal, 1993).

The major topic of the fifth and sixth article of the thesis – solar radiation – was intensively studied in various crop combinations and arrangements (e.g. Awal et al., 2006; Gao et al. 2010; Harris et al., 1987; Jurik and Van, 2004; Marshall and Willey, 1983; Rodrigo et al., 2001; Tsubo and Walker, 2002; Watiki et al., 1993; Zhang et al., 2008). Keating and Carberry (1993) gave a first good overview of the research attempts and approaches conducted to determine light availability within intercrop canopies. They mainly distinguished between three types of intercrop canopies: canopies with two separate layers (e.g. pearl millet/groundnut or maize potato), canopies which are separate in the upper layer, but mixed in the lower layer (e.g. maize/soybean or maize/okra) and canopies, which are completely mixed (e.g. wheat/soybean or maize/sorghum). The system investigated in the present research inevitably belongs to the first group. Shading of Chinese cabbage on maize occurs in spring during the first days of emergence of maize. However, the Chinese cabbage plants, which reach a maximum height of 50 cm, reduce the incoming radiation only in the early morning and late evening. Effects on soil surface temperature and total daily available PAR are considered to be marginal. On the other side, a significant reduction in incoming radiation occurs in the understorey crop Chinese cabbage. Keating and Carberry (1993) furthermore remind to consider the time span, the two crops are intercropped. Effects will be stronger the longer the two companion crops are grown in parallel. In the conducted field experiments, only the summer sets of Chinese cabbage in Exp.1 and Exp.4 were exposed to competition by maize over the entire growing period. In the spring and autumn plantings, the growing seasons overlapped approximately one month, with another month of growing being undisturbed. Tsubo et al. (2001) investigated the effect of different row orientations in intercropping systems. They found no significant effects of row orientation on radiation use efficiency and yield in maize/bean intercrops. As the results were obtained in a row intercropping system comparison to the present study is limited. The radiation measurements in the four executed field experiments of the PhD research, which were all north-south oriented, indicated that the findings of Tsubo et al. (2001) cannot be transferred to strip systems. Significant differences in available solar radiation were observed depending on the location within the strip over the course of the day. However, there is strong evidence that the narrower the strips are, the smaller is the impact of the row orientation.

In the field experiments the fraction of available radiation was determined by fast consecutive measurements using a PAR-ceptometer. Measurements were conducted several times over the day to account for the changing position of the sun. To improve the accuracy of the data, especially with respect to changing cloudiness, the permanent installation of several sensors, as applied by Gao et al. (2010) or Sinoquet and Bonhomme (1992) is advantageous. However, a great amount of sensors is necessary to account for the heterogeneity of the canopy, and to allow measurements above, below and at different layers of the canopy. The great advantage of handheld devices, which were used in the present study is, that they allow numerous consecutive measurements at any place within a canopy.

As observed in the experiments, degree of competition varies strongly over the cropping season. When determining cause and effect relationships, consideration of the timing of competition is crucial (Vandermeer, 1989). The results of the field experiments showed that during spring production of Chinese cabbage below ground competition was dominant, while in summer and autumn competition for solar radiation was more effective (Munz, 2010). In spring the roots of the Chinese cabbage plants at the border to the spring maize penetrated the maize strip, before maize establishment. In this way the bordering plants obtained significantly more soil nutrients. However, the supplementary available nitrogen only resulted in a higher leaf mass, but not in a higher head yield (Munz, 2010). Overall, competition occurred above and below ground. The observed effects depended strongly on the time in the season. The complexity that characterizes intercropping is reflected in the difficulty for the researcher to separate the cause-effect relationships within the system.

Performance of maize within the system

Within the six articles, which constitute the main part of the PhD thesis, the performance of maize was not presented. The results will be presented in upcoming publications, which are not part of this study. However, the results are interesting and complement the picture of Chinese cabbage/maize intercropping and will therefore be shortly illustrated. Only data of spring maize (Exp.3 and Exp.4), and not of sweet corn (Exp.1 and Exp.2) is presented. In all three cases (Quzhou 2008, Quzhou 2009, and Ihinger Hof 2009), the maize rows next to Chinese cabbage produced significantly higher yields compared to the rows in the center of the strips (Fig. 13). Those results are in line with the results of previous investigations in strip intercropped maize. Ghaffarzadeh et al. (1994) determined 20 % to 24 % higher yields in border rows. West and Griffith (1992) even investigated 26 % yield increase. In the field experiments, increase in total biomass production was marginal, but harvest index was significantly higher. Another interesting feature was identified, which can mainly be attributed to varietal differences. Whereas the increased yields in Germany were a result of an increased cob number in the first rows, the plants in the Chinese experiment showed no significant difference in number of cobs. Increased yield was purely a result of an increased number of kernels per cob and kernel weight. Ghaffarzadeh et al. (1997) identified that all yield forming parameters increased in the border rows of maize next to soybean; a higher number of cobs, higher number of seeds per cob and higher thousand seed weight. The findings of the PhD experiments indicate the importance of identification of varietal traits, when selecting cultivars used in intercropping systems.

