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What would happen to barley production in Finland if global warming exceeded 4 °C? A model-based assessment

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ABSTRACT

In research to date, projected climate change has been considered to be beneficial for agriculture under Nordic conditions, where crop production is mainly limited by low temperatures resulting in short growing seasons. However, with the rapid increases in global mean temperature implied at the high end of the uncertainty range of current projections, which are typically amplified at high latitudes, conditions for crop production could change so dramatically that yields would be reduced, even accounting for the positive effects of CO_2 fertilization.

In this study, we used the WOFOST crop growth simulation model to examine crop yield responses to a set of plausible scenarios of climate change for Finland up to 2100, including some that exceed 4 °C global mean temperature increase relative to pre-industrial. We selected spring barley (*Hordeum vulgare* L.) as an indicator crop and calculated water-limited yields for two Finnish locations, Jokioinen and Jyväskylä and for a clay and a sandy soil. Scenarios included systematic increases in temperatures, changes in precipitation distribution and altered daily climatic variability using the M&Rfi weather generator. We also examined the effectiveness of a few adaptation options, such as shifts in sowing dates and hypothetical new crop cultivars.

Increasing temperature reduced total growth duration and yield considerably, even with adjusted earlier sowing. A reduced number of rainy days had marked negative effects only in combination with increases in temperature of 4 °C or greater, leading to distinctly higher yield losses on the sandy soil than on the clay. Prolonged dry spells clearly increased yield variability. For scenarios with temperature increases of +6 °C and +7 °C, yield losses at Jokioinen were highest; losses at Jyväskylä were generally less pronounced. Neither CO_2 fertilization nor adjusted sowing could compensate the yield losses from temperature changes exceeding +4 °C. On clay soils, yield loss could be compensated by new cultivars. For sandy soils even with new cultivars, there would be yield loss at temperature increases exceeding +3 °C.

It can be concluded that the positive effects of climate warming and elevated CO_2 concentrations on cereal production at high latitudes are likely to be reversed at temperature increases exceeding 4 °C, with a high risk of marked yield loss. Only plant breeding efforts aimed at increasing yield potential jointly with drought resistance and adjusted agronomic practices, such as sowing, and adequate nitrogen fertilizer management and plant protection, holds a prospect of partly restoring yield levels and reducing the risks of yield shortfall.

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1. Introduction

In research to date, projected climate change has been considered to be beneficial for agriculture under Nordic conditions, where crop production is mainly limited by low temperatures (Olesen and Bindi, 2002). However, according to current high-end projections (Betts et al., 2011), conditions for crop production in the North could also change so dramatically that yields would be reduced, even accounting for the positive effects of CO_2 fertilization.

It has been argued for some time that changes in climate variability such as in the frequency of extreme events or in precipitation patterns can be more important for crop yield and yield stability than changes in the means (Katz and Brown, 1992; Semenov and Porter, 1995). Crops can respond non-linearly, show abrupt responses to thresholds and are subject to multiple stress factors (Rötter and van de Geijn, 1999; Porter and Semenov, 2005; Challinor et al., 2009). Despite these insights, there are still relatively few climate change impact assessments for agriculture that take shifts in climate variability into account. This is possibly why even in the Fourth Assessment of IPCC Working Group II (e.g. Easterling et al., 2007) it has been suggested that agricultural crops in Northern Europe would mainly benefit from climate change.

The introduction of new crops combined with mild winter conditions can be expected to increase the risk of pest and disease outbreaks (e.g. Hakala et al., 2011). Increased autumn rainfall will probably limit the cultivation window and suitable times for harvest. Although these factors are not directly considered in our study, they are important. If we take into account that some weather extremes (e.g. drought in spring and early summer) are also likely to become more frequent (Klein Tank and Können, 2003; Jylhä et al., 2004), farmers will need to develop a range of new risk strategies to cope with these challenges. Still, in recent climate change impact assessments for Finland (e.g. Peltonen-Sainio et al., 2009a,b) it is mainly the opportunities for agriculture that are highlighted while the potential risks are not fully taken into account.

However, cereal breeders in Europe have generally succeeded in creating crop cultivars with higher yield potential in combination with improved stress tolerance (Öfversten et al., 2004; Ewert et al., 2005; Tester and Langridge, 2010). Genetic improvement largely accounts for the considerable yield increases over the last decades. For barley, Slafer and Peltonen-Sainio (2001) found yield increases of 1.5% per annum attributing 40% of that gain to genetic improvement.

