

CLIMATIC CHANGE AND POTENTIAL AGRICULTURAL PRODUCTIVITY IN CHINA

With 20 figures and 1 table

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Zusammenfassung: Klimawandel und potentielle landwirtschaftliche Produktivität in China

Die im Rahmen des globalen Klimawandels auftretenden Klimaänderungen werden in den nächsten Dekaden vermutlich zu weit reichenden Konsequenzen in landwirtschaftlichen Anbausystemen führen. Der Umfang der landwirtschaftlichen Produktion in China, dem bevölkerungsreichsten Land der Welt, wird auch Auswirkungen auf die globale Nahrungsmittelversorgung haben.

Um die Effekte eines möglichen Klimawandels auf die chinesische Landwirtschaft zu modellieren, wurde ein hochauflösender Raster-Klimadatensatz ($0,25^\circ$, monatliche Zeitreihen für Temperatur, Niederschlag und potentielle Evapotranspiration) mit digitalen Bodendaten in einem GIS kombiniert. Aus Trends der Monatsmittelwerte und ihrer interannuellen Schwankungen wurden Klimaszenarien für das Jahr 2030 entwickelt, die sowohl mittlere Bedingungen wie auch 'best case' und 'worst case' Szenarien enthalten. Regionale Pflanzkalender mit Berücksichtigung von Fruchtwechsellsystemen und einer Anpassung von Beginn und Dauer der Anbausaison an die jeweiligen Klimabedingungen wurden in das Wasserbilanzmodell der FAO integriert, um potentielle Erträge im Regenfeldbau für den Zeitraum 1951–1990 und die Klimaszenarien zu berechnen.

Im Zeitraum 1951–1990 weisen die potentiellen Erträge erhebliche Schwankungen sowohl in räumlicher wie auch in zeitlicher Hinsicht auf. Die Zukunftsszenarien deuten auf eine Fragmentierung der heutigen Anbauzonen und eine Vergrößerung der subtropischen Anbauzone hin und nicht, wie von GCM-Modellen vorhergesagt, auf eine generelle Verschiebung von Anbauzonen nach Norden. Die interannuellen Schwankungen des Klimas werden wahrscheinlich weitaus höhere Auswirkungen auf die zukünftigen Anbaubedingungen haben als eine polwärtige Verschiebung der Anbaugrenzen.

Summary: The anticipated change of climatic conditions within the next decades is thought to have far-reaching consequences for agricultural cropping systems. The success of crop production in China, the world's most populous country, will also have effects on the global food supply.

To model the effects of climate change on crop production in China a high resolution (0.25° , monthly time series for temperature, precipitation and potential evapotranspiration) gridded climate data set that specifically allows for the effects of topography on climate was combined with digital soil data in a GIS. Observed long-term trends of monthly means as well as trends of interannual variations were combined for climate scenarios for the year 2030 with average conditions as well as 'best case' and 'worst case' scenarios.

Regional cropping calendars, with allowance for multiple cropping systems and the adaptation of the begin and length of the growing season to climatic variations, were incorporated in the FAO water balance model to calculate potential yields for rainfed cropping systems for the period 1951–1990 and the climate scenarios.

During the period 1951–1990 potential yields displayed a tremendous variation both in temporal and spatial respects. Future scenarios indicate a fragmentation of cropping zones and an enlargement of the subtropical cropping zone rather than a general northward drift of all zones as predicted by GCM models. The effects of interannual variability are thought likely to have more impact on future cropping conditions than the anticipated poleward migration of cropping zones.

1 Introduction

The general warming of the earth's atmosphere during recent decades has been established with a fair degree of accuracy (IPCC 2001). On regional scales climatic variations however exhibit both positive and negative trends. In particular, trends of precipitation or evapotranspiration show a variety of complex regional patterns. The effect of changing climatic patterns on terrestrial ecosystems and particularly on agricultural food production cannot be deduced directly from these observed climatic trend values as plant response to climate depends on the interactions of climatic and edaphic factors.

Crop production in China has received considerable attention as any climate-induced variations of the natural environment may have severe impacts on the food production of one of the largest population centres of the world (HARRIS 1996). Rice as the staple crop of East Asia is a particularly water-consuming plant and production could be severely disrupted if a timely water supply cannot be guaranteed. Wheat production in Northeast China is already severely hampered by a lack of precipitation and irrigation water (KHARIN et al. 1999; SMIL 1993). In addition, changing consumer preferences in China have led to an increased demand for fodder grains (REID 1998), adding further pressure on agricultural production.

A number of studies have attempted to model the effects of climate on Chinese crop production with different data sets (e.g. CHEN et al. 1992; FISCHER et al. 2000; HELIG et al. 2000; HULME et al. 1992; TAO 2003; THOMAS 2000b; ZHENG 1994). Simulating the effects of changes in water-balance components (precipitation, evapotranspiration and soil moisture) on crop production patterns depends strongly on the climate data sets available. In this respect the majority of the available gridded climate data show considerable shortcomings. They either have a coarse resolution ($> 0.5^\circ$), are based on a limited number of climatic stations, or have been interpolated with statistical methods that fail properly to represent the effects of topography on the three-dimensional spatial variation of climate. As the major part of China consists of hilly to mountainous terrain, it is mandatory to use climate data surfaces that incorporate variations due to topographical effects, such as orographic precipitation or rain-shadow areas, in order to arrive at realistic results. The same applies to inter-annual climatic variability. Year to year variations are of a much higher concern to farmers than average conditions, which are implied with the use of long term average climate data in most of the cited studies. In addition evapotranspiration estimates are in many cases calculated from low-quality gridded data itself or from long-term data values resulting in questionable evapotranspiration estimates. The omission or generalized representation of wind speed measurements in the calculation procedure is a particular concern as wind is a key component of the evaporative environment of many regions in China (THOMAS 2000a; CHEN, D. et al. 2005; CHEN, S. et al. 2005).

This study presents the results of water balance calculations for China with high-resolution gridded climate data sets that overcome the limitations described above. To estimate changes in potential future cropping conditions climatic scenarios are developed from observed trends rather than from GCM results. Particular emphasis is put on the effects of inter-annual climatic variability in the proposed scenarios.

2 Data and methods

To assess cropping conditions either climate data generated by General Circulation Models (GCM) or observed climate data or a combination of both have been used. GCM data typically have a low resolution of several degrees, lack both the spatial and temporal precision necessary for detailed regional analyses and in many cases have problems simulating even present-day climate (BONAN et al. 2002). In a composite GCM pre-

cipitation data field of East Asia (HULME et al. 1992) neither the spatial distribution nor the amount of annual precipitation could be reliably reproduced. Evapotranspiration estimates derived from GCMs are regarded as extremely unreliable (PALUTIKOF et al. 1994) leading CHATTOPADHYAY and HULME (1997, 71) to state that “the results from GCM experiments should be regarded as exploratory and provisional”. Climatic variations induced by the topography are in general not captured, due to the low resolution of the underlying digital elevation models (BENISTON 1994). Only with the development of high resolution GCMs or improved downscaling methods will GCM data be a useful alternative for regional studies in the future. Consequently, climate data fields derived from observed climate data have been used.