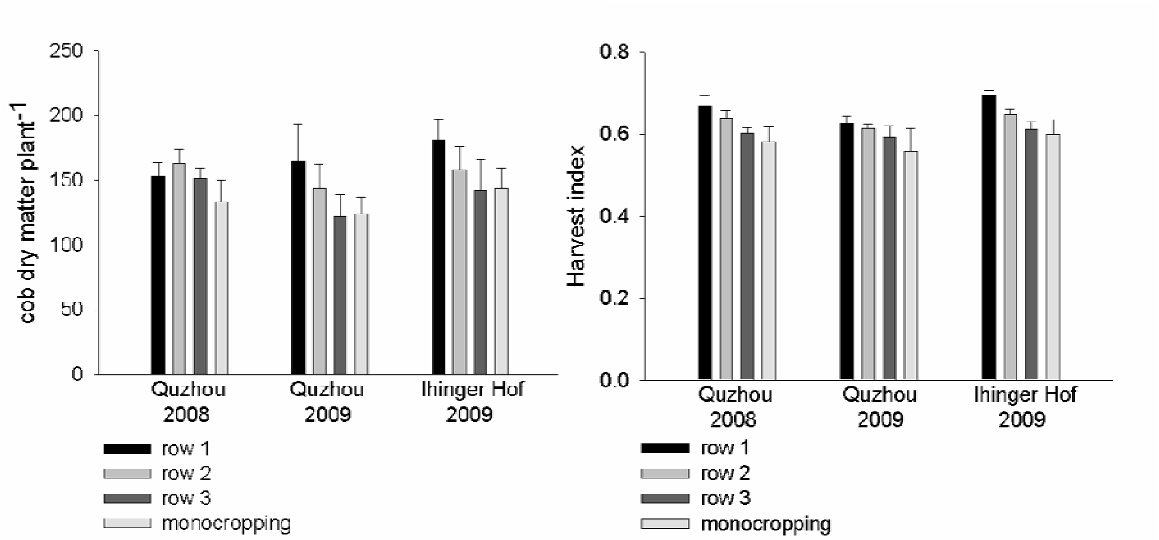

Fig. 15. Cob dry matter (left) and harvest index (right) of spring maize of Exp.3 and Exp.4. Error bars indicate the standard errors of mean.

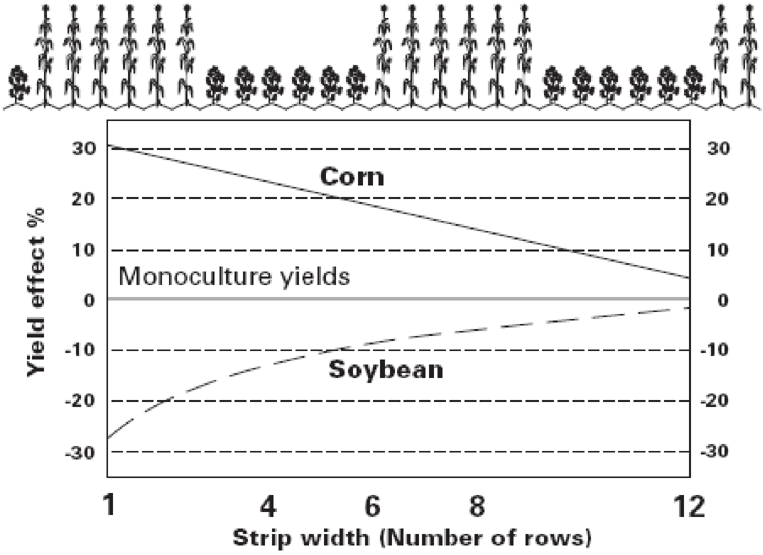

Fig. 16. Maize and soybean potential yield change as strip width increases (Source: Ghaffarzadeh, 1999).

