Yield 2050: Risks and opportunities for the German agriculture - A modelling approach

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Abstract: Increasing temperature as well as elevated CO_2 concentration, and an extended vegetation period might result in increases of crop yields in northern Germany. This development may be counteracted by drought conditions due to less rainfall during the vegetation period, or other plant physiological effects induced by changes in environmental conditions. Climatic conditions, however, will not only affect the average yield level, but will also influence yield variability (risk) since the abundance of extreme weather conditions, such as summer heat and heavy rainfall events, is assumed to increase. Modelling of cropping systems provides a suitable approach for (i) assessing risks in future crop production systems, and (ii) developing crop management strategies to reduce yield risk. Therefore, the process-based decision support system for agrotechnology transfer (DSSAT) was validated with statistical wheat yield data (comprising up to 20 years) for four regions representing the environmental conditions of the North German Plain. The climate change impact on winter wheat yield was assessed by running three climate scenarios for the 2040 to 2060 period, and compared with the yields of the period from 1990 to 2010. We parameterised a general DSSAT wheat plant growth model for the North German Plain. It is capable of qualitatively reproducing the observed mean wheat yields. Further, we can show: there are risks for crop production and these risks are increasing with climate warming. Especially, strong climate warming will lead - without changes in the production scheme - to a reduction of crop yield and an increase of yield variability.

Keywords: Crop yield, critical phases in plant growth, yield risk, modelling, DSSAT, regional model, NaLaMa-nT project

Introduction

It is widely accepted that climate change will have an impact on European crop production. In the case of winter wheat, for example, some studies assume heat stress to substantially increase the vulnerability of wheat production, while others suppose water deficiency to be the major factor influencing wheat yield (Semenov and Shewry 2011; Eitzinger and Thaler 2012). The North German Plain, being a major area of European crop production, may be expected to face serious challenges over the next decades. Modelling seems a suitable tool to analyse climate change impact on crop yield and environmental effects, and to evaluate adaptation strategies (Perry et al. 2004; Ewert et al. 2005).

The objective of the current study is to test DSSAT's potential to model yields of the North German Plain. The study is embedded within the NaLaMa-nT project funded by the German Federal Ministry of Education and Research (BMBF) framework for sustainable land management module B. The project aims to develop comprehensive concepts for a sustainable land use management, based on four representative regions in northern Germany. A special focus is given to risk assessment and adaption strategies for plant production.

Applying DSSAT (Jones et al., 2003; Hoogenboom et al. 2012), a widely accepted internationally applied model, allows to analyse scenarios with adaption strategies and management techniques not yet applied in the North German Plain. It is hypothesised that (i) DSSAT is capable to simulate crop yields under current climatic conditions of the North German Plain, (ii) winter wheat, as the most important crop of this region, can be modelled with high accuracy, (iii) future climate change will have a substantial influence on wheat development by decreasing yield, due to the negative impact during the critical stages of growth. The current work thus comprises two modelling studies. The first study finds a general parameterisation for the DSSAT wheat model in order to reproduce historic winter wheat yields for the 1990 to 2010 period for each of the four representative regions (Table 1). The parameterised wheat model is then applied in the second study to analyse future climate change impact (2040-2060) on wheat yield.

Table 1: Overview on the regions investigated: position (WGS 84), weather station representing each area, utilised soils of the DSSAT soil data base, and regional land use.

Region		DH	UE	FL	OS
Weather station	name	Diepholz	Uelzen	Wittenberg	Fürstenwalde/Spree
	id	15013	16014	22011	18109
latitude	[°]	52.59	52.95	51.89	52.35
longitude	[°]	8.35	10.54	12.65	14.07
altitude	[m]	39	49	105	38
soil		med silty loam	med sandy loam	shallow sand	shallow sand
clay	[%]	22.8	11.0	2.5	2.5
silt	[%]	38.5	22.7	9.6	9.6
sand	[%]	38.7	66.3	87.9	87.9
area					
total	[km²]	2000	1500	2100	2200
agricultural	[%]	75	50	40	40
precipitation	[mm]	701	714	663	685

