Improving crop models with respect to yield variability and climate extremes as a precondition for food security assessments

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Agriculture is a cornerstone of food security, producing eighty percent of the calories that we consume either directly as food or indirectly as animal feed. Production increases in agriculture have contributed to achieve food security for the large majority of people in recent decades, with 'food security' defined as a situation where all people at all times have nutritious and sufficient food. Nevertheless, there are still more than one billion people who are malnourished, and multiple threats are looming for the future of food security. A growing population and dietary shifts towards more animal-based food will increase the demand for agricultural production. At the same time, production capacity is under pressure, in particular by climate change. Even though the impact of climate change is uncertain, climate variability and extremes are likely to increase with it and may diminish harvests. Hence it is decisive to quantify the influences of climate on production. An important tool to quantify climatic influences on crop yields are crop models, which are mathematical descriptions of plant growth and yield. These crop models have matured over decades, but deficiencies remain. Therefore this thesis aims at improving crop models by addressing deficiencies with respect to yield variability and climate extremes. It consists of four parts.

The first part is a meta-study, presenting a new appraisal and structurization of the abundant literature knowledge on crop physiology. A novel method is used to build a network-based encyclopedia, which enables a consistent and systematic classification of diverse physiological influences on crop growth. The network then allows for deducing improvement suggestions for crop models. Two of these suggestions, namely crop damage from ozone pollution and extreme temperatures, are treated in the remaining chapters.

The second part presents a study of ozone damages on historical crop yields. A newly developed ozone module is implemented in the global crop model LPJmL. The enhanced model is used to simulate global historical wheat and soybean yield losses from ozone pollution. Crop water status, temperature and CO2 are considered as modulators of ozone damage, which constitutes an improvement over previous global assessments that were based on linear correlations between ozone and yield. The analysis indicates that ozone is a major problem for crop production, causing yield losses up to occasional 50%.

The third part contains an analysis of the effects of high temperatures on yield losses in the US, a major crop producing country. Heat waves are likely to occur more frequently under global warming, which requires crop models to correctly simulate their effects on crop yields. Yet it has recently been doubted whether current models are capable of doing so. Hence it is assessed to what extent nine state-of-the-art crop models can reproduce observed effects of high temperatures on maize, soybean and wheat yields in the US. The analysis reveals that the ensemble of crop models reproduces observed yield losses in the correct quantities. The novel combination of statistical and process-based crop models applied here allows for new mechanistic insights, suggesting that yield losses stem from water stress rather than direct heat damages. This justifies irrigation as an effective adaptation measure, at least until a temperature threshold of approx. 36°C where sufficient observations are available. Furthermore, it is

hypothesized that future US yields are likely to suffer from heat losses even under elevated CO2. This is contrary to current convictions and deserves further investigation in experiments.

The fourth part describes a statistical model to assess the global share of weather-driven yield variability and the influence of individual weather variables during different phenological phases. It is decisive to know these influences for designing yield insurances and projecting future yields. An existing statistical model is enhanced by penalties for hot and cold temperature stress, as suggested by the meta-study in part one. With the enhanced model the influence of weather on yield variability of maize, wheat and soybeans is quantified as 15-42% globally, with magnitude and robustness depending on crop and yield input data quality. The model can also be applied for near-term yield forecasting during the growing season. Such pre-harvest knowledge of expected yields is important for management planning at the farm and regional level. First results with a forecasting capacity of more than 50% two months before harvest in several countries merit further development.

Taken together, this thesis underlines the negative influence of ozone and high temperature stress on agricultural production and, consequently, food security. Different crop models are utilized and improved and the benefits of using diverse types of models are highlighted. Perspectives for further research on ozone, extreme heat stress and yield forecasting are presented.