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

R. Žydelis[1*], L. Weihermüller[2], M. Herbst[2], A. Klosterhalfen[2], S. Lazauskas[1]

[1]Institute of Agriculture, Lithuanian Research Centre for Agriculture and Forestry, Lithuania
[2]Agrosphere Institute (IBG-3), Forschungszentrum Jülich GmbH, Germany

[*] Corresponding author: Renaldas Žydelis, renaldas.zydelis@lammc.lt

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.

Keywords: AgroC, AquaCrop, Potential yield, Temperature stress, Water stress.

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 (2014), 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 et al. 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).

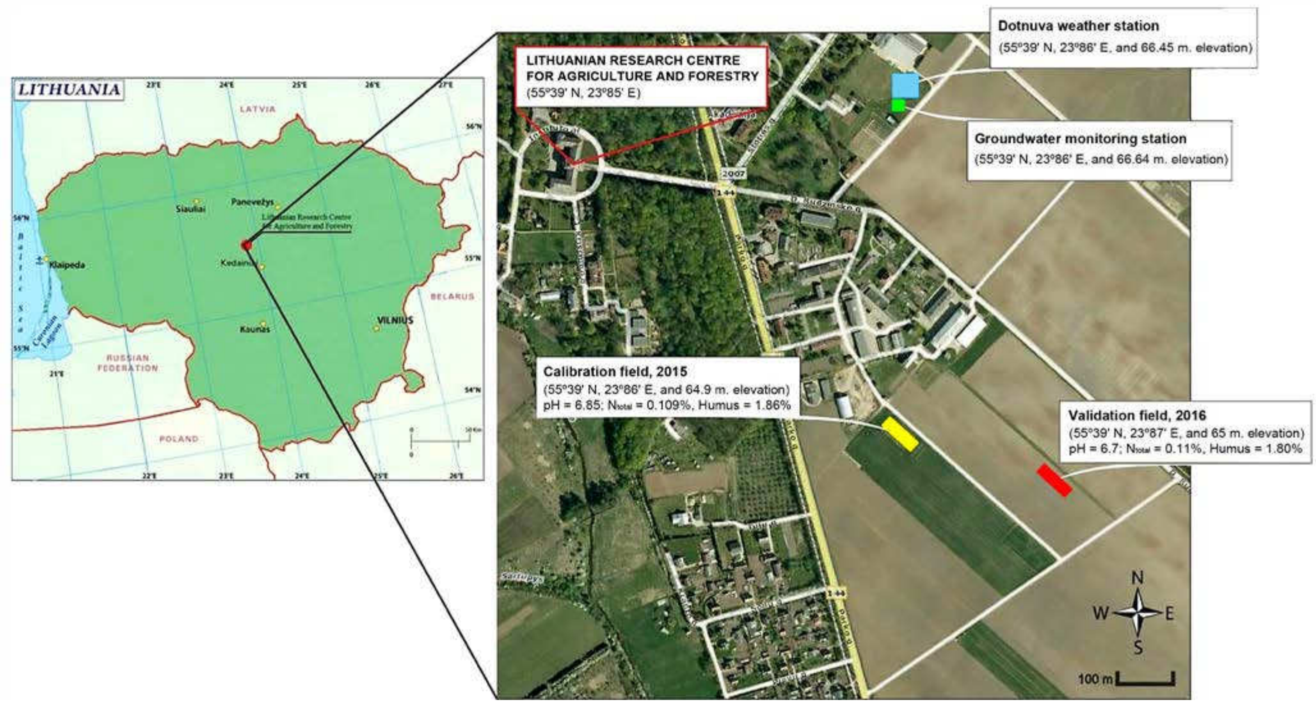

Fig. 1 Location of the experimental sites of the Lithuanian Research Centre for Agriculture and Forestry in Akademija for the years 2015–2016.

The area is typical for the intensive cash crop production regions in Lithuania. The climate is humid continental with warm summers and rather severe winters, which is classified as *Dfb*, according to the Köppen climate classification (Kottek et al. 2006) with an average annual precipitation of 557 mm and a mean annual air temperature of 7 °C (mean values over 30 year period 1981–2010). The main soil is Hypocalcic Stagnic Luvisol (Loamic, Drainic) (WRB 2014), which is the predominant soil type in Lithuania. The soil texture of the experimental site is sandy loam with a humus content of about 1.8%. The main soil agrochemical characteristics are presented in Table 1. Groundwater levels are rather deep to the surface and fluctuated between 194 and 289 cm below the surface over the growing season.