Ghaffarzadeh (1999) presented an explanatory illustration of yield potential in maize/soybean strip intercropping systems of different strip width in Iowa. His results for maize yield potential agree with the findings of the field experiments. On the other side, the level of yield decline in soybean can only partially be confirmed for Chinese cabbage in the experiment. Yields in autumn production did not decline significantly, which suggests that the tested crops present a suitable combination under the conditions of North China in autumn.

Importance of farmers' knowledge

As described above complex interactions within intercropping systems appear at multiple levels. There are infinite possibilities to arrange two companion crops in time and space, resulting in numerous plant responses (Connolly et al., 2001). The research efforts undertaken in the field of intercropping since the emergence of modern science are countless. Nevertheless, it seems that up to now no all-embracing approach could be developed that is able to be globally applicable to the diversity inherent in intercropping. When explaining the interactions among species, the results of most publications are valid for the tested crop combination under the environmental conditions of the experimental sites and years, the used cultivars, and all other management options included. Transferring the findings to other years, locations, etc is much more ambiguous for intercrops compared to sole cropping. In this respect the role of farmers' knowledge becomes crucial.

Kiros-Meles and Abang (2008) acknowledge the importance of farmer's knowledge with respect to crop disease management. Using farmers' knowledge to cope with spatial soil variability is investigated by Lamers and Feil (1995). Both studies were conducted in Africa, and one has to say that the recognition of indigenous knowledge seems fairly small in the Chinese context. In the eyes of the author a great loss of knowledge must have occurred during the years of collectivization of agriculture since the middle of the last century. Before the communist takeover in 1949, the individual family farm had been the agricultural production system for thousands of years (Lin, 1990). Step by step the collectivization enforced the establishment of big work units. Finally the cooperatives consisted of 150 to 200 households. Individuals were no longer farmers, but employees of state enterprises, who were told what to do. During the years of collectivization, which lasted about 30 years (Huang, 1998), a huge loss in individuals farmers' knowledge must be assumed.

Nowadays, the threat of loosing indigenous knowledge appears even stronger. With the tremendous changes happening in rural China, and millions of people moving into other sectors accumulated knowledge and experience is irretrievably lost. The manifested top-down approach of knowledge transfer (Yao, 2006) is furthermore counteracting the integration of indigenous knowledge into research.

With regard to intercropping, the accumulated experience and knowledge on local level is an essential source of information. Farmer-developed intercropping systems are the result of hundreds of years of field experimentation, optimizing crop combinations, cultivar selection, spatial and temporal arrangements and input levels, which had been passed on from generation to generation. This vital source of information has to be tapped and integrated to design new high yielding production systems. Information flow not only needs to be improved from research into practice, but at the same time in the reverse direction (Fig. 17).

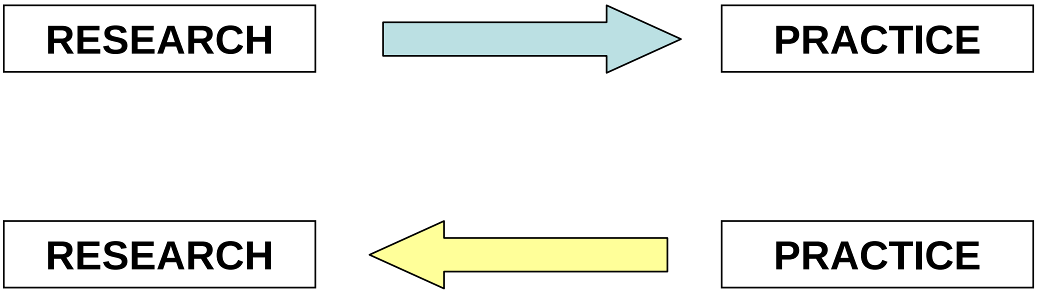

Fig. 17. Necessary knowledge transfer between research and practice.