2.1 Data

Monthly climate data fields of temperature, precipitation and potential evapotranspiration (PET) gridded at 0.25° resolution for the period 1951–1990 covering East Asia (15° N, 65° W to 55° N, 135° W) have been used in this study (Fig. 1). The data fields were generated with the REGEOTOP method that combines multivariate statistical and geostatistical principles to interpolate data fields from climate data observed at meteorological stations. The influence of topography on climatic spatial variability is taken into account by relating observed climatic values to position and topography surrounding each station. Topography is represented in form of ‘base topographies’ which are statistically independent relief forms that are derived from a digital elevation model of the study area with the help of a principal component analysis. Regression analysis and geostatistics are then used to calculate final data fields. Published climate data and climate data collected during field trips were combined to form one of the most comprehensive climate data bases covering the PR China containing time series of more than 600 and 500 station for precipitation and temperature, respectively. Monthly estimates of PET were calculated with the Penman-Monteith approach (ALLEN et al. 1998) for 196 stations within the borders of the PR China. Details of the method can be found in THOMAS and HERZFELD (2004).

Total available soil water (SW, in mm/m soil depth) was estimated from soil texture data provided by the FAO digital soil map of Eurasia (FAO 2000), using the values given in DOORENBOS and KASSAM (1986). For a small portion south of the Himalayas, where no data is available from the FAO data set, the ISRIC-WISE digital soil map (BATES 1996) was used. The vector data

of the FAO map were re-sampled to a 0.25° grid. The coarser 1° ISRIC-WISE data were also re-sampled to 0.25° with a nearest-neighbour assignment.

2.2 Methods

To estimate soil water conditions and potential yield a water balance model based on the FAO Agro Ecological Zones methodology (FAO 1978; FISCHER et al. 2000) was used. The model assumes undifferentiated one-layer soil moisture storage and calculates soil moisture content in monthly time steps from plant-specific evapotranspiration, precipitation and residual soil moisture of the previous month. Details of the method are given below.

In 1999 39.7% of the available cropland, including the major part of the rice based cropping systems in China, was irrigated (FAO 2002). Irrigation allows potential maximum yield to be obtained while rainfed

crop yields are limited by natural moisture supply. This study concentrates on rainfed crop production and does not analyse irrigated agriculture. For irrigated crops the methodology used here cannot give information on actual yields, but rather gives an indication of the necessary irrigation to reach the potential maximum yield. While water balance calculations can serve to calculate irrigation requirements, the estimation of actual irrigation amounts is, however, beyond the scope of this paper.

Compared to other studies that are based on FAO methodology the approach presented here integrates less agronomic constraints but offers superior spatial resolution, a realistic spatial distribution of climate data allowing for the influence of topography, the use of time series as compared to mean values and a detailed view on the effects of both long-term and inter-annual climate variability on multiple cropping systems in China.

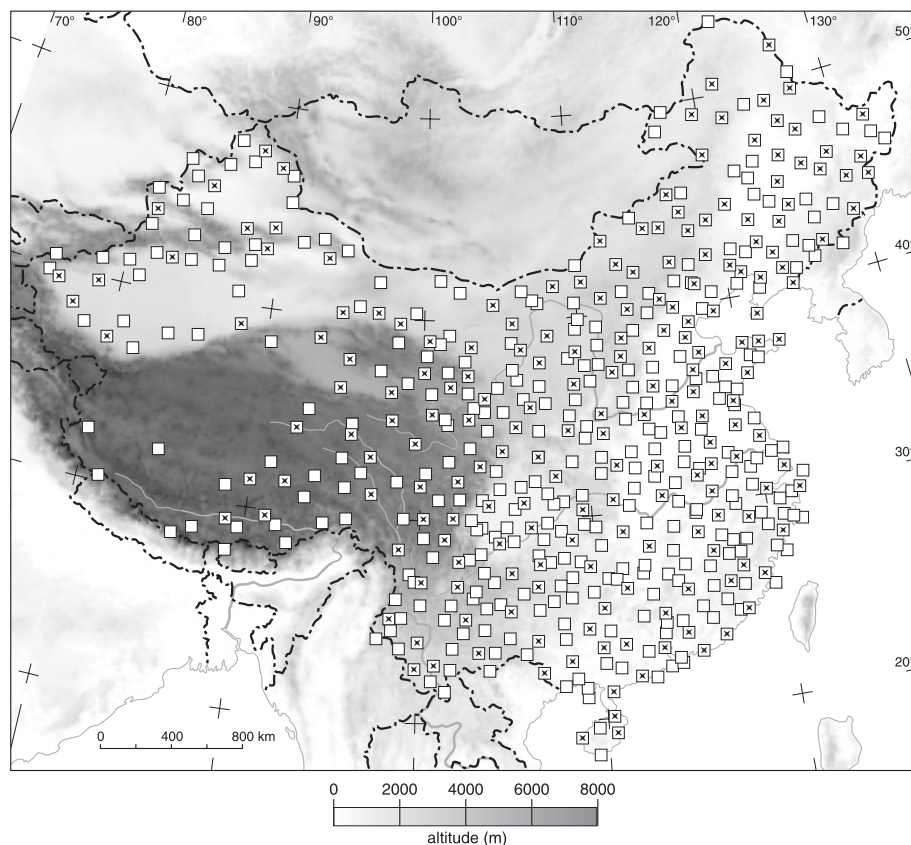


Fig. 1: Study area and distribution of meteorological stations contributing to REGEOTOP data fields (open squares: temperature and precipitation, stars: potential evapotranspiration)

Untersuchungsgebiet und Lage der für die REGEOTOP-Datenfelder verwendeten meteorologischen Stationen (Quadrate: Temperatur und Niederschlag, Sterne: Potentielle Evapotranspiration)

Table 1: Cropping systems in China according to thermal requirements and altitude

Landwirtschaftliche Fruchtfolgesysteme in China in Relation zu thermischen Bedingungen und Höhenlage						
Zone name	Abbreviation	acc. temp. ≥ 10 °C	alt < 1,500 m		alt ≥ 1,500 m	
			harvest/a	cropping system	harvest/a	cropping system
cold		< 1,500	–	–	–	–
cold temperate	W	1,500 – < 3,200	1	wheat	1	maize
warm temperate	RW	3,200 – < 4,500	1.5	rice/wheat	1.5	maize/wheat
northern subtropical	RR	4,500 – < 5,000	2	rice/rice or	1.5	rice/wheat
southern subtropical	RRW	5,000 – < 7,000	2.5	rice/rice/wheat	1.5	rice/wheat
quasi-tropical	RRS	7,000 – < 8,000	3	rice/rice/sweet potato	2	rice/rice
tropical	RRR	≥ 8,000	3	rice/rice/rice	–	–

Source: REN (1985); ZHANG a. LIN (1992); ZHENG a. NEWMAN (1986), own field work
1.5 and 2.5 harvests signify planting in autumn with a harvest in the next spring

Quellen: REN (1985); ZHANG a. LIN (1992); ZHENG a. NEWMAN (1986), eigene Feldarbeiten
1,5 und 2,5 Ernten bedeuten eine Aussaat im Herbst mit Ernte im folgenden Frühjahr

2.2.1 Phenology and cropping systems

In China a variety of cropping patterns are in use that are adapted to the local climatic conditions. To simulate realistic cropping patterns, potential cropping zones were delineated based on accumulated temperatures (Tab. 1). To each potential cropping zone a typical combination of field crops were assigned based on information by REN (1985), ZHANG and LIN (1992) and ZHENG and NEWMAN (1986). For mountainous regions above 1,500 m separate cropping patterns (THOMAS 2000b) were selected to account for the delayed response of crops to lower thermal resources. In the quasi-tropical zone sweet potato was selected as a proxy for several field crops which are grown in combination with rice.

