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A model study on the effect of water and cold stress on maize development under nemoral climate

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ABSTRACT

Farmers in northern latitudes face significant risks because of low temperatures and water shortage when attempting to benefit from climate warming by expanding maize for grain. The study was aimed to investigate maize development and suitability of two models to simulate maize growth in a cool climate.

Field experiments were conducted at the Lithuanian Research Centre for Agriculture and Forestry on sandy loam soil. Management was performed to guarantee optimum growth. The AquaCrop and AgroC models were calibrated and validated using the data sets from 2015 (cool/dry season) and 2016 (warm/wet), respectively.

Both models provided adequate results in terms of simulating total above-ground biomass, grain yield, canopy cover, and soil water content. Grain yield losses due to abiotic stress (low temperature and water shortage) simulated with AquaCrop were 3.41 t ha^{-1} in cool/dry and 2.02 t ha^{-1} in warm/wet seasons and for AgroC 4.32 and 2.84 t ha^{-1}, respectively.

Maize grain yield above 9 t ha^{-1} (dry weight) was obtained under favourable temperature and rainfall regime in nemoral climate. Low air temperature, is the main factor defining yield losses, while the water stress, which occurs occasionally, is of secondary importance.

1. Introduction

Three-quarters of the global maize production is concentrated in warm climate regions: mainly in the American Midwestern, Central Mexico, Southern Brazil, the maize belts of Argentina and China, parts of Western Europe, South Africa, and some areas of India and Indonesia (Ray et al., 2015). In general, maize production is still expanding due to an increasing market and an increasing interest in maize for non-food use (e.g., bioenergy and sugar production). Therefore, it is predicted that by 2050 maize prices will significantly increase and the maize demand will double in the rapidly developing world (Rosegrant et al., 2009). However, climate projections for the 21st century suggest that precipitation and available soil water content for maize production will decrease in many parts of the world's grain maize production regions such as Northern Brazil, North and South Africa. On the other hand, the predicted increase of precipitation and air temperature for higher northern latitudes (Fraser et al., 2013) might stimulate grain maize production in these regions.

Climate change, new varieties, and growing demand for grain maize have encouraged the expansion of grain maize cultivation outside the traditional zones such as regions of cooler climate (Soane et al., 2012; Spiertz, 2014). In the Nordic-Baltic countries, successful maize forage production is possible to at least 58 °N. Currently, only a minor proportion of maize is harvested as grain maize in Denmark, Lithuania, and Sweden (Swensson, 2014). At present, the main limitations of maize growing for grain production in Northern Europe are the short growing seasons, early and late frosts, and the variability of precipitation at sowing and harvesting, as well as the occurrence of drought within the vegetation period. As a consequence of climate change, a reduction in frost risk in this region is expected, associated with more frequent and severe drought periods (Olesen et al., 2011).

As stated above, short vegetation periods and lower temperatures are critical environmental conditions for maize growing in high northern latitudes and the tolerance to lower temperatures has been a serious issue for a long time. However, short-cycle varieties have facilitated cultivation under low temperature conditions (Riva-Roveda et al., 2016).

Most experiments analysing cold stress have been conducted in controlled environments and have helped to unravel the effect of temperature on plant development (phenology), plant growth, and leaf photosynthesis. Nevertheless, the results concerning the base temperature for maize are ambiguous. According to Sanchez et al. (2014),

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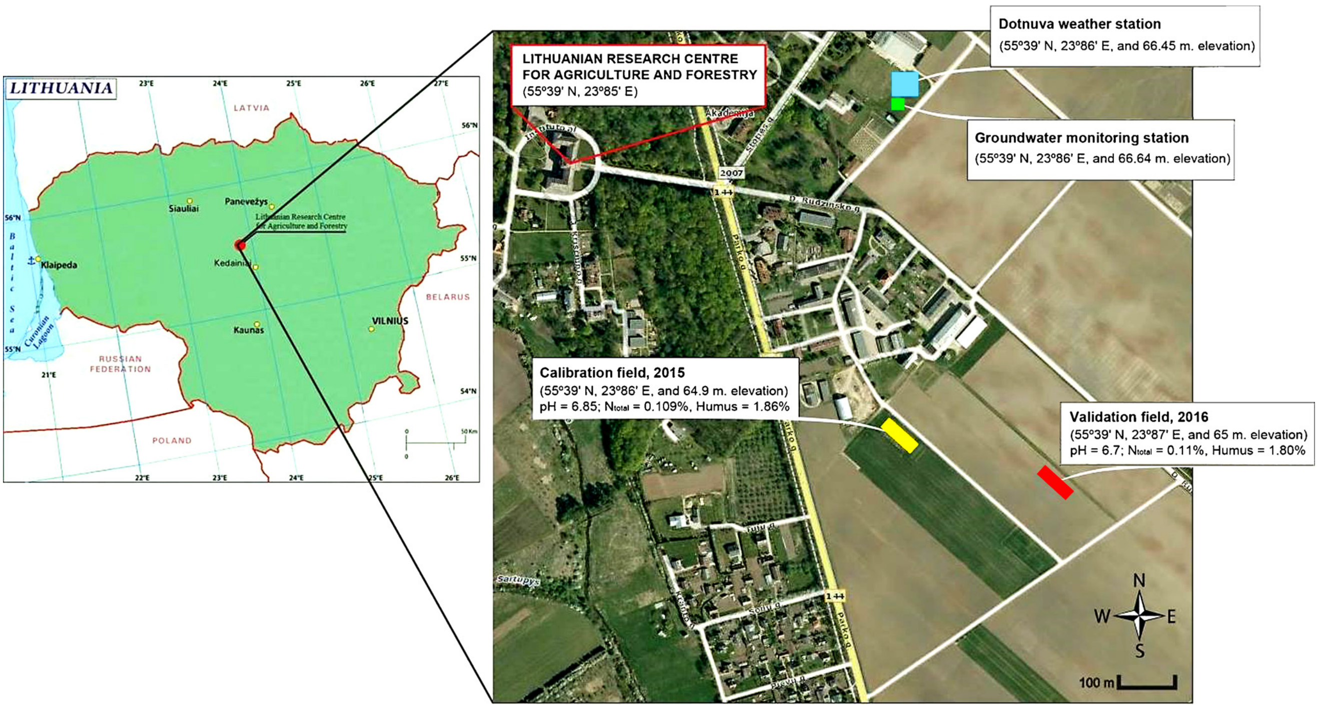

