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Lengthening of the growing season in wheat and maize producing regions

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ABSTRACT

Human-induced increases in atmospheric greenhouse gas concentrations have led to rising global temperatures. Here we investigate changes in an annual temperature-based index, the growing season length, defined as the number of days with temperature above 5 °C. We show that over extratropical regions where wheat and maize are harvested, the increase in growing season length from 1956 to 2005 can be attributed to increasing greenhouse gas concentrations. Our analyses also show that climate change has increased the probability of extremely long growing seasons by a factor of 25, and decreased the probability of extremely short growing seasons. A lengthening of the growing season in regions with these mostly rain-fed crops could improve yields, provided that water availability does not become an issue. An expansion of areas with more than 150 days of growing season into the northern latitudes makes more land potentially available for planting wheat and maize. Furthermore, double-cropping can become an alternative to current practices in areas with very long growing seasons which are also shown to increase with a warming climate. These results suggest that there is a strong impact of anthropogenic climate change on growing season length. However, in some regions and with further exacerbated climate change, high temperatures may already be or may become a limiting factor for plant productivity.

1. Introduction

The global number of undernourished people has decreased from over a billion (or 18.7% of global population) in 1990–1992 to around 805 million people (11.3%) in 2012–2014. Reaching the Millennium Development Goal of halving the proportion of undernourished people in developing countries between 1990 and 2015 might be possible (FAO, IFAD, WFP, 2014). Several factors have contributed to reducing world hunger in the last decades. In general, an increase in agricultural production can be obtained through an increase in the area under production or an increase in the productivity on existing farmland. The most important factor for the decline in hunger over recent decades is increased crop yields (Foley, 2011), i.e. the productivity per unit area. Both developing new crop varieties and increasing planting densities can increase yields (McClung, 2014). Production can further be increased by harvesting two crops on the same field each year (double-cropping). Double-cropping is currently still relatively insignificant (Brochers et al., 2014) and mostly confined to the tropics (Siebert et al., 2010), but could have huge potential for food security as it can nearly double yields.

Wheat and maize are the crops with the largest area harvested and second only to sugarcane in their annual production (data for 2012, FAO statistic, 2014). Both agricultural output (production) and yields have increased steadily over the last decades, while the area harvested has stayed nearly constant (Fig. 1). In order to meet future demands, it is projected that production would need to reach 891 and 1343 million tonnes for wheat and maize, respectively, by 2050 (Ray et al., 2012).

Climate change can have either negative or positive impacts on crop production, depending on the region (Cheng et al., 2011; Porter et al., 2014). In high latitudes, warmer temperatures lead to longer growing seasons and an increase in potential agricultural land (Gornall et al., 2010). We here select areas where wheat and maize are grown to investigate whether growing season (GS) length (GSL) in such important agricultural areas has increased and whether it can potentially contribute to increased production. We therefore first analyze whether the area with GS long enough to grow wheat and maize or to do double-cropping has increased. We further investigate

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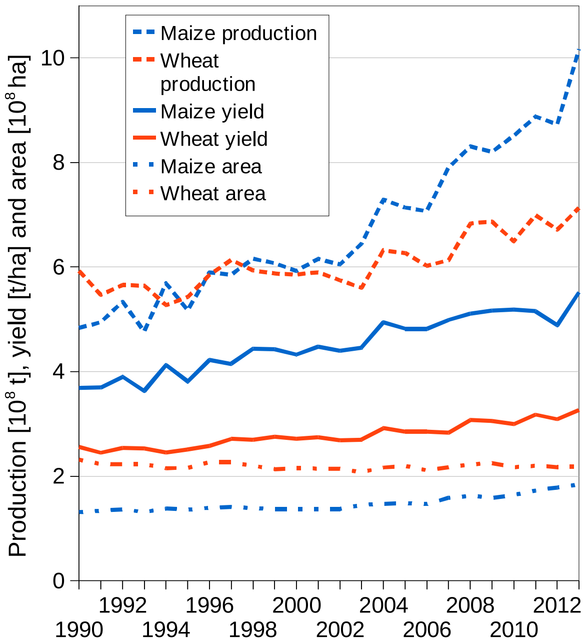

Fig. 1. Production, yield and area harvested for wheat (red) and maize (blue) over the last two decades. *Data source*: FAO homepage (2014). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

whether changes in GSL in wheat and maize areas can be attributed to human activity. A significant lengthening in nearly-global GS has been found and attributed to an increase in anthropogenic greenhouse gas concentrations (Christidis et al., 2007). However, such an attribution has not been previously done specifically for wheat and maize regions. We also employ a larger set of climate model simulations and more recent data than Christidis et al. (2007).