In order to allow a detailed understanding of cropping conditions, water balances were calculated separately for each crop in multiple cropping systems, giving up to three results per growing season in the quasi-tropical and tropical zone.

Accumulated temperatures and beginning and length of the growing season (BGS and LGS, resp.) were determined, based on the number of months with temperatures above 10 °C for each grid node location. BGS and LGS are used to scale crop coefficients and rooting depths that determine potential water consumption by the crop.

The maximum water demand by the crop is described by maximum crop evapotranspiration ET_m . ET_m increases from planting, reaches a maximum during flowering and decreases during the maturity stage. ET_m is related to PET as

$$ET_m = PET * k_c$$

where k_c is the crop coefficient for the specific phenological stage. k_c values were taken from DOORENBOS and KASSAM (1986) and interpolated according to the duration of the phenological phase in relation to calculated LGS with the help of a cubic spline. During fallow periods and winter dormancy of winter wheat, k_c values of 0.2 and 0.3, respectively were assumed. Rice cultivation in regions above 1,500 m is corrected for prolonged seed bed periods (HE 1981) and slower development at higher altitudes (LI a. LIU 1988). Possible intercropping or relay cropping has not been accounted for.

Similar to plant transpiration, rooting depth (RD) increases with plant life until it reaches a maximum during the maturity stage. Rooting depth determines the amount of soil water actually available to the plant (maximum plant available soil water SW_m) as a fraction of SW. Rooting depths vary considerably with crop species and phenological stage. Setting a fixed rooting depth independent of crop and phenological stage instead using plant specific and development-dependant values can severely under- or overestimate plant available soil water (FRÉRE a. POPOV 1979). In addition plough soles in wetland rice cultivation often limit rooting depths for rice to 0.3 m and pose a problem for winter wheat in rice-wheat cropping systems (TIMSINA a. CONNOR 2001). Consequently maximum rooting depths of rice and wheat were restricted to 0.3 m in all rice-based cropping systems and to 1.0 m for wheat in rice-wheat cropping systems, respectively. Rooting depths for other crops were taken from SMITH (1992). Rooting depths were interpolated the same way as k_c values.

2.2.2 Calculation procedure

The water balance was calculated for each grid node on a monthly basis for the period 1951–1990. For each growing season the potential cropping zone of each grid node was determined. Monthly k_c and RD values were interpolated according to BGS and LGS of the cropping system in the respective year. Monthly SW_m was calculated from SW and RD as

$$SW_{m\ i} = SW_i * RD_i$$

with i as the index of the month.

Compared to the original FAO concept developed primarily for tropical and subtropical regions the potential delayed contribution of winter precipitation to the soil water balance in the form of snow melt (SM) has been introduced. Precipitation at temperatures $< 0^\circ\text{C}$ is regarded as snow and is summed separately. The use of the PET concept is of limited value under such conditions, as the assumptions of conditions similar to a green grass cover are violated. Instead direct evaporation from the snow cover is based on empirical observations and is accounted for as

$$ET_s = k_s * PET$$

with ET_s as monthly snow evaporation total, PET as monthly PET total and k_s as an empirical conversion factor set to 0.3 as the average value for snow-covered surfaces in China (ZHENG 1994).

Monthly melt rates SM were calculated according to FISCHER (1997) as

$$SM = 165 * T^{-1}$$

with T as monthly temperature $> 0^\circ\text{C}$.

Not all measured precipitation is directly usable by the plant. To allow for effects of crop interception and run-off effectiveness of precipitation (DASTANE 1974) was set to 0.9, giving effective precipitation (P_e) as 90% of observed monthly precipitation values. Lateral as well as vertical water movements in the soil were not accounted for, as their spatial variability within the 0.25° grid cells is not known and the temporal variability is too high to represent them correctly at this scale (HENDERSON-SELLERS 1996).

To initialise the soil water balance calculations for the first year were run twice, assuming that after one year soil water conditions in January are representative of actual conditions. Monthly soil water content was calculated as

$$SW_{a\ i} = SW_{a\ i-1} + P_{e\ i} - ET_{a\ i} + SM_i$$

with SW_a as actual soil water, ET_a as actual evapotranspiration and SM as snow melt. ET_a is determined based on the contribution by precipitation, snow melt and residual soil moisture of the preceeding month. If ET_m surpasses the available water supply in month m

$$ET_{m\ i} > SW_{a\ i-1} + P_{e\ i} + SM_i$$

$ET_{a\ i}$ is set to the total amount of available water:

$$ET_{a\ i} = SW_{a\ i-1} + P_{e\ i} + SM_i$$

If ET_m is lower than the total contribution by SW_a , P_e and SM

$$ET_{m\ i} \leq SW_{a\ i-1} + P_{e\ i} + SM_i$$

then ET_a is set to be equal to ET_m

$$ET_{a\ i} = ET_{m\ i}$$

with the surplus assumed to be lost by surface run-off.

At the end of a growing season the relation between total crop water demand ΣET_m and total crop water supply ΣET_a gives information about the magnitude of a possible water deficit. The yield index YI expresses to which extent the cumulative crop water demand has been satisfied and is defined as

$$YI = \Sigma ET_m / \Sigma ET_a * 100$$

with ΣET_m and ΣET_a as ET_m and ET_a totals over the growing season, respectively. Accumulated crop water deficits during the growing season are thought to be related directly to actual yield and explain about 80–85% of observed yields (DOORENBOS a. KASSAM 1986).

2.2.3 Representing inter-annual climatic variability

Most climate change studies have focussed on changes in the mean climatic conditions that represent long term averages. Changes in climatic patterns should, however, reveal themselves rather in changes of the extreme values (KATZ a. BROWN 1992). Extreme events (droughts or floods) are more important for farming operations than average values, which in some climates with large inter-annual variability may never occur in reality. The same applies to trends of annual means of precipitation and temperature that have been used to describe cropping conditions (e.g. HULME et al. 1994; SCHÄFER 2001; TAO et al. 2003). However, most crops are grown during the summer season so that annual trends are not representative. In addition winter and summer trends often

show opposing signs cancelling each other at least partially when annual trends are considered. As a result annual trends have a low significance for agricultural purposes (SMIT a. YUNLONG 1996).

OLDEMAN and FRÈRE (1982) proposed using the probability of exceedance to study the impact of inter-annual precipitation variability on crop production. The probability of exceedance, however, is based on a normal distribution and is a poor indicator particularly for precipitation probabilities in many regions in China where strongly skewed and bi- or trimodal distributions are observed. Instead the use of the decile difference DD defined as:

$$DD = D90 - D10$$

is proposed, where D90 and D10 are the upper and lower deciles of a distribution, respectively. DD defines the range of values that have occurred in 80% of the observed years and gives a more precise representation of climatic variability than parametric variability measures that rely on a normal distribution. To investigate if and to which extent inter-annual climatic variability has changed trends of DD over the period 1951–1990 have been prepared. DD is extracted from sub-samples contained in moving windows of 10 years width (i.e. 1951–1960, 1952–1961 ... 1981–1990) from the monthly time series for each grid node. Arranged in sequential order, they represent a time series of inter-annual variability for which in turn a trend can be extracted. Linear regression was used to calculate DD trends.