Materials and Methods

Climate data

Historic climate data for a range of weather stations were provided by the Deutscher Wetterdienst (DWD). The data were homogenised - i.e. removing non-climate change bias e.g. correction due to change of instruments, or relocation of station, etc. (Caussinus and Mestre 2004) - by the Potsdam Institute for Climate Impact Research (PIK). Further, PIK provides future climate scenarios for the four regions. Scenarios are situated in the continuum of the RCP 8.5 climate change scenario of the Intergovernmental Panel on Climate Change (IPCC). These three scenarios representing **max**, **med**, and **min** specifications of climate are based on three general circulation model (GCM). **Min** scenario is a run from the INM-CM4 of the IMN, Russia, **med** scenario is a run from ECHAM6 of the Max-Planck-Institute (MPI), Germany, and **max** scenario is a run of the ACCESS1.0 model from CSIRO-BOM, Australia. Each scenario represents a singular model run. Scenarios are regionalised utilising the statistical regional model (STARS). Table 2 comprises the range of available climate scenario data.

Yield data

The observed statistical crop yield data used for validation of the wheat model (MOD1) were provided by the Federal Statistical Office of Germany (public access). In the following, these data will be referred to as observed data (Obs). Yield data were available for a time period of 20 years (1990 to 2010). Region Fläming is assembled of three administrative units from the statistical data base. The other regions are each identical with administrative units from the statistical data base.

Model study 1 (MOD1)

The four regions comprise Diepholz (DH), Uelzen (UE), Fläming (FL) and Oder-Spree (OS) (Table 1). All regions are located in northern Germany along a transect representing the gradient of increasing continental influence from west to east (Table 1). Each modelling region is simplified to a homogenous area with respect to climate, soil and yield. Daily solar radiation [J cm^{-2}], temperature's daily min [°C] and max [°C], as well as precipitation [mm] were required as input for the crop model. For each region a uniform, characteristic soil type was chosen (Hartwich et al., 1995) and implemented using the corresponding default soil parameters provided by DSSAT (Table 1). Winter wheat (**Triticum aestivum** cv. Newton) is grown continuous for 20 years (1990 to 2010). Crop growth was simulated with the DSSAT CERES-wheat model, where initial conditions were adjusted for each region as follows: previous crop before initial year: fallow, root weight: 4000 kg ha^{-1} and crop residue: 6000 kg ha^{-1}, nitrogen incorporation was set to 100% within the first 15 cm of soil. Due to a comparable production scheme, we applied a total fertiliser each year of 150 kg nitrogen for each site. Fertiliser was applied in each year with planting (50 kg N ha^{-1}) and in April of the following year (100 kg N ha^{-1}). Harvest was set to take place when physiological maturity was reached. No irrigation was applied. Sowing date was fixed to the 15th September in each year with the following set-up: sowing density 400 grains per m². We tested the means of the modelled and the observed 20 year period with a Student's t-test for differences. Furthermore, a linear regression was performed between observed (Obs) and modelled crop yields (MOD1) to quantify model fit.

Model study 2 (MOD2)

The second model study (MOD2) investigated the wheat yield under climate change impact. Accordingly, MOD2 was run with the same parameterisation as described in MOD1 for the four regions with three different climate scenarios, i.e. **max**, **med**, and **min** (Section 2.1, and Table 2). The set-up was altered only by changing the time period to 2040-2060 and by increasing the carbon dioxide concentration from current 380 ppm to predicted 480 ppm (Pachauri and Reisinger 2007). All crop modelling was performed using DSSAT v 4.5.The statistical computation software R was applied for the graphical and statistical evaluations (R Core Team, 2013).

Results

Temperature and precipitation

There is a significant difference in mean annual temperature between the historic weather data and the three climate scenarios **med**, **min**, and **max** (Table 2), with higher future temperature. Changes in the mean annual precipitation sum could not be detected (data not shown).