Potentials and limitations of crop models

As elaborated in the third article crop growth models are a powerful tool for the understanding complexities within and the improvement of cropping systems. The increased demand for information in the agricultural sector could hardly be satisfied through conventional field experimentation (Jones et al., 2003). Crop models are especially useful, when it's about transferring the research results from one location to another. Given that information on climatic and soil conditions is available, the performance of a crop or cropping system can be simulated under the changed conditions (Uehara and Tsuji, 1998). To reliably simulate plant behavior in different environments, the model has to be evaluated, comparing model output with real data. Scale and purpose of the model application, will partly determine the extent of model testing. For the development of a "globally" applicable crop growth model, it is essential to base development and testing on data collected under a wide range of environments (Piper et al., 1998). This recommendation had been followed in the model development and testing of the third and fourth article. Greenhouse experiments were conducted testing crop development under temperatures ranging from just above 0 °C up to 26 °C average daily temperature. Additionally the field experiments covered all growing season, spring, summer and autumn, and were conducted at two distinct locations. Model validation confirmed good predictive capacity of the model over the range of temperate environments. However one has to keep in mind that Chinese cabbage is cultivated even under tropical conditions, using especially heat tolerant varieties. The cultivar-, ecotype-, and maybe even species-specific parameters may be adjusted to enable the accurate simulation of those cultivars under tropical conditions. One has to keep in mind that models are just simplified explanations of reality, which can never include all the relationships that occur within natural systems. Realizing the limitations of model prediction is crucial when interpreting its results.

The simulation of interspecies competition is still a major challenge in modeling research. Up to now, most models focus on a singular aspect of competition, with no model being globally applicable. An often used approach is the application of the Beer-Lambert law, when simulating competition for solar radiation. The law considers the absorption coefficient of a substance, and the distance a beam of light has to travel through that substance. It is a useful correlation, when simulating availability of solar radiation within fairly homogenous canopies, as applied to several mixed cropping systems (Carberry et al., 1996; Corre-Hellou et al., 2009; Debaeke et al., 1997; Sonohat et al., 2002). Taking into account the LAI, and height of a cropping system, the fraction of available sunlight can be estimated within the canopy. However, the concept can hardly be transferred to different crop combinations and especially strip systems. Moreover, the developed approaches did not exceed the stage of development and evaluation. Within the present thesis, a simple approach was developed in article five and six that enables the estimation of the fraction of available PAR in strips of different widths of the understorey crop (Chinese cabbage) within maize strip intercropping systems. The validated CROPGRO model was used to test the performance of Chinese cabbage under such conditions of reduced radiation over the entire NCP. To further improve the predictive capacity, especially over different seasons at all latitudes, the connection to or integration of another tool, that is able to simulate the position of the sun at any place and time is recommended. If that feature was available and light extinction coefficients would be appropriately defined for the respective crops, radiation availability could be simulated for any system at any season and location in the world. The data on fraction of available radiation would have to be calculated on a daily basis and could then be used to simulate crop growth in CROPGRO, STICS or similar models, which run on a daily time step.

Integrated decision support system (IDSS)

The integration of the knowledge and ideas of farmers regarding the practice of vegetable intercropping into the research approach is essential. It not only makes it possible to comprehend the overall situation, but to ask the right research questions. In the context of this PhD work, the further research, field experimentation and model work were designed accordingly, to answer the urging question: what will be the impact of the conversion of the traditional row systems to strip systems? The results clearly indicated that it depends on the location, and additionally the design of future systems, whether Chinese cabbage will suffer significant yield reductions in strip intercropping with maize or not. The linkage with the GIS allowed a regionalization of the results and their illustration in yield maps. The knowledge of farmers' practices helped furthermore in checking and ensuring the plausibility of the model simulation results.

The research approach developed in this study can and should be extended, both from an agronomic, methodological and a systemic point of view. The inclusion of the performance of maize is on the way, and will significantly contribute to the expressiveness of the decision support system. Including and testing of alternative crops within the seasonal rotation in the cropping system is the main topic of the third phase of subproject 2.1 of the IRTG. The research of the successor Ph.D.-candidate additionally focuses on shade tolerance among vegetable species and cultivars to further optimize the system.

From the systems point of view, integration of socio-economic factors including the market prices of the respective agricultural products (O'brien et al., 2002), as well as invested time and cost of labor adds additional value to the IDSS. Furthermore weed and pest management strategies should be developed and their respective costs integrated in the calculations (Perini and Susi, 2004). Huge opportunities are also present in the extension of the GIS, including information at various levels, ranging from soil maps to point data like locations of wells and streams (Jankowski, 1995). Overall, the developed approach offers great opportunities to support future sustainable development in rural China through agricultural research and to ensure the viability and competitiveness of the so much important intercropping systems in China.

12 Summary

To feed its 1.3 billion and still growing population on declining land resources, China has to find new ways to ensure food security in a long run. In that respect, production of vegetables can fulfill two tasks i) provision of nutritional quality and ii) generation of income to reduce the ever widening rural-urban income gap. Intercropping, which is a traditional cropping system in China, is considered a means of producing high and stable yields with limited inputs. The question remains, under what conditions can the benefits of intercropping be utilized, and in what way can agricultural research contribute to tap the full potential of intercropping to foster a sustainable rural development in China.