The aim of this study is to examine responses in crop yield to a set of variants of anticipated changes in climatic conditions for Finland using the WOFOST crop growth simulation model (Boogaard et al., 1998). The set-up of the study has been co-determined by the need to focus on global temperature increases exceeding +4 °C, as part of a wider investigation of impacts of such changes across multiple sectors, populations and systems (www.eci.ox.ac.uk/4degrees/). Such levels of warming are likely to occur by the end of the century in the absence of rigorous greenhouse gas emission reductions (Betts et al., 2011).

The scenarios examined here include systematic increases in the mean and variability of temperatures, and changes in precipitation amounts and their daily persistence. In addition, effects of enhanced CO_2 concentration and different adaptation options are also studied, including shifts in sowing dates and adoption of new crop cultivars better adapted to a +4 °C world. For comparison, simulations are also conducted for climate projections assuming atmospheric composition consistent with the SRES A1FI and B1 emissions scenarios published by the IPCC (Special Report on Emissions Scenarios – Nakicenovic et al., 2000), for the time slice 2071–2100. We use spring barley (*Hordeum vulgare* L.) as an indicator crop, since this is the most widespread cereal cultivated in Finland.

2. Materials and methods

2.1. Set-up of the climate sensitivity study

The dynamic crop growth simulation model WOFOST (Boogaard et al., 1998) was applied for two locations, Jokioinen and Jyväskylä, representing the southwestern and central Finnish barley growing environments, respectively (Table 1). The model runs for both sites were made for a clay and a sandy soil representing two extremes across the wide range of agricultural soils found in Finland.

We analysed the crop response of the widely grown, two-row barley cultivar Scarlett (Plant Variety Board Official Journal, 2007) for the reference period 1971–2000 and set of scenarios (Table 2) including systematic variations in average daily air temperature (*T* in °C) and precipitation. We also modified some crop model parameters for enhanced CO_2 concentration of 560 ppmv (Table 4), along the lines proposed by Rötter and van Diepen (1994) to study the combined effect of enhanced CO_2 concentration and increased temperature from +4 °C to +7 °C (i.e. T4CO2, T5CO2, T6CO2 and T7CO2). Variations in summer precipitation and soil moisture conditions included prolonging the runs of dry spells in the year, and in summer (Table 2). We also carried out several other runs that are not shown since the impacts within them were negligible. These included, for instance, altering summer and winter rainfall amounts separately by increments of between −40% and +40% relative to observed, or increasing summer rainfall (by 20%) in combination with longer dry spells.

For comparison, we also performed runs for SRES scenarios A1FI and B1 (Nakicenovic et al., 2000) for the time slice 2071–2100. In these, changes in monthly long-term means between the periods 1971–2000 and 2071–2100 simulated by a single General Circulation Model (GCM), HadCM3 (Gordon et al., 2000), were applied for temperature, precipitation and cloud cover. Values were extracted from Mitchell et al. (2004) who applied pattern-scaling methods for the A1FI scenario and prepared scenarios on a $10' \times 10'$ grid. We applied the same A1FI and B1 scenarios for Jyväskylä as for Jokioinen for two reasons. First, it was readily available, having been extracted previously for the Jokioinen case. Second, using the same adjustments at both sites provided us with a direct comparison of the sensitivity of crop response to a typical seasonally varying GCM-based scenario between sites as well as with responses to the constant changes assumed in the incremental scenarios. In the two scenarios, the variability of the observed time series was not changed. The increases in mean annual temperature are 3.8 °C (B1) and 6.7 °C (A1FI) for both sites.

Adaptation options included change in time of sowing and in crop cultivar. We tested effects of using different sowing criteria and we designed several new crop cultivars (Cultivars C1, C2, C3, C4; see Section 2.5 and Table 3) that were exposed to different levels of enhanced atmospheric CO_2 concentration: 560 ppmv approx. corresponding to concentrations of the SRES B1 scenario at the end of the 21st century and 840 ppmv as in the SRES A1FI scenario (see Section 2.5 and Table 4). The underlying breeding aims (Blum, 2005; Tester and Langridge, 2010) for the "new cultivars" were to combine late maturing characteristics with other adapted characteristics to better exploit the extended growing season under 4+ °C.

2.2. Weather generator M&Rfi

To modify within-season variability of temperature and persistence in precipitation occurrence and simultaneously preserve all remaining characteristics (e.g. cross-correlations and lag-correlations among the daily weather characteristics), we used the M&Rfi weather generator (WG). This is a successor of the Richardson-type (Richardson, 1981) Met&Roll generator (Dubrovsky et al., 2004). Validation tests were used to demon-