2.2.4 Definition of climate scenarios

To describe recent and possible future cropping conditions different sets of climate scenarios are developed from observed time series and trends. Instead of using the results of GCMs to extrapolate recent climate data fields into the future (e.g. TAO et al. 2003) climatic scenarios are derived from observed trend values. Trend-based scenarios assume that regional circulation patterns will remain stable over the predicted time period, leaving the corresponding spatial distribution, namely of precipitation and PET, unaltered. While only GCM results can be expected to give physically-based predictions of future climates, observed climate trends may stand as indicators of future climatic conditions provided observed trends represent stable long-term climatic conditions. An analysis of all possible observation periods (combinations of observation duration and begin) has shown that the majority of climatic trends in China have remained stable for at least 40 years

(THOMAS 1999), supporting the idea that observed climatic trends can be used to develop climate scenarios.

Each set of climate scenarios consists of a mean scenario and two extreme scenarios. The mean scenarios are based on the mean conditions observed or predicted for the years 1951–1990 and 2030 (SMEAN and S2030, resp.). Climate data for the S2030 scenario are extrapolated from regression trends derived from the 1951–1990 gridded time-series climate data:

$$S2030 = SMEAN + (t * Tr_A)$$

where S2030 denotes extrapolated monthly values for the year 2030, SMEAN observed mean monthly values for the period 1951–1990, Tr_A annual trends of observed monthly climate values for the period 1951–1990 and t the number of years between the temporal mean of the 40-year time-series and the scenario. As the temporal mean of the time-series corresponds to 1970 t equals 60 years. Extreme scenarios represent artificial ‘best case’ (warm and humid) and ‘worst case’ (cold and dry) climatic conditions. Each extreme scenario is based on the respective mean scenario plus observed or extrapolated upper (SMEAN_U and S2030_U) or lower (SMEAN_L and S2030_L) boundaries of variation as described by DD values or DD trend values, resp.

$$\begin{aligned} SMEAN_L &= SMEAN - DD/2 \\ SMEAN_U &= SMEAN + DD/2 \\ S2030_L &= S2030 - (t * DDTr_A)/2 \\ S2030_U &= S2030 + (t * DDTr_A)/2 \end{aligned}$$

with S2030_U and S2030_L as extrapolated upper or lower values for the year 2030, respectively and $DDTr_A$ as annual trends of observed monthly DD values for the period 1951–1990.

Water balances of the S2030 scenario are calculated based on 12 mean monthly values while the SMEAN scenario represents the mean result of the 40-year time-series. Potential cropping zones were calculated based on BGS and LGS derived from each of the 6 scenarios in order to identify possible spatial changes in the cropping patterns.

The resulting scenarios depict both temperature and humidity-related effects on agricultural production. Temperature defines BGS and LGS and therefore the possible cropping system, as well as the extent of arable areas of each cropping system. Precipitation and PET, and in turn the water balance, gives an indication of the obtainable yields under rainfed cropping conditions in the form of YI. Where climatic conditions allow multiple cropping systems separate YI values are obtained for each crop.

3 Results

With up to three crops possible in the tropical and quasi-tropical zones of China, each crop is depicted in separate maps to allow a better representation of spatial features. Crops are identified as main, second and third crop according to the cropping system columns in table 1. The main crop is defined as the crop usually sown with the onset of the monsoon season in late spring or early summer. The growing season of the second crop depends, however, on the crops being grown in the south-subtropical to tropical zone (double or triple cropping system, rice planted in late summer or autumn) or in a north-subtropical or temperate double cropping system (winter wheat sown in late autumn and harvested next spring). The results of both cropping systems are presented in the same map.

3.1 Main crop

The basic spatial arrangement of cropping systems of the main crop in the SMEAN scenario is shown in figure 2. As figure 2 maps potential cropping areas based on thermal requirements, a direct comparison with the observed distribution of cropland is not meaningful as available land use maps (IIASA 1992; IRSA 1994; WU 1991) primarily map the distribution of land use rather than of cropping systems. However, a visual inspection of figure 2 confirms that the general

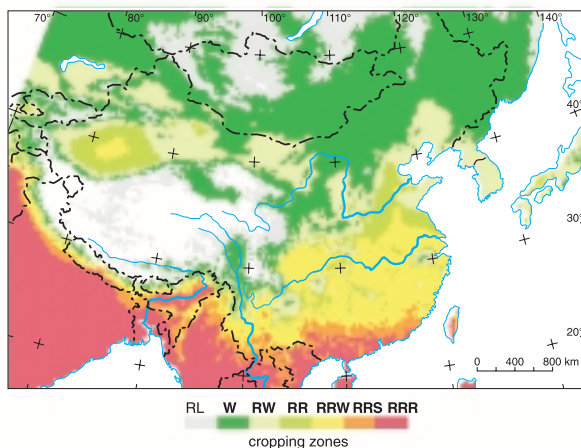


Fig. 2: Spatial distribution of cropping systems for the SMEAN scenario (1951–1990). RL signifies range land, other abbreviations are given in table 1

Abbildung 2: Räumliche Verteilung der Anbausysteme im SMEAN-Szenarium (1951–1990). RL bezeichnet Weideland, die anderen Abkürzungen in der Legende beziehen sich auf Tabelle 1

arrangement of cropping systems overlaps with the appropriate land use classes.

Figure 2 shows that triple cropping is possible over large parts of the coastal areas in the tropical and quasi-tropical zones but the major part of China is dominated by subtropical and temperate double-cropping systems. The resolution of the raster data is still sufficient to show the agricultural areas of the large river valleys such as the Yangtze and Mekong extending into the Tibetan Plateau, where agriculture is mostly restricted to animal husbandry.

Under average climatic conditions rainfed agriculture was possible over the major part of China (Fig. 3). In the SMEAN_L scenario drought restricts high yields to the cropping area of the main crop to the region south of the Yangtze (Fig. 4). The subtropical basin of Sichuan, which represents another important centre of agricultural production, is not limited by drought conditions. Drought-prone areas occur along the Huang He (Yellow River). Despite the highest annual precipitation rates in China the tropical zone is also vulnerable to drought. Only parts of the coastal tropical zone and Southwest China experience stable cropping conditions in drought years.

In very warm and humid years (SMEAN_U, Fig. 5) climatic conditions would allow the extension of cropping zones considerably towards the north. The results indicate that during the 1951–1990 period the range of theoretical movement of the polar boundary of the individual cropping systems due to interannual variations amounted to ~300 km.

The S2030 scenario anticipates that areas experiencing the strongest variability in the SMEAN scenarios will also be most affected in the future (Fig. 6). Northeastern China is predicted to see reductions in YI by more than 25%. Only the Yarlong Tsangpo valley on the Tibetan Plateau is thought to be more affected with YI reductions of more than 30%. Even under climatically stable conditions (mean conditions), cropping conditions in the lower Huang He valley would not allow economically competitive agriculture under rainfed conditions. Increases are most notably predicted for the foothill zone of the Qilian Shan north of the Qinghai Plateau (the so-called Hexi corridor) and the southern Altay Mountains.