Table 1 Soil characteristics and management

	2015	2016
Soil (FAO classification)	Hypocalcic Stagnic Luvisol	Hypocalcic Stagnic Luvisol
Soil pH_{KCl} (1 N KCl extraction)	6.85	6.70
Soil P_2O_5 (mg kg^{-1}) (Egner-Riehm-Domingo (A–L))	154	129
Soil K_2O (mg kg^{-1}) (Egner-Riehm-Domingo (A–L))	138	140
Soil humus (%) (Tjurin)	1.86	1.80
Soil N total (%) (Kjeldahl)	0.109	0.110
Previous crop	Spring rape	Spring rape
Maize cultivar	AGIRAXX (FAO 190)	AGIRAXX (FAO 190)
Maize seeding dates, row spacing, plant spacing	8 May 2015, 0.75 m, 0.18 m	10 May 2016, 0.75 m, 0.18 m
Maize density	7 plants m^{-2} (70,000 plants ha^{-1})	7 plants m^{-2} (70,000 plants ha^{-1})
Plot size	3 × 10 m	3 × 10 m
Maize fertilization (kg ha^{-1})	No fertilization, Ammonium nitrate 90, 170 kg N (5 May 2015)	No fertilization, Ammonium nitrate 90, 170 kg N (9 May 2016)
Weed control in maize	Herbicide MAISTER OD rate 1.7 l ha^{-1} (growth stage V2–V6)	Herbicide MAISTER OD rate 1.7 l ha^{-1} (growth stage V2–V6)
Maize harvesting	12 October 2015	10 October 2016

Soil nutrient status was assessed each year before maize seeding. For the analysis, composite soil samples were taken from a depth of 0–20 cm from 12 different locations within the field, and soil pH, humus content, total nitrogen (N_{total}), plant available phosphorus (P_2O_5), and potassium (K_2O) content were analysed. All soil chemical analyses were conducted in the Agrochemical Research Laboratory of the Lithuanian Research Centre for Agriculture and Forestry in Kaunas. In 2017, soil hydraulic properties of one field were determined using the HYPROP® (UMS, München, Germany) method as described by Schindler et al. (2010) in combination with the WP4® Dewpoint Potentiometer (Decagon Devices, WA, USA). Saturated hydraulic conductivity, K_{sat}, was measured using the KSAT system from UMS (München, Germany). For all measurements, 10 undisturbed soil samples of 250 cm^3 were extracted from the major soil horizons at depths of 15–20, 40–45, 70–75, 90–95, and 120–125 cm.

2.2. Maize experiments

The early season maize hybrid (characterized as FAO 190) – AGIRAXX was grown in the years 2015 and 2016, respectively. The short season maize variety was bred in France by the RAGT seed company (Saffron Walden, UK). It was selected because of the early maturity and suitability to the region of interest. This hybrid is characterized by a high amount of dry matter allocation to the grains combined with a slow leaf senescence rate. The maize was grown after conventional tillage. Fertilizers were applied manually according to the protocol of the experiment and incorporated into the soil before maize drilling. Amounts of fertilizer and pesticide used are documented in Table 1. The day after fertilization, maize was sown at a density of 7 plants m^{-2} (70,000 plants ha^{-1}) at a depth of 6–8 cm; the maize was sown when the soil temperature reached 8–10 °C. Harvest was performed manually after the first autumn frosts.

2.3. Experimental set up

The experimental design for the two years included three treatments with different nitrogen fertilizer levels: no fertilization (N 0), 90 kg ha^{-1} (N 90), and 170 kg ha^{-1} (N 170). Treatments were arranged in four randomized blocks with a total plot size of 30 m^2, whereby only the inner parts of the plots (12 m^2), were harvested. In this study, where the effect of low temperatures and water stress was analysed, we concentrated on the N 170 plots with mineral fertilization to ensure optimal (no nutrient limited) growth. Individual experimental plots consisted of four rows, 10 m in width and 3 m in length with 0.75 m rows and 0.18 m plant spacing. Two center rows were used for plant observations and measurements.

2.4. Plant measurements

During the maize vegetation period, the stages of crop development were recorded weekly. Vegetative and reproductive development stages were determined on the entire treatment when 50% or more of the plants were at a particular development stage. The Leaf Collar method (Ritchie et al. 1986) was used to assess the development of vegetation stages, while reproductive stages are based on established visual indicators of kernel development. The leaf area (cm^2 cm^{-2}) was measured five times during the growing season using a CL 203 Handheld Leaf Area meter (CID ® Inc, WA, USA), from which the leaf area index (LAI) was calculated. When converting LAI into green canopy cover (CC), an exponential function according to Hsiao et al. (2009) was used (Equation 1).