We investigate changes in the occurrence of extremely long or short GSL since both types of extremes can substantially impact crop production. Based on an ensemble of possible GSLs from observationally constrained climate model simulations, we investigate changes in the probability of extreme GSL over recent years and estimate the effects that human-induced greenhouse gas emissions have had on these probabilities.

2. Regions with wheat and maize production

Due to their importance for global food production, our analyses are focused on wheat and maize areas. The definition of areas with wheat and maize is based on data from EarthStat (www.earthstat.org), a collaborative effort between the University of Minnesota's Institute on the Environment-Global Landscapes Initiative and McGill University's Land Use and the Global Environment lab. EarthStat provides harvested area and yields for 175 crops around the year 2000, which they obtained by combining national and sub-national agricultural census records with satellite imagery. The data are described in Monfreda et al. (2008).

Fig. 2 shows the areas where wheat and maize are produced (data for year 2000, interpolated to 2.5° × 3.75° grid). For each crop, we consider grid cells that are more than 1% covered with the respective crop. Note that the areas partly overlap and our results for the two crop areas are thus not independent. We obtain 4.54% of all land area as our wheat area and 4.65% as maize area.

3. Observed growing season length

Even though some varieties of wheat can resist temperatures down to −20 °C in their early stages of growth, wheat and maize cannot tolerate frost during their main growth period. Minimum daily temperatures of about 5 °C are needed for measurable growth of both winter and spring wheat, and slightly higher temperatures are required for maize. The optimum temperature for wheat growth is between 15 to 20 °C. We select a temperature threshold for our growing season definition of 5 °C, above which wheat and maize both grow well and for which a global observational GSL dataset, the HadEX2 dataset (Donat, 2013, see below), is available. The annual length of the growing season is defined as the number of days between the first span of at least 6 days with daily mean temperature warmer than 5 °C and the first span of 6 days with daily mean temperature below 5 °C. For this calculation, a year lasts from 1st January to 31st December in the northern hemisphere and from 1st July to 30th June in the southern hemisphere (Frich et al., 2002).

Observational GSL data on a 2.5° × 3.75° latitude–longitude grid are obtained from HadEX2, which provides gridded land-based data of a variety of temperature and precipitation indices, many of which are pertinent to extremes. The data can be downloaded from www.climdex.org.

GSL can be seen as an indicator for potential plant productivity, and we evaluate its value for estimating changes in plant growth. Fig. 2 (bottom) shows correlations of observed annual GSL values and corresponding satellite-derived Normalized Difference Vegetation Index (NDVI) values from the Advanced Very High Resolution Radiometer (AVHRR), which is an indicator of vegetation greenness (see Supplementary Fig. A1 for correlations with an alternative NDVI dataset). In the extratropics, the correlations are relatively good. As the agreement is especially high north of 40°N, we use these areas (Asia, Europe, America) indicated with boxes in Fig. 2 for our temporo-spatial detection and attribution analysis (see Section 5). In temperate climates, wheat is usually grown as a rain-fed crop (FAO homepage, 2014). As such, water is usually not limited and warm temperatures are likely more important than rainfall for crop growth. We therefore select the northern and southern temperate zones (north of 25°N and south of 25°S, extratropics) for our analyses, i.e. the entire extratropical region.

Even though a relatively small area of the surface is used to grow wheat and maize (Section 2), from a temperature perspective alone, a much larger fraction of the land surface is suitable to grow wheat and maize. Fig. 3 shows the percentage of extratropical land area with GS longer than 100, 150, 200, 250 and 300 days. These GSL thresholds encompass a range of lengths needed to grow wheat and maize: 100–130 days for spring wheat, 180–250 days for winter wheat, and 100–200 days for maize (FAO homepage, 2014). The change in land area with GSL of 250–300 days is particularly important as it potentially allows double-cropping of winter wheat (~200 days) and summer maize (~100 days) if enough water and sun light are available. These areas increase from 35% of extratropical land areas to 38% (250 days) and 27% to 28% (300 days) over our 50-year analysis period. Areas for all thresholds show a positive trend over the time-period 1956–2005, but are largest for the shorter thresholds, with an increase from 96 to 97% and 53 to 60% for the 100 day and 200 day thresholds, respectively. This might be related to larger warming in cold areas (northern high-latitudes) than warmer areas (Seneviratne et al., 2014), which is confirmed by the extension of areas with GS longer than 150 days into the northern latitudes in Supplementary Fig. A2.

4. Model data and data processing

Climate model simulations were obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model ensemble (Taylor et al., 2012) for the years 1956–2005. We considered temperature from CMIP5 simulations from three experiments: (1) changes in