Extreme scenarios predict quite different consequences. In dry years most parts of China would be strongly affected. Cropping conditions south of the Yangtze River would suffer heavily while figure 7 indicates individual regions with increased YI between the upper Yangtze River basin and the Huang He. In contrast conditions between SMEAN_U and S2030_U (Fig. 8) are predicted to remain mostly stable with changes

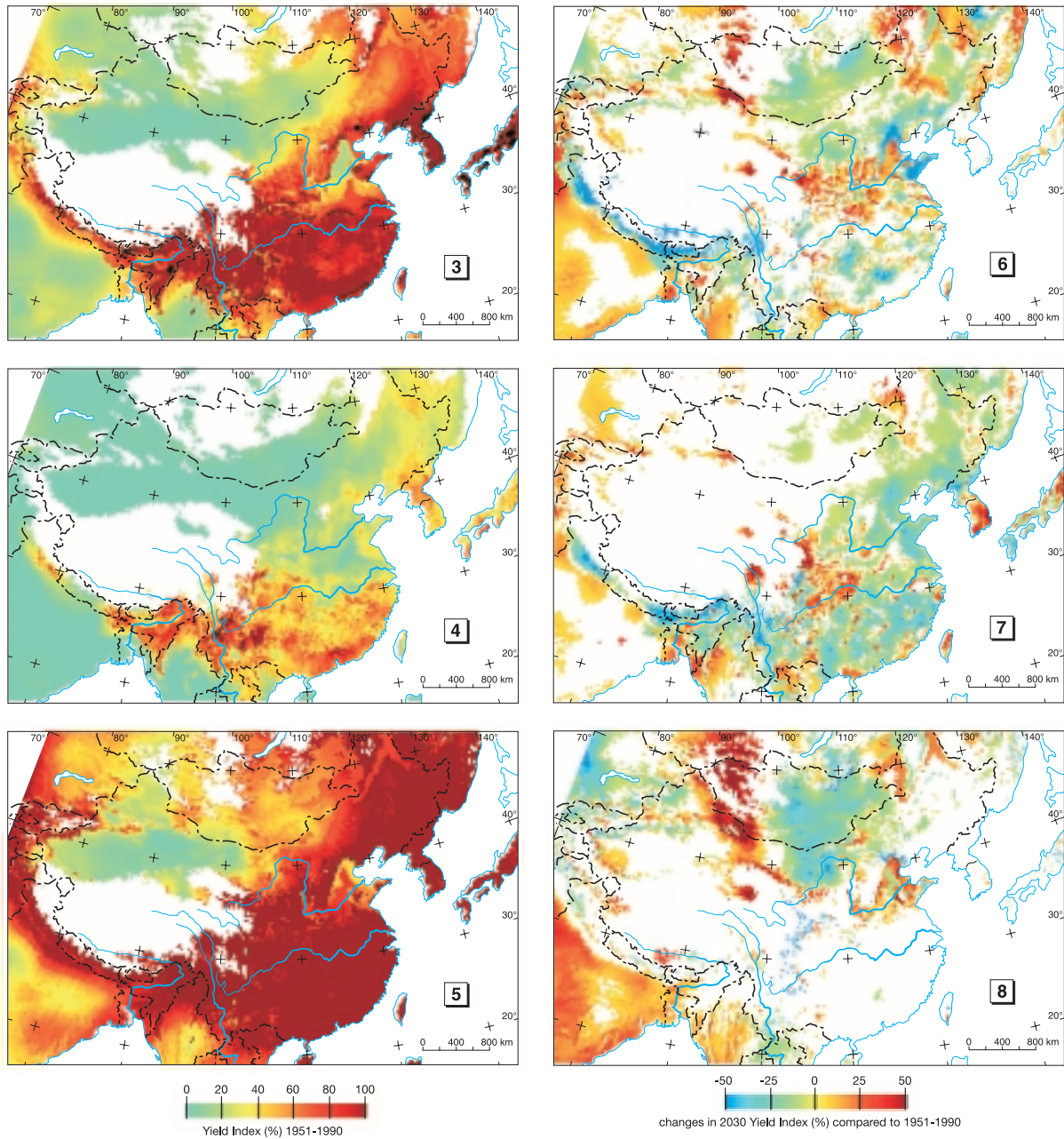


Fig. 3, 4 and 5: Spatial distribution of the Yield Index for the SMEAN scenario (1951–1990) of the ‘main crop’ and their respective ‘worst case’ and ‘best case’ scenarios

Räumliche Verteilung des Yield-Index im SMEAN-Szenarium (1951–1990) der Hauptanbausaison und die beiden zugehörigen ‘worst case’ und ‘best case’ Szenarien

Fig. 6, 7 and 8: Spatial distribution of the differences between the SMEAN Yield Index and the Yield Index for the S2030 scenario of the ‘main crop’ and their respective ‘worst case’ and ‘best case’ scenarios. Values $\leq \pm 5\%$ are not shown

Räumliche Verteilung der Differenzen zwischen dem SMEAN-Yield-Index und dem Yield-Index im S2030-Szenarium der Hauptanbausaison und die beiden zugehörigen ‘worst case’ und ‘best case’ Szenarien. Werte $\leq \pm 5\%$ sind nicht dargestellt