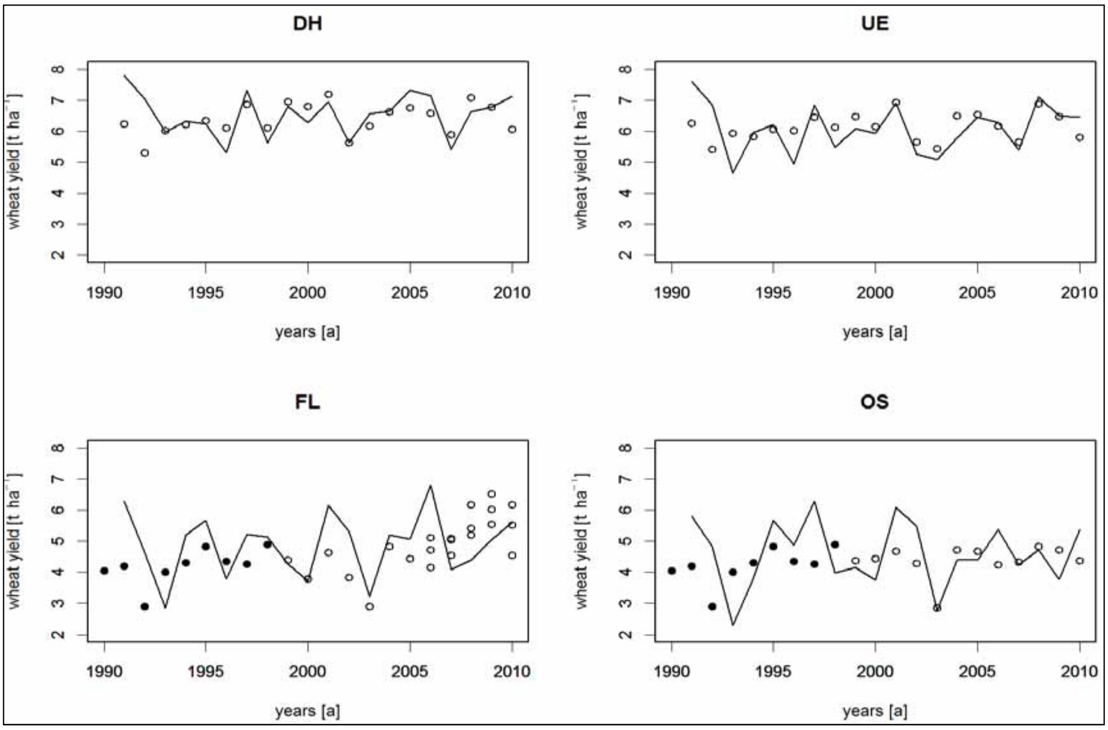
Table 2: Mean annual temperatures for the period 1990-2010 (Obs) and predicted by three climate models (**med**, **min**, and **max**) applied in MOD2 for modelling the years 2040-2060 at the sites. Levels of significance concerning the difference in mean temperatures of the periods are indicated by stars (*).

Region		DH			UE			FL			OS		
		[°C]			[°C]			[°C]			[°C]		
Obs		9.7	±	0.7	9.3	±	0.7	10.7	±	1.2	9.7	±	0.8
med	MOD2	11.6***	±	0.6	10.9***	±	0.6	12***	±	0.6	11.9***	±	0.6
min	MOD2	10.8***	±	0.6	10.2***	±	0.7	11***	±	0.7	11***	±	0.7
max	MOD2	12.3***	±	0.9	11.6***	±	1	12.7***	±	1.0	12.5***	±	1.0

MOD1

The CERES-wheat model was able to satisfactorily reproduce the mean wheat yields of the four investigated regions (Figure 2 and Table 3). It was especially successful in reproducing the yields of DH and UE (Figure 2). There were no significant differences between means in modelled and observed yield data (Table 3). The standard deviation and hence the yield variability for observed and simulated data ranged between 10% and 20% (Figure 2).

Figure 1: Observed (circle) vs. simulated wheat yield (line) for the investigation regions. Historic yield data for the regions FL, and OS was only available from 2000. Thus, the time series was supplemented by Brandenburg state yield data (black dots, not accounted for evaluation). Reckon multiple yields in FL is due to region overlapping administrative units (Section 2.2).



Although mean crop yields were reproduced satisfactorily, there were still weaknesses with respect to the temporal pattern of wheat yields (Figure 1, Table 3). This effect was most pronounced for regions with shallow sandy soils (FL and OS), where the time course was not well reflected, as indicated by low R^2 values. For regions characterised by heavy soils (DH and UE), in contrast, coefficients of determination of 0.39 and 0.56 indicate a better model fit.

Table 3: Observed and modelled mean wheat yields with standard deviation simulated for the 1990-2010 in the four NaLaMa-nT regions. *) Statistical yield data were only available for 2000 to 2010. Model fit was quantified by the coefficient of determination. Levels of significance are indicated by stars (*).