$$CC = 100.5\ [1 - \exp(-\,0.60\ LAI)]^{1.2} \qquad [1]$$

To evaluate total plant biomass, five plants were sampled from each plot. In general, 20 randomly selected plants from each treatment were selected for each growth stage: V8 (vegetative leaf stage 8), V14 (vegetative leaf stage 12), R1 (reproductive silking), R3 (reproductive milking), and R6 (physiological maturity). The plants were separated into five components: leaf (leaf blades), stalk (stalk and leaf sheaths), reproductive (cob and husk), tassel, and grain for biomass determination. Therefore, the individual maize components were weighed (fresh mass weight) and dried until constant weight at 65±5 °C (dry mass weight). Finally, crop biomass and grain yield were determined by harvesting all plants from an area of 8 x 1.5 = 12 m^2 (77–89 plants). Samples were taken from all the replicates and oven dried at 65±5 °C until constant weight to obtain dry biomass and yield weight.

2.5. Soil water content and climatic data

In the years 2015 and 2016, the soil volumetric water content (SWC) was measured periodically at a depth of 0–10 cm using a TRIME-FM2 TDR System (IMKO, GmbH, Ettlingen Germany). In total, eleven measurements were carried out in 2015 and eight in 2016. Additionally, soil water content was determined using site specific calibrated “Watermark” soil moisture meters (Irrometer Company, Riverside, CA, USA) at 30 and 60 cm depths every 7–14 days. Thereby, measurements were performed after weather conditions changed, i.e. after precipitation events or after extended dry periods.

Daily weather data was taken from the Dotnuva meteorological station of the Lithuanian Hydrometeorogical Service (Ministry of Environment) located ~500 m from the experimental field (55°39′ N, 23°86′ E, at 66.45 m elevation). Daily data used for simulation included precipitation (mm), maximum and minimum air temperature (T_{max} and T_{min}) (°C), relative humidity (%), wind speed at 2 m height (m s^{-1}), and actual duration of daily sunshine (hours). Based on this data, the reference Penman-Monteith evapotranspiration (ET_0) (mm day^{-1}) was calculated according to Allen et al. (1998). Groundwater levels were recorded by the Lithuanian Geological Survey (Ministry of Environment). The groundwater monitoring station was located at a distance of 5 m to the Dotnuva meteorological station.

2.6. Models

2.6.1. AquaCrop

AquaCrop was developed by the Land and Water Division of the FAO to simulate yield response to soil water availability for several crops (Hsiao et al. 2009; Raes et al. 2009; Steduto et al. 2009). Generally, AquaCrop calculates final crop yield in four steps: 1) simulation of crop development, 2) simulation of crop transpiration, 3) simulation of above ground biomass production, and 4) simulation of crop yield. A full description of the AquaCrop model can be found in Raes et al. (2017). In our study, AquaCrop 6.0 was applied. As AquaCrop was mainly developed for applications such as irrigation scheduling, some of the parameters were not directly accessible. For example, several plant parameters are hard-coded for various crop types and cannot be changed if different varieties are used. Additionally, the soil compartment is simulated by a bucket approach, which is in general less accurate in predicting water flow and water availability in the soil (e.g., Herbst et al. 2005). AquaCrop estimates daily cumulative aboveground biomass production (*TAB*), as follows (Raes et al. 2017):

$$TAB = WP * \sum\left(\frac{Tr}{ET_0}\right) \quad [2]$$

where *Tr* is the daily crop transpiration, ET_0 is the reference evapotranspiration, *WP* is the normalized biomass water productivity. When calculating crop transpiration, water stress (*Ks*) and temperature stress (Ks_{Tr}) are considered:

$$Tr = Ks\ (Ks_{Tr}\ Kc_{Tr,})\ ET_0 \quad [3]$$

where $Kc_{Tr,}$ is the crop transpiration coefficient. In AquaCrop there are four water stress response coefficients that are interpreted as affecting the expansion of canopy cover, inducing stomatal closure and early canopy senescence, and reducing harvest index (HI). Temperature stress is assumed to influence crop transpiration, but not final production. Water and temperature stress are indicated by thresholds at which plant growth starts to be stressed: an upper threshold, a lower threshold at which growth is fully inhibited by stress, and a shape parameter that determines the extent of the stress effect on the processes of plant growth between these bounds.