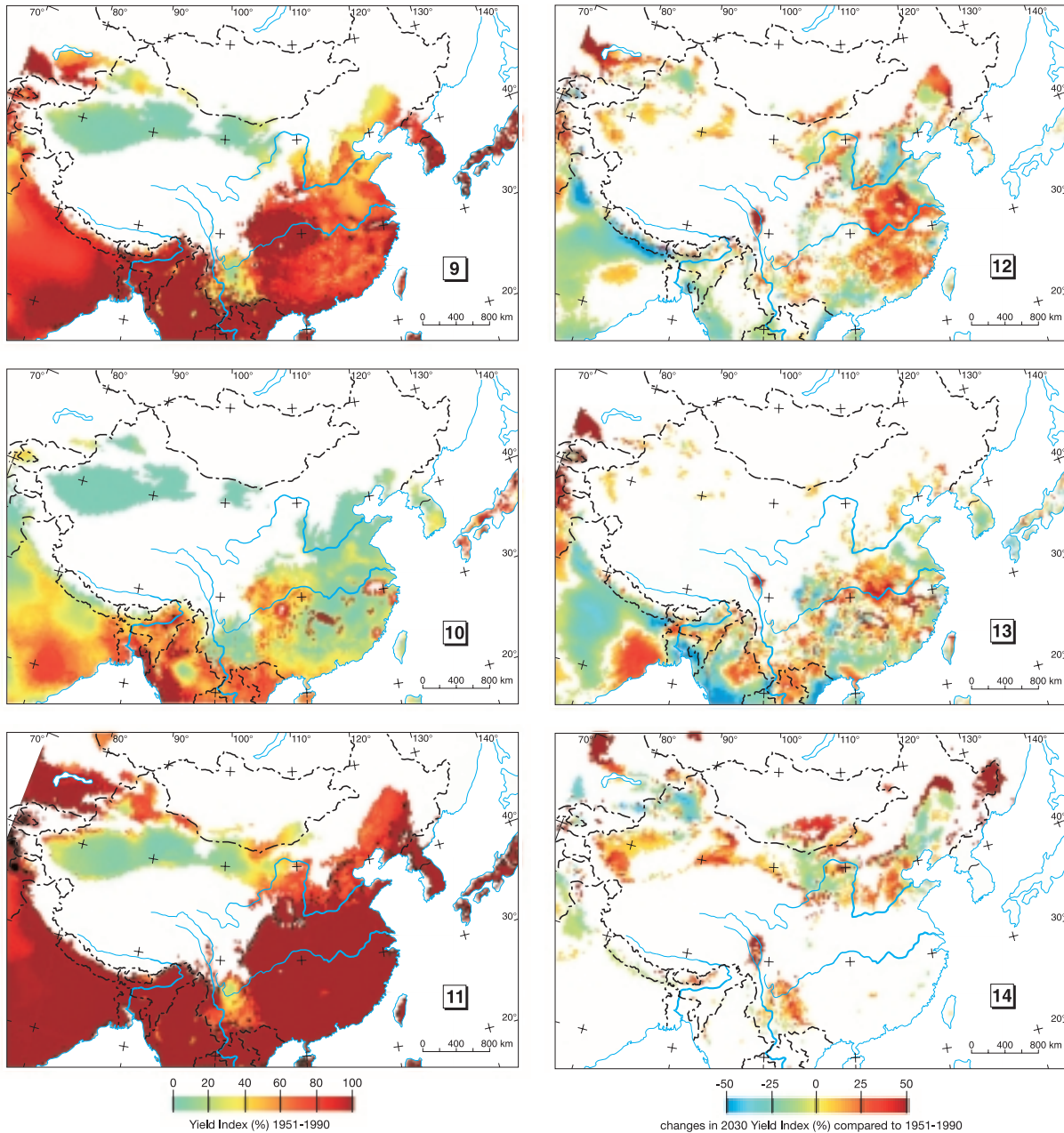


Fig. 9, 10 and 11: Spatial distribution of the Yield Index for the SMEAN scenario of the 'second crop' and their respective 'worst case' and 'best case' scenarios

Räumliche Verteilung des Yield-Index im SMEAN-Szenarium der zweiten Anbausaison und die beiden zugehörigen 'worst case' und 'best case' Szenarien

Fig. 12, 13 and 14: Spatial distribution of the differences between the SMEAN Yield Index and the Yield Index for the S2030 scenario of the 'second crop' and their respective 'worst case' and 'best case' scenarios. Values $\leq \pm 5\%$ are not shown

Räumliche Verteilung der Differenzen zwischen dem SMEAN-Yield-Index und dem Yield-Index im S2030-Szenarium der zweiten Anbausaison und die beiden zugehörigen 'worst case' und 'best case' Szenarien. Werte $\leq \pm 5\%$ sind nicht dargestellt

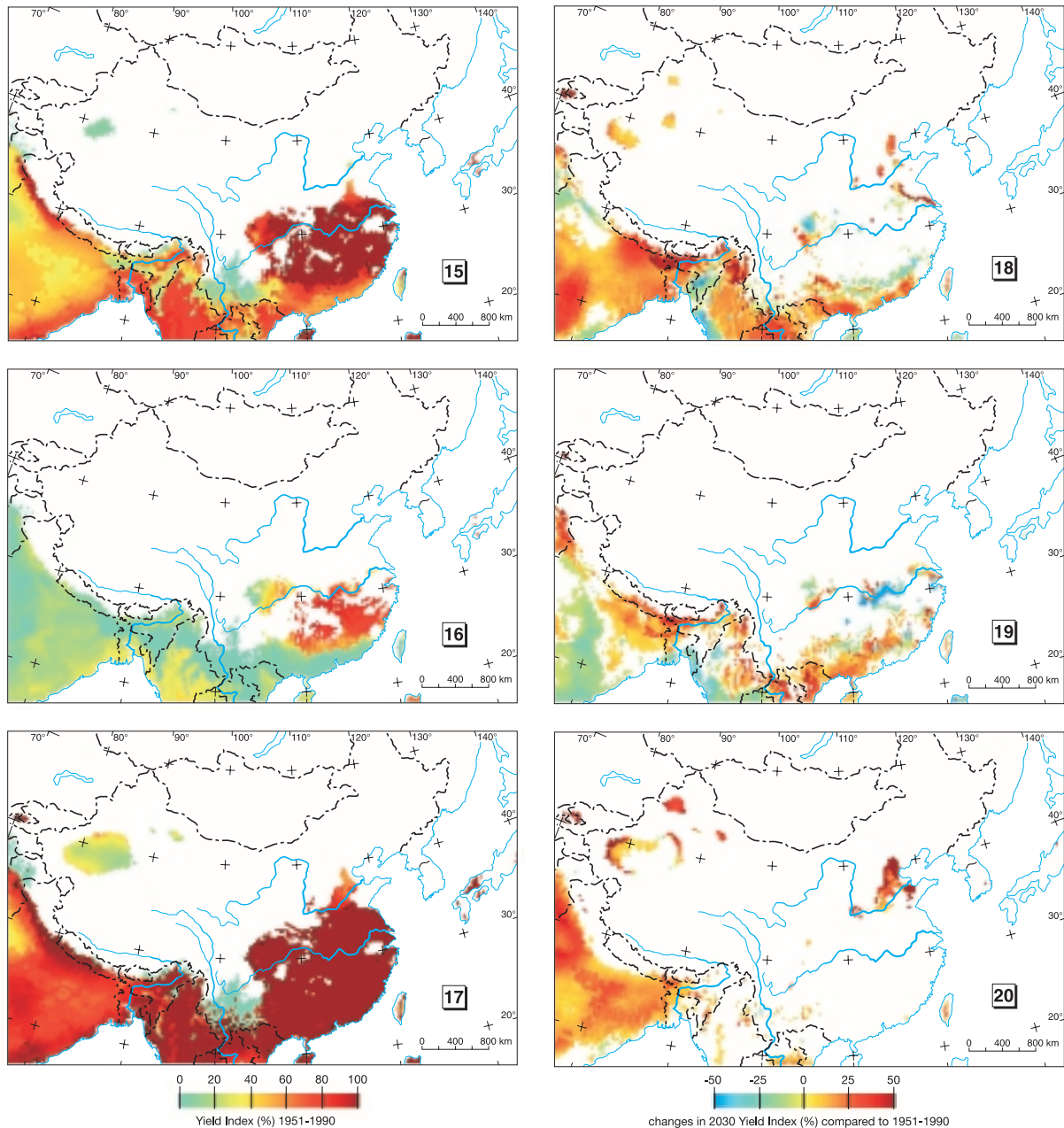


Fig. 15, 16 and 17: Spatial distribution of the Yield Index for the SMEAN scenario of the 'third crop' and their respective 'worst case' and 'best case' scenarios

Räumliche Verteilung des Yield-Index im SMEAN-Szenarium der dritten Anbausaison und die beiden zugehörigen 'worst case' und 'best case' Szenarien

Fig. 18, 19 and 20: Spatial distribution of the differences between the SMEAN Yield Index and the Yield Index for the S2030 scenario of the 'third crop' and their respective 'worst case' and 'best case' scenarios. Values $\leq \pm 5\%$ are not shown

Räumliche Verteilung der Differenzen zwischen dem SMEAN-Yield-Index und dem Yield-Index im S2030-Szenarium der dritten Anbausaison und die beiden zugehörigen 'worst case' und 'best case' Szenarien. Werte $\leq \pm 5\%$ sind nicht dargestellt

restricted to individual regions in northern China. The main cropping areas in the Sichuan Basin, the Yangtze valley and large parts of southern China are predicted to see stable conditions. Parts of Northwest China are even expected to see improved cropping conditions.