Region		**DH**			**UE**			**FL*)**			**OS*)**		
Obs	[t ha^{-1}]	6.3	±	0.8	5.9	±	0.7	4.7	±	1	4.6	±	10.4
MOD1	[t ha^{-1}]	6.5	±	0.7	6.1	±	0.8	4.9	±	1	4.6	±	10.6
	R^2 [-]			0.39*			0.56***			0.11			0.25

MOD2

The wheat yields obtained by the climate change scenarios suggest a comparable level as observed in the reference period (MOD1, Table 4). In contrast, the **max** scenario produced significantly smaller mean yields than in the reference period for all tested regions. The **min** scenario gave intermediate wheat yields for regions DH and UE, while for regions FL and OS the yield was similar to **max**. Visual inspection of the boxplots (Figure 2) reveals higher yield variability for **max** and **min** MOD2 scenarios for FL and OS. The outlier in the **min** scenario of region DH can be traced back to the year 2055, where unfavourable weather conditions caused a very low yield for all regions. This year's crop failure for FL region lies in the range of the standard deviation.

Table 4: Mean simulated wheat yields of the 2040-2060 period with standard deviation as obtained by the three climate change scenarios (med, max, min). Each climate scenario's mean yield is t-tested on differences to MOD1 mean yield. Significance-levels are indicated by stars (*).

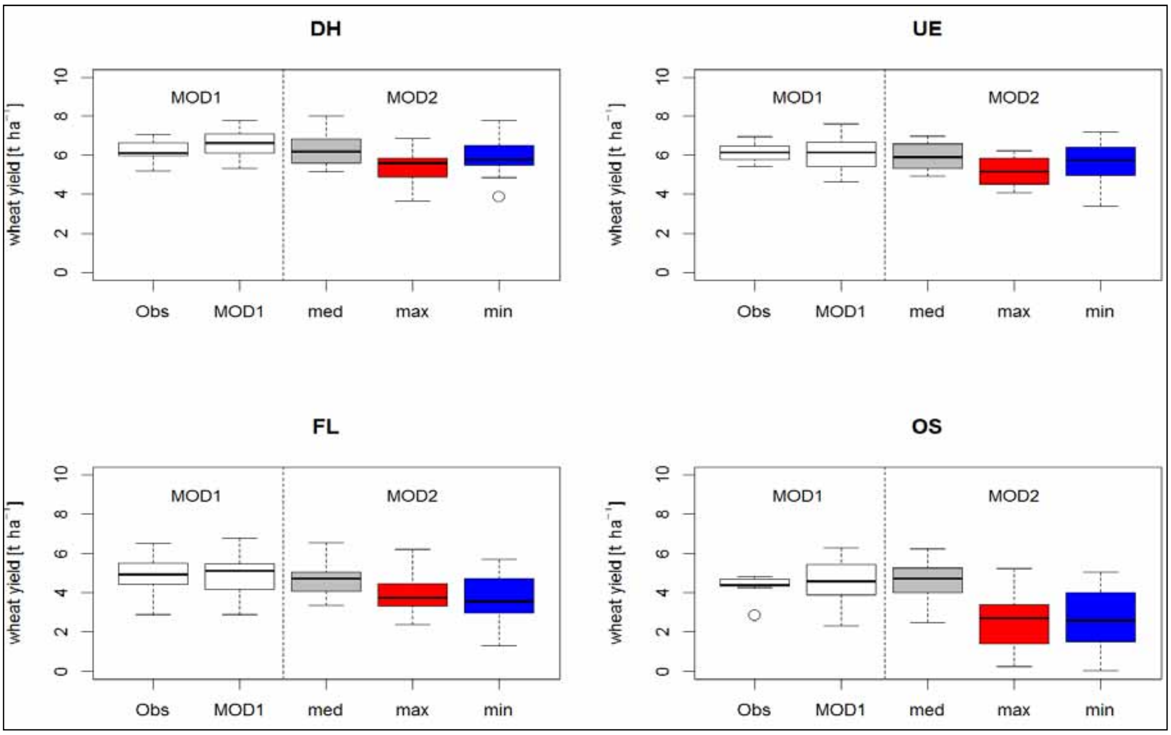
Region		**DH**			**UE**			**FL**			**OS**		
MOD1	[t ha^{-1}]	6.5	±	0.7	6.1	±	0.8	4.9	±	1	4.6	±	1.1
med	[t ha^{-1}]	6.3	±	0.8	5.9	±	0.7	4.7	±	1	4.6	±	1
max	[t ha^{-1}]	5.5***	±	0.8	5.2***	±	0.7	3.9**	±	1	2.6***	±	1.3
min	[t ha^{-1}]	6	±	1	5.7	±	0.9	3.7**	±	1.3	2.6***	±	1.5

Discussion

MOD1

We achieved reasonable results in reproducing statistical winter wheat yields with the DSSAT wheat model for the North German Plain. The means and the range of wheat yield are reflected to a satisfactory degree by the general model set-up (MOD1). This is in good agreement with two model comparison studies on barley and winter wheat finding DSSAT to be a suitable tool for simulating crop yields under European conditions (Taru et al. 2011; Rötter et al. 2012).