This cumulative dissertation consists of six papers published, accepted or submitted to international high standard journals or books. The work was accomplished within the frame of the "**International Research Training Group**" on "Sustainable Resource Use in the North China Plain" (NCP). To detect and describe the status quo of vegetable intercropping in the NCP, a survey was conducted from autumn 2007 to spring 2008. The results of the interviews with researchers, extensionists and farmers embedded in the **first article** revealed a huge variety of intercropping systems being practiced by farmers in the region. The first article furthermore elaborated farmers' underlying motives and concepts and described the knowledge transfer systems involved. When evaluating the prevailing systems against the background of the rapidly changing socio-economic frame conditions for farming in rural China, it became obvious that a great proportion of the systems practiced nowadays are prone to extinction in a long run. With people moving out of agriculture and the use of agricultural machinery rapidly increasing, the very hand labor intensive row-intercropping systems are impracticable. Therefore the **second article** discussed possible adjustments of the intercropping systems to fit the demands of modern agriculture, while maintaining their potential agronomic and environmental benefits. To enable mechanization, it was suggested to either adjust the machinery to the traditional row intercropping systems, or adjust the cropping system to the prevailing and available machinery. The latter approach was then followed throughout the thesis, using an agronomic modeling approach. The combination of Chinese cabbage (*Brassica rapa* ssp. *pekinensis*) and maize (*Zea mays* L.) was selected, as it is a traditional intercropping system, with strong interspecific effects and both crops being of highest agronomic and economic importance in the study region. In the course of this study, the two crops were strip intercropped in four field experiments at three sites in Germany and in China in 2008 and 2009.

To understand, explain and predict plant behavior under the impact of complex cropping structures, crop growth models present a viable and powerful tool. However, two constrains had to be overcome within the framework of this thesis i) Chinese cabbage is not integrated in the common process-oriented crop growth models, ii) a method had to be developed to quantify resource competition and simulate intercropping. Therefore the integration of Chinese cabbage, the number one field vegetable of China, into the CROPGRO model constituted the first step for the simulation of intercropping systems in China. Two greenhouse experiments, testing crop growth and development under different temperature regimes, served as the data base for the accurate parameterization of Chinese cabbage and built the baseline for the **third article**. Cardinal temperatures of Chinese cabbage were identified by correlating mean relative growth rates and mean leaf appearance rates to temperature. Minimum growth temperature was identified at 0 °C, optimum temperature ranges between 14 °C and 24 °C, and maximum temperature is 34 °C. The further adjustment and testing of the model, which was executed on up to six independent data sets, is presented in the **fourth article**. Optimum input levels of irrigation and fertilizer, as well as optimum planting dates were identified for the Chinese experiment site using sensitivity analysis on nine years of actual weather data. The results showed that an increase of nitrogen input from 100 to 200 kg N ha^{-1} does not lead to a significantly higher yield level. End of August was identified to be the latest recommendable sowing date that ensures the production potential.

The key to successfully simulate intercropping systems is the knowledge on changes in resource availability compared to monocropping. Therefore, a method was developed to quantify the availability of the most crucial growth factor solar radiation at any location within a Chinese cabbage strip, presented in the **fifth article**. The method was extended in the **sixth and final article** to enable the estimation of available radiation in Chinese cabbage strips of different widths. According to the results of the field experiments, a reduction in available radiation due to the shading by the neighboring maize not automatically caused significant yield losses in Chinese cabbage. At the German experiment site, which is located at much higher latitude compared to the Chinese site, incoming daily radiation was approximately half of the available radiation in China. Consequently, a similar degree of shading by maize at both sites resulted in a significant yield reduction at the German site, while yields were not reduced in China, due to higher solar radiation per se. The "environmental modifications" option of CROPGRO was then employed to simulate the effects of the estimated reduction in incoming radiation in Chinese cabbage strips of different width. Simulations were conducted over up to thirty years of weather data of 12 locations throughout the NCP, and were additionally tested on different soil texture types. The results were extended over the entire NCP by linking them to a GIS-system. It was shown that yield reductions of up to 18 % occurred in the narrow strips with strong shading, but in the wider strips with a lower degree of shading, even yield increases could be observed at some locations and soil types. The developed approach constitutes a reliable decision support for the optimization of the spatial arrangements in Chinese cabbage strip intercropping systems, according to local soil and climate conditions. The described approach can be extended to develop a comprehensive decision support system that allows testing of various intercrop combinations under a wide range of climate and especially radiation environments.