3.2 Second crop

A second rice crop in southern China and spring wheat in rice-wheat cropping systems in subtropical and temperate zones in northern China constitute an important part of the Chinese agricultural production. Figure 9 shows that during the last 40 years high yields could be expected under normal conditions (SMEAN) in southern China and the Sichuan Basin. Only south of the Huang He would winter wheat production show yields of similar magnitude. The entire northeast and southwest of China experienced no adequate yields without additional irrigation. Drought years, however, affected almost the entire country with the exception of small isolated areas in southern China (SMEAN_L, Fig. 10). In favourable years (SMEAN_U) rainfed agriculture would lead to high yields (Fig. 11) almost everywhere in China even in oasis towns such as Hami and Turpan at the northern Gobi desert margin.

The S2030 scenario predicts a similar spatial pattern (Fig. 12). The lower Yangtze valley is thought to see improved cropping conditions while in Northeast China YI varies regionally to a considerable extent. In drought years under the S2030_L scenario (Fig. 13) yields would decrease mainly in the coastal regions. Even under optimum conditions predicted YI would only lead to a marginal 50%. S2030_U (Fig. 14) predicts pronounced local increases and decreases in yield conditions that may appear in close local context particularly on the Loess plateau and along the Huang He. Yields are predicted to increase particularly in the southwest China mountain region.

3.3 Third crop

The core zone of the third crop in China is restricted to frost-free regions south of 22° N where tropical crops are cultivated. Up to 32° N a third crop of winter wheat is possible where climatic conditions meet the vernalisation requirements. The two cropping systems are easily distinguishable (SMEAN, Fig. 15) as both rice and sweet potato in the immediate coastal region consume considerably more water than winter wheat. Consequently winter wheat attains higher yields. While Southwest China meets the temperature requirements for a third crop, yields are marginal due to the prevailing dry season conditions. In comparison to the

SMEAN scenario of the main and second crop, the spatial extent of the cropping zone varies considerably between SMEAN_L (Fig. 16) and SMEAN_U (Fig. 17). Under optimum winter conditions the entire south of China up to the Huang He River, including the mountain regions, are suitable for a third crop (Fig. 17), while in cold years only parts of the Sichuan Basin and the region south of the Yangtze offer reasonable cropping conditions. With the exception of Southwest China YI range from 100% in SMEAN_U to less than 20% in SMEAN_L. Even in drought years, however, winter wheat is assumed to produce acceptable yields while rice yields a minimal YI.

Predictions for 2030 (S2030, Fig. 18) show no changes in the central parts of the cropping zone while the south China coast, the southern Sichuan Basin and the northern cropping boundary should expect some yield increases. An exception would be the small quasi-tropical zone parallel to the coast and the northern Sichuan Basin. In S2030_L (Fig. 19) reductions in cropping area are predicted to remain similar to those of the S2030 scenario. The Sichuan Basin would, however, almost completely lose its potential for a third crop and the polar boundary of the triple cropping zone (with the exception of the lower Yangtze valley) would retreat to 26° N. Virtually no changes are foreseen in the S2030_U scenario except in Northwest China and at the northeastern boundary of the triple cropping zone (Fig. 20).

4 Discussion

The results show that during the last decades cropping conditions in China have been subject to considerable variations both due to inter-annual and intra-annual climatic variability. The same applies to the modelling results of assumed future cropping conditions. Both temperature and humidity-related effects can be identified: while temperature determines the extent of potential cropping areas humidity variations are reflected in YI values.

4.1 Temperature

Accumulated temperatures have been used to define LGS, which in term delineates potential cropping areas. The effect of temperature variability is most pronounced in mountainous terrain where thermal belts shift or even disappear in relation to temperature changes. These effects are clearly visible in Central Tibet where the potential cropping area is restricted to the Lhasa Basin under average climatic conditions

(Fig. 2). In warm years wheat cultivation should be possible up to 4,500 m, which is in agreement with field observations. In contrast it shrinks to marginal areas in cold years. The major part of the agricultural production area of China both in terms of area and yield is part of the cropping area of the main crop. A movement of this core zone of more than 500 km to the north, due to the effects of global warming, has been predicted by GCM results (HULME et al. 1992; JIN et al. 1994). The model results of the S2030 scenario, however, indicates that if present trends remain stable the displacement might be almost negligible. Present-day variation of polar boundaries of cropping zones due to inter-annual climatic variability as represented by $SMEAN_U$ and $SMEAN_L$ scenarios are far more pronounced than the anticipated northward movement of cropping zones in the S2030 scenario. Instead of a general northward migration of all cropping zones, a slight expansion of the southern subtropical (rice-rice-wheat) cropping system and a dissection of cropping zones are foreseen under the given climatic trends. A stronger fragmentation of vegetation zones rather than a general northward movement is also predicted by CHEN et al. (2003) for the natural vegetation of China under climate change conditions based on GCM results.

While the potential cropping areas of the main and second crop are subject to some variation in response to seasonal temperature variability, it is the third crop during the winter season that is most affected. Winter temperatures in South China are controlled by erratic intrusions of cold air from Central Asia that bring plummeting temperatures and frost to subtropical and tropical regions of South China (DOMRÖS a. PENG 1986; ZHANG a. LIN 1992). While these 'cold waves' are singular events even a single outbreak can lead to widespread frost damage and yield losses in South China down to approximately 26° N. The northern boundary of the triple cropping zone in the L scenarios is more or less directly defined by the maximum southerly extent of cold waves. The S2030_L scenario predicts an intensification of the occurrence of cold waves that would leave only rudimentary cropping areas south of 25° N in cold years.

4.2 Humidity

Potential yields are related to moisture availability. Variability of PET is low compared to that of precipitation, consequently the exact representation of both spatial and temporal distribution (timing and amount) of precipitation in a spatially distributed water balance model is crucial for realistic results.

YI values better than 50% approximately define economically stable cropping conditions. The area described by the SMEAN scenario for a YI > 70% coincides roughly with the main Chinese agricultural production area as defined by ZHENG (1994) that includes 88% of the agricultural production area and 93% of China's agricultural production (CIESIN 1996).

Spatial inter-annual variability of the boundary of this region (difference between L and U scenarios) can in most cases be traced to intra-annual variations of precipitation, particular to the onset and to some extent to the end of the rainy season. The total amount of precipitation over the monsoon season is of secondary importance as low soil moisture in the early stages of crop development cannot be overcome by sufficient soil moisture at later stages (DOORENBOS a. KASSAM 1986).