Fig. 1. Location of the experimental sites of the Lithuanian Research Centre for Agriculture and Forestry in Akademija for the years 2015–2016.

the minimal average temperature for maize growth and development is 6.2 °C, whereas other authors have stated that it is 8 °C (Fischer et al., 2014). On the other hand, some specific effects of temperature, such as the timing of cold stress or feedback with other stress factors (e.g., water, nutrients, and pest stress), can only be analysed in the field when separating different processes adversely affecting the plant.

Another issue related to maize cultivation is water stress. In Europe, drought is not restricted to the Mediterranean region; it can also occur in high and low rainfall areas across Europe and in any season. One extreme example is the summer drought in 2003, which resulted in the warmest temperatures on record in Central Europe since 1500 (Luterbacher et al., 2004), giving rise to massive declines in crop yield (Fink et al., 2004). Even though large areas of Europe will face moderate to extreme drought conditions in the future, a shift towards wetter conditions is estimated for Northeast Europe (Lloyd-Hughes and Saunders, 2002), favouring agricultural productivity. Nevertheless, drought might play an important role in crop production in single dry years.

The study of Ray et al. (2015) suggested that for the last three decades, growing season temperatures and precipitation can explain ~22% (~0.9 tons ha^{-1} $year^{-1}$) or more of year to year variations in global average maize yield. Moreover, yield variations are mostly greater in the areas of lower yields. A study in France (Ceglar et al., 2016) highlighted remarkable spatial differences in the contribution of the main meteorological drivers to crop yield variability. Temperature and global solar radiation was identified as the most important variables influencing grain maize yields over Southern, Eastern, and Northern France, while rainfall variability dominates yield over the central and north-western parts of the country.

Because cold temperatures and water stress impact grain maize yield in northern regions and little is known about potential yields and adaptation to climate change, more research is needed to provide data for policy makers and farmers. Crop models are generally available for major crops like maize. This enables the simulation of potential yields accounting for variations in meteorological conditions across years and regions as well as major interactions among crops, weather, soil, and management (van Ittersum et al., 2013). Despite the potential grain maize expansion to northern regions in the near future, there is still a lack of experimental data, especially in boreal regions (Chung et al., 2014). Nevertheless, the separation of the effects of cold stress and water stress in an experimental way is tedious and expensive. Crop models provide the means to capture spatial and temporal variation in crop development and yield in response to cold stress and water stress, given that calibration and validation data is available. For example, Salo et al. (2016) performed a large crop model inter-comparison based on eleven widely used crop simulation models simulating spring barley under boreal climate and noticed that specific weather events, such as low temperature and high precipitation, were not properly accounted for in their study.

In comparison to Salo et al. (2016) we only run the simulation using two different models, namely the AgroC and the AquaCrop model. Hereby, the AgroC model was chosen because of its physically-based soil water module, which might be potentially superior compared to classical water bucket models implemented in most crop growth models, to simulate maize growth under water stress conditions. Unlike the previously mentioned model, AquaCrop is rather simple model with a bucket type soil water module but a comparable crop growth routine as most models used in Salo et al. (2016). Additionally, due to its graphical user interface AquaCrop is intended mostly for practitioners e.g. farmers, technicians, and policy makers.

The aims of this study are i) to provide data from a comprehensive grain maize experiment in the northern latitudes with contrasting climatic conditions within the years, ii) to test the ability of two crop growth models with varying complexity to simulate maize growth at this location, and iii) to disentangle and quantify the confounding impact of cold and water stress.

2. Materials and methods

2.1. Site description

The maize field experiments (*Zea mays L.*) were carried out at the Lithuanian Research Centre for Agriculture and Forestry located in Akademija, Central Lithuania (55°39′ N, 23°86′ E) (see Fig. 1).

The area is typical for the intensive cash crop production regions in Lithuania. The climate is humid continental with warm summers and