The presented thesis is a valuable contribution to the development of sustainable vegetable production systems in the NCP. A new method to quantify availability of solar radiation in strip intercropping was developed, which can be applied in various other intercropping systems. The integration of Chinese cabbage into CROPGRO, offers great opportunities not only for studying intercropping systems, but also for improving input levels and resource use efficiency in Chinese cabbage production in China and throughout the world. Understanding farmers' concepts and estimating the production potential of intercropped Chinese cabbage created additional value, which substantially contributes to realizing the potential of intercropping in the NCP.

13 Zusammenfassung

Um seine 1.3 Milliarden fassende und stetig wachsende Bevölkerung auf sich verringernden Agrarflächen ernähren zu können, muss China neue Wege finden, die Ernährungssicherheit langfristig zu gewährleisten zu können. In diesem Zusammenhang kann die Erzeugung von Gemüse zwei Aufgaben erfüllen i) Sicherung einer ausgewogenen Ernährung und ii) Einkommensmöglichkeiten in ländlichen Gebieten, die der sich stetig weitenden Einkommensdisparität zwischen Stadt und Land entgegenwirken. Mischanbausysteme sind ein traditionelles Ackerbausystem in China, das die Möglichkeit der Erzeugung hoher und stabiler Erträge bei gleichzeitig geringem Einsatz landwirtschaftlicher Produktionsmitteln bietet. Die Frage bleibt, unter welchen Bedingungen die Vorteile von Mischanbausystemen nutzbar gemacht werden können, und auf welche Weise Agrarforschung dazu beitragen kann, das volle Potential von Mischanbausystemen auszuschöpfen, um eine nachhaltige ländliche Entwicklung in China zu fördern.

Die vorliegende kumulative Dissertation besteht aus sechs Publikationen, die in internationalen Fachzeitschriften oder Büchern veröffentlicht, akzeptiert oder eingereicht wurden. Die Arbeit wurde im Rahmen der "**International Research Training Group**" die sich um eine nachhaltige Ressourcennutzung in der Nordchinesischen Tiefebene (NCT) bemüht durchgeführt. Um den Status Quo von Gemüsemischanbausystemen in der NCT zu erkennen und zu beschreiben, wurde eine Erhebung von Herbst 2007 bis Frühjahr 2008 durchgeführt. Die Ergebnisse der Befragungen von Agrarforschern, landwirtschaftlichen Beratern und Bauern, die in der **ersten Publikation** dargelegt sind, zeigten die Fülle der praktizierten Mischanbausysteme in der Region auf. Des Weiteren werden die zugrunde liegenden Motive und Konzepte der Bauern ausführlich dargelegt und die existierenden Wissenstransfersysteme beschrieben. Wenn man die vorherrschenden Mischanbausysteme vor dem Hintergrund der sich rapide verändernden sozioökonomischen Rahmenbedingungen der Landwirtschaft im ländlichen China betrachtet, muss man erkennen, dass ein Grossteil der heute praktizierten Systeme auf Lange Sicht zum Aussterben verdammt ist. Bedingt durch die Abwanderung vieler Arbeitskräfte in andere Sektoren und den rasant ansteigenden Einsatz landwirtschaftlicher Maschinen, werden die sehr handarbeitsintensiven Mischanbausysteme immer unpraktikabler. Daher wurden in der **zweiten Publikation** die Möglichkeiten der Adaptierung der Mischanbausysteme an die Bedürfnisse der modernen Landwirtschaft unter gleichzeitiger Beibehaltung der agronomischen und umweltschutztechnischen Vorteile der Systeme diskutiert. Um die Mechanisierung zu ermöglichen, wurde empfohlen entweder die

Landmaschinen and die traditionellen Reihenmischanbausysteme anzupassen, oder die Anbausysteme an die vorhandenen und vorherrschenden Landmaschinen anzupassen. Der letztgenannte Ansatz wurde im weiteren Verlauf der Dissertation durch einen agronomischen Modelansatz verfolgt. Die Kombination von Chinakohl (*Brassica rapa* ssp. *pekinensis*) und Mais (*Zea mays* L.) wurde ausgewählt, da sie einem traditionellen Mischanbausystem mit starken interspezifischen Effekten entspricht, und beide Kulturarten von höchster agronomischer und ökonomischer Bedeutung in der Forschungsregion sind. Im Rahmen dieser Forschungsarbeit wurden die beiden Kulturarten an drei Standorten in Deutschland und in China in streifenförmigem Mischanbau 2008 und 2009 angebaut.