In general, three types of variability induced precipitation types and associated regions can be discerned:

- regions where the total amount of precipitation over the growing season is in general sufficient but the onset of the rainy season is highly variable,
- regions where the total amount of precipitation always meets crop water demands but high intra-annual variability of individual months during the rainy season may inflict sporadic drought damage to crops,
- and regions where the total amount of precipitation is in general barely sufficient to meet cropping needs but, due to high interannual variability, a number of years with sufficient precipitation totals can be observed.

The first type can be exemplified with the Sichuan Basin where yields of the second crop can surpass those of the main crop if the onset of the monsoon is late. In this case the main crop starts with a low soil moisture budget while the second crop can rely on a fully charged soil profile at the end of the rainy season. High variability of the onset of monsoon rains is characteristic for Southwest China (THOMAS 1993) that is located along the boundary between Southwest and Southeast Monsoons (ZHANG 1988). Consequently Southwest China experiences lower YIs as compared to neighbouring Sichuan Basin despite higher amounts of monsoonal precipitation.

The second type occurs in South and Southeast China which are generally classified as fully humid areas. If only long-term monthly totals are considered, no water deficit occurs over the growing season due to the 'plum rains' that bring abundant precipitation. However, S2030 scenarios predict that YI will decrease sharply by more than 20%, particularly in dry years south of the Yangtze river basin. This is related to an observed increase in precipitation variability during individual monsoon months. Despite partially increasing precipitation totals over the entire rainy season crop

water availability may be reduced as monthly precipitation totals vary considerably.

The third type is most pronounced at the northern margins of the summer monsoon precipitation belt in Northeast China and Inner Mongolia where the northern extent of the monsoonal rain belt varies in response to the intensity of the monsoonal circulation. Summer monsoon precipitation may reach as far as 45° N but is usually restricted to the area south of 35° N. Between these two boundaries inter-annual precipitation variability is high leading to highly variable yields. At the northern margin along the Huang He S2030 scenarios see an increase in YI that can be interpreted as an intensification of the monsoonal activity and related rainfall fields. Signs of an enhanced circulation activity have been reported by GONG and HO (2003). Further to the northeast water availability in already drought stricken Northeastern China is predicted to be reduced even further, which in turn may be related to an increased variability of the northern monsoon region boundary.

Soil induced variability clearly is of secondary importance in the central cropping areas of China. Several authors have stressed the importance of using exact soil data to estimate water balances (FRÉRE a. POPOV 1979; FEDDEMA 1998). In the central cropping zones of China about 75% of annual precipitation is received in the main growing season, making soil moisture storage a minor concern. Only in semi-arid regions or regions where either the beginning or the end of the rainy season extends to a considerable part beyond the growing season, and where monthly water availability is lower than the soil water storage capacity, does soil moisture capacity play an important role. Spatial information on soil type and soil depth can be reliably estimated from digital soil data bases such as in FAO (2000).

The adaptation to climatic change is a central aspect of Chinese farming systems (SMIT a. YUNLONG 1996). The model used in this study incorporates anticipated reactions by farmers to changed environmental conditions by selecting cropping systems according LGS. In most cases the results remain inconspicuous; however, an interesting example of the effects of changed cropping patterns can be seen in Northeastern China (Fig. 13). A projected temperature increase would allow adjusting cropping systems from temperate rice-wheat rotation to subtropical double cropping of rice. In this case the second crop growing season shifts from autumn, winter and spring (winter wheat) to late summer and autumn (second rice crop) where precipitation totals tend to drop sharply at the end of the monsoon season. During this period soil moisture reservoirs are

then not able to sustain the crop without additional irrigation, leading to sharply reduced yields. A critical investigation of the results turns up similar, albeit less conspicuous, areas where the decision for a different cropping system leads to reduced yields.

5 Conclusions

This study has shown that inter-annual climatic variability is a key factor in evaluating the effects of climate change on Chinese agricultural production. In most studies (CHEN et al. 1992; HULME et al. 1992; HEILIG et al. 2000; TAO et al. 2003) climatic variability has, however, not been accounted for. Both inter-annual and intra-annual variability has to be represented in climate data in order to arrive at a realistic model of actual or future cropping conditions. While the described climate scenarios can give only a statistical representation of potential future climates and their variability, they can be seen as a sensitivity analysis of future cropping conditions that represent both long-term variability as well as extremes under the conditions of climate change.

The same applies to the required spatial resolution of input data and models. Studies on climate change in China have shown highly variable spatial trend patterns not only of temperature and precipitation (BÖHNER 1996; SCHÄFER 2001; HULME et al. 1994; YATAGAI a. YASUNARI 1994), but also of PET (THOMAS 2000a), sunshine duration, cloudiness, relative humidity (KAISER 2000) and air pressure (BÖHNER 1996; GONG a. HO 2003). Any meaningful climatic scenarios of future cropping conditions obviously cannot be based simply on adding fixed values of temperature and precipitation changes taken from GCM results to present-day spatial climate patterns (e.g. TAO et al. 2003). This approach contradicts the observed spatial variability of trends that include regionally distributed positive and negative trends for all climatic variables.

In addition, gridded climate data with a spatial resolution of about ≤ 25 km are required to represent the local climate of morphological features such as river valleys or intramontane basins that are important sites of agricultural production in China. GCMs have not been able to offer an adequate resolution (BENISTON 1994; HULME et al. 1992) but give rather coarse and general information in spatial terms. Advanced GCMs, coupled to a regional circulation model to give high resolution output (e.g. JACOB a. PODZUN 1997) or down-scaling methods with particular attention to topographic effects (e.g. LEUNG a. GHAN 1998) may solve the problem of insufficient spatial resolution of gridded climate data describing future climates.

The model presented here incorporates a dynamic response to inter-annual climatic variability by selecting type of cropping system and begin and length of growing season according to climatic conditions. This is particularly important in China where multicropping has attained a multicropping index (total sown area / cultivated land in %) of > 151% with grain production from multicropping reaching about 3/4 of the total grain output (ZHENG 1994). Multiple cropping systems account for about 50% of China's agricultural areas and are more sensitive to the timing and frequency of moisture and temperature conditions than average temperature or precipitation (SMIT a. YUNLONG 1996). Including the option to simulate multiple harvests with adequate climate-controlled setting of cropping calendars should be regarded as mandatory for agricultural models. Considerable attention has to be placed on this point as this study has shown that a mechanistic decision for a given cropping system based on a simple criterion is not a suitable tool for agricultural planning, even at continental scales.

This study evaluated the possible effects of climate change on rainfed agriculture and did not account for irrigation or other agronomic techniques. Farming techniques like inter-cropping or relay cropping, above ground water-storage on bunded fields or the use of mulch were not accounted for but may alter the water

balance considerably. State-of-the-art models, such as the LPJ model (GERTEN et al. 2004), will only make advances in our knowledge of cropping conditions if detailed regional cropping calendars and parameterization of local farming methods are added that match the detail of the model in general. The same applies to the fact already mentioned that the majority of the climatic input data available today have no adequate spatial resolution and suffer from several shortcomings, exhibiting considerable deficiencies particularly in data that allow calculating PET.

About 70% of the cropping area in China is irrigated, either to increase or stabilize yields or to make cropping possible in arid regions that otherwise offer favourable cropping conditions. The capacity to supply irrigation water in arid regions is the key to future sustainable agriculture. Based on the techniques described here present-day and anticipated irrigation requirements for China have been simulated and will be described in a future publication.

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