Figure 2: Box plots of winter wheat yields for observed data (Obs) and the MOD1 and the MOD2 study conducted for four northern German regions. MOD2 study includes three different climate change scenarios **max**, **med**, and **min**.



The weaknesses which became apparent with respect to the temporal yield pattern of the FL and OS region characterised by light soils are most likely due to the modelling approach designed for a better comparability among regions than for region-specific accuracy. Thus, model parameterisation will need refinement by (i) using a larger data set and (ii) by adaptations with respect to site specific characteristics, such as soil texture, and region-specific crop management schemes. This includes the selection of appropriate wheat cultivars parameters. The wheat cultivar (Newton), which had been used for all tested regions, was bred for the hard red winter wheat regions of the United States (Upadhyay et al. 1984) and probably does not represent well German winter wheat cultivars. In future modelling work, we will adopt more site specific cultivars to improve model fit. Low quality of statistical winter wheat data may have further limited model fit.

The static production scheme applied here does not fit the changing environmental conditions. Especially, the static fertiliser application scheme might not match the actual plant needs for further modelling we intend to apply a more flexible fertiliser management to fit the actual plant requirements. The - due to the comparability of the sites - standardised amount of applied fertiliser is not representative. It overestimates the amount for OS and FL (approx. 120 kg N ha^{-1}), and underestimates the amount for DH and UE (approx. 200 kg N ha^{-1}, according to German fertilisation ordinance (DÜV)). Further, the grain density at sowing is on upper limit of what is usual winter wheat for the North German Plain.

MOD2

Modelling study MOD2 revealed that mean wheat yields under climate change conditions (**med** scenario) are on a similar level as today. A substantial reduction in future wheat yield was detected for the max scenario at all regions. Heat and drought stress are expected to increase in this scenario due to higher mean temperature and constant precipitation (Table 2, Section 3.1). This may lead to an increasing water deficit. It was remarkable to find that the **min** climate scenario produced smaller crop yields with a higher variability than the **med** scenario. We had expected that the impact on yields through the **min** climate change scenario would be smaller than for the **med** climate change scenario. Obviously, outliers were responsible for the higher variability of the MOD2 **min** scenarios, e.g. the year 2055. However, annual temperature ranging between 10.5 and 10.6°C and annual precipitation of 572 to 754 mm do not indicate extreme weather conditions for this year. We thus assume that adverse weather conditions during critical stages of plant growth caused low yields. For this year drought in March and April is ostentatious (data not shown) and might be responsible for the poor yield. High water use in this growth stage seems to be a critical factor for growth winter wheat (Schneekloth et al. 2009). Stress experienced during critical stages of plant growth (eg. germination) will lead to substantial yield reduction (Semenov and Shewry 2011; Lobell et al. 2012). The consideration of critical plant growth stages and their impact on crop yield, seems not to be addressed adequately in many crop models (Rötter et al. 2012), but obviously is reflected in the DSSAT CERES-wheat model.

Conclusion

The DSSAT wheat model has proven suitable to model winter wheat production in the northern German plain. Our results indicate that the model is able to reflect the sensitivity of wheat to adverse weather conditions during critical stages of plant growth. With further model refinement and a profound validation, the model will serve as a powerful tool to evaluate future crop management strategies under the impact of climate change in the northern German plain.

We assume a more flexible production scheme will be adequate to react to critical situations occurring during to plant growth. Hence, risks for yield losses seem to be related to precipitation's distribution over the year more than to a general reduction in precipitation sum. We suggest fertilisation and irrigation schemes that promote the growth of an extensive root system for more efficient use of stored water is an adequate countermeasure to these risks. Further, the extended vegetation period might lead to drought stress in periods critical for plant development, e.g. early spring, not yet common in the North German Plain. This stress potential could be compensated by irrigation strategies.

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