Um das Verhalten von Pflanzen unter dem Einfluss komplexer Anbausysteme zu verstehen, zu erklären und vorhersagen zu können, stellen Pflanzenwachstumsmodelle praktikable und wertvolle Hilfsmittel dar. Hierfür mussten im Rahmen der Dissertation jedoch zwei grundsätzliche Probleme gelöst werden i) Chinakohl ist nicht in den verbreiteten prozessorientierten Pflanzenwachstumsmodellen vertreten, ii) eine Methode musste entwickelt werden, um die Konkurrenz um Wachstumsfaktoren zu beschreiben und den Mischanbau zu simulieren. Somit war der Integrierung von Chinakohl, dem Nummer eins Gemüse in China, in das CROPGRO-model der erste Schritt auf dem Weg Mischanbausysteme in China zu simulieren. Zwei Gewächshausexperimente, bei denen Wachstum und Entwicklung unter unterschiedlichen Temperaturregimen getestet wurde, dienten als Datengrundlage für die präzise Parametrisierung von Chinakohl und bildeten die Grundlage für die **dritte Publikation**. Kardinaltemperaturen von Chinakohl wurden identifiziert, indem die durchschnittliche Wachstumsrate und Blattbildungsrate mit der Temperatur korreliert wurde. Die minimale Wachstumstemperatur wurde bei 0 °C identifiziert, die optimale Temperaturspanne reichte von 14 °C bis 24 °C, und die Maximaltemperatur lag bei 34 °C. Die weitere Adjustierung und das Testen des Models wurde an bis zu sechs unabhängigen Datensätzen durchgeführt und wurde in der **vierten Publikation** veröffentlicht. Die optimale Einsatzmenge von Bewässerung und Düngung, sowie die Bestimmung des optimalen Aussaatzeitpunkts wurden durch Sensitivitätsanalyse aufbauend auf neunjährigen Wetterdaten für den chinesischen Versuchsstandort bestimmt. Die Ergebnisse zeigen, dass eine Erhöhung des Stickstoffeinsatzes von 100 auf 200 kg ha-1 zu keinen signifikanten Ertragserhöhungen führt. Ende August wurde als spätester zu empfehlender Aussaatzeitpunkt identifiziert.

Der Schlüssel zu einer zuverlässigen Simulation von Mischanbausystemen ist das Wissen über die veränderten Ressourcenverfügbarkeiten im Vergleich zur Reinkultur. Daher wurde eine Methode entwickelt, die es ermöglicht die Verfügbarkeit des wichtigsten Wachstumsfaktors Sonneneinstrahlung, an jedem Ort innerhalb eines Chinakohlstreifens zu quantifizieren, veröffentlicht in der **fünften Publikation**. Die Methode wurde in der **sechsten und letzten Publikation** dahingegen ausgeweitet, die verfügbare Einstrahlung in Chinakohlstreifen unterschiedlicher Breite abschätzen zu können. Die Ergebnisse der Feldversuche zeigten, dass die Reduzierung der verfügbaren Einstrahlung aufgrund der Beschattung durch den benachbarten Mais, nicht zwangsläufig zu signifikanten Ertragseinbussen im Chinakohl führt. Am deutschen Versuchsstandort, der sich an einem wesentlich nördlicheren Breitengrad befindet als der chinesische Standort, war die tägliche Summe der Einstrahlung nur ungefähr die Hälfte dessen, was in China eingestrahlt wurde. Konsequenterweise führte eine anteilig ähnliche Reduktion der Einstrahlung, die das Resultat der Beschattung durch den Mais ist, zu signifikanten Ertragseinbußen am deutschen Standort, während die Erträge in China, aufgrund des per se höheren Einstrahlungsniveaus nicht sanken. Die „environmental modifications" Option in CROPGRO wurde dann genutzt, um die Effekte der reduzierten Einstrahlung in Chinakohlstreifen unterschiedlicher Breite zu simulieren. Die Simulationen wurden auf bis zu 30 jährigen Wetterdaten von 12 Orten über die gesamte NCT durchgeführt, und zusätzlich auf fünf verschiedenen Bodentexturklassen getestet. Die Ergebnisse wurden auf die gesamte NCT ausgeweitet, indem sie mit einem geographischen Informationssystem (GIS) verknüpft wurden. Es wurde gezeigt, dass Ertragseinbussen bis zu 18 % in engen Streifen mit starker Beschattung auftreten können, wohingegen in breiteren Streifen mit geringerer Beschattung sogar leichte Ertragsvorteile an bestimmten Standorten und Bodentypen festgestellt wurden. Der entwickelte Ansatz stellt ein verlässliches Entscheidungshilfesystem für die räumliche Optimierung von Chinakohl in Streifenmischanbau unter Berücksichtigung der lokalen Boden und Klimabedingungen dar. Der entwickelte Ansatz kann dahingegen ausgeweitet werden, ein umfassendes Entscheidungshilfesystem zu entwickeln, dass es erlaubt die Kombination verschiedenster Kulturpflanzen in Mischanbausystemen unter einer breiten spanne klimatischer und besonders sonneneinstrahlungstechnischer Bedingungen zu testen.

Die vorliegende Arbeit liefert einen wertvollen Beitrag zur Entwicklung nachhaltiger Gemüseanbausysteme in der NCT. Eine neue Methode zur Quantifizierung der verfügbaren Sonneneinstrahlung in Streifenmischanbausystemen wurde entwickelt, die auf verschiedenste andere Mischanbausysteme übertragen werden kann. Die Integrierung von Chinakohl in CROPGRO, bietet nicht nur großartige Möglichkeiten zur Optimierung von Mischanbausystemen, sondern kann genauso zur Verbesserung der Ressourcennutzung und

Optimierung von Düngung und Bewässerung im Chinakohlanbau in China und weltweit genutzt werden. Das Verständnis der Konzepte der Landwirte und die Bestimmung des Produktionspotentials von Chinakohl im Mischanbau schufen einen zusätzlichen Wert, der entscheidend zur Ausschöpfung des Potentials von Mischanbau in der NCT beitragen kann.

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Acknowledgments

I would like to thank Prof. Dr. Wilhelm Claupein for giving me the opportunity to conduct my research under his supervision and support.

Thanks to Prof. Dr. Simone Graeff-Hönninger, for her valuable inputs, time-consuming and essential corrections, and for her ever open ears.

Thanks to Dr. Judit Pfenning for her support with the greenhouse and field experiments in Hohenheim, and for hosting me during the last months of my thesis.

Thanks to Prof. Dr. Chen Qing for his tireless support regarding the field experiment and survey in China.

Thanks to Prof. Dr. Dr. h.c. Hans-Peter Liebig, to agree the co-review of the Ph.D. thesis. Thanks also to Prof. Dr. Reiner Doluschitz, for being the third reviewer and putting me in charge of the execution of the International Research Training Group.

I highly appreciate the help of all the students, who conducted the data collection for their B.Sc., M.Sc. or Diploma-thesis within the frame of this Ph.D. and were involved in the execution of the greenhouse and field experiments in Germany and in China, as well as the survey. I especially want to thank Sun Dongmei, Sebastian Nanz, Kristin Nerlich, Jakob Johannson, Zhai Chengjie, Jana Gisin, Sebastian Munz and Anke Müller, who all gave essential contributions to the accomplishment of the present research work.

Furthermore I want to thank all members of the International Research Training group; first of all, Dr. Diana Ebersberger for her patience and support. I am also very grateful for the help, support and friendship I experienced from the Chinese partners in the project, during my stays in Beijing and Quzhou station. Special thanks to Prof. Wang Pu, Dr. Tang Aohan, Meng Qingfeng, Shen Jianlin, Hu Xiaokang, Qiu Shaojun, Guo Buqing, Pan Ying, all students of Prof. Chen's group, all students of Prof. Wang's group, and all the other Professors and students who supported and helped me in having a very good and prosperous time in China.

Thanks to all partners from Hohenheim University, especially the PhD-students of the IRTG for the good cooperation, interesting discussions, data exchange and last but not least the friendship and great time we could experience together in the last three years.

I am furthermore very thankful to the entire staff of the "Ihinger Hof", especially Helmut Kärcher for their tireless work. A special thanks also to all the members of the Institute 340, especially to Birgit Beierl for her hard work and support during the last three years. Thanks also to Fabian Gaiser, Gerrit Kleemann and the gardeners of the research station of horticulture for their support.

I would like to thank all the people who contributed positively towards this work.

Last but not least I want to thank my family for their strong support, efforts and patience during the last three years. Thanks for being there for me.