2.6.2. AgroC

In comparison to the AquaCrop model, the AgroC model was developed as a mechanistic model based on different submodels for the soil compartment: SoilCO2 (Šimůnek and Suarez 1993) and RothC (Coleman and Jenkinson 2008) for the carbon turnover. Additionally, SUCROS (Spitters et al. 1989) was implemented for the plant growth (Klosterhalfen et al. 2017). In general, all parameters for the soil, carbon, and plant routines are accessible and can therefore be modified. In particular, the soil compartment differs from the bucket model as implemented in AquaCrop. In AgroC the Richards equation (Richards 1931) is solved for water flow and the parameterization of the soil hydraulic conductivity, and retention characteristics is done according to the Mualem-van Genuchten approach (van Genuchten 1980). For the estimation of the actual transpiration T_a (cm d^{-1}) the soil pressure head h (cm) is taken into account. The reduction of the potential transpiration T_a to the dimensionless reduction factor α (-) according to Feddes (1978) was applied:

$$T_a = T_P \alpha(h) \qquad [4]$$

The reduction factor α is calculated from four specified threshold heads h_0, h_1, h_2, and h_3 (cm) according to:

$$\alpha(h) = \begin{cases} \dfrac{h_0 - h}{h_0 - h_1} & h_0 \leqslant h \leqslant h_1 \\ 1 \qquad \text{for} & h_1 \leqslant h \leqslant h_2 \\ 10^{\frac{h_2 - h}{h_3}} & h_2 \leqslant h \leqslant h_3 \end{cases} \qquad [5]$$

where h is the soil pressure head at a specific soil depth. In this study, h_0, h_1, h_2, and h_3 were set to 15, 30, 800, and 5000 cm, respectively (Klosterhalfen et al. 2017). Over the profile depth, α was averaged and weighted according to the normalized root density function to compute the water stress index α_{avg}, which was subsequently used to reduce the carbon assimilation rate according to water stress. For consistency with AquaCrop, α_{avg} was converted to water stress as (1- α_{avg})*100. In AgroC, the measured air temperature affects the crop development via the degree-day method as well as via the instantaneous assimilation rate. A detailed description of the AgroC model can be found in Herbst et al. (2008) and Klosterhalfen et al. (2017).

2.6.3. Parameterization, calibration and validation procedures

Both models were partly calibrated based on the experimental data of 2015 (dryer year) and validated for 2016 (wetter year).

For the calibration of AgroC, a two-step calibration procedure as used in Klosterhalfen et al. (2017) was applied, where, first, the plant growth was adjusted manually to reproduce plant phenology and biomass of the single organs in a reasonable way, and subsequently the soil saturated hydraulic conductivity K_{sat} was estimated. This was necessary because the simulations based on the Mualem-van Genuchten parameters estimated from the HYPROP® data and laboratory K_{sat} measurements did not reproduce the in-situ measured soil water contents well. Laboratory measurements of K_{sat} do not necessarily describe effective plot scale water movement due to spatial variability and changes in many orders of magnitude within short distances (Loague and Gander 1990; Mohanty et al. 1994; Mohanty and Mousli 2000; Nielsen et al. 1973; Sharma et al. 1987). For the calibration of K_{sat}, the global optimization routine shuffled-complex-evolution University of Arizona (SCE-UA), as described by Duan et al. (1992, 1994), was used, and the mismatch between observed and simulated water contents was minimized using the root mean square error (RMSE) according to Willmott (1982):

$$RMSE = \frac{\sqrt{\sum_{i=1}^{n}(S_i - O_i)}}{n} \qquad [3]$$

where S_i is the simulated water content for each single observation and time i and O_i are the observed water contents. After this step, the parameters describing plant development and growth were adjusted again by modifying the base temperature, the effectiveness of CO_2 assimilation, and the partitioning factors of assimilates between different organs (leaf, stalk, cob, grain) (Table S1).

For the AquaCrop model, the input parameters for the simulation of canopy cover (CC) data (plant density, germination rate) were first entered into AquaCrop model. Further, the time of maize development expressed in growing degree days (GDD) was adjusted (sum of GDD for emergence, max canopy, senescence, maturity), and the parameters which indicate canopy expansion and decline were modified (maximum canopy cover, canopy growth coefficient (CGC), and canopy decline coefficient (CDC)). Finally, the parameters (crop coefficient for transpiration (Kc_{tr}), crop water productivity (WP), and reference harvest index (HI)), which regulate dry matter (biomass and grain yield) and soil water content during the period of maize growth were adjusted. GDD plays a paramount role in crop development, whereas the calculation of GDD is based on the base and upper temperatures for the crop, and these two temperatures are mostly dependent on maize variety and climate conditions. When grain maize is grown in northern regions, accurate determination of these temperatures is quite complicated due to the lack of experimental results and the fact that producers of maize varieties do not provide such information. Thus, we used default values for base and upper temperatures (8 and 30 °C) in this study. An overview of the parameters used for calibration in AquaCrop is given in Table S2 and Table 3. It should be noted that, during the field survey, a soil profile with seven horizons was detected; however, AquaCrop can only account for five soil horizons in contrast to AgroC, which is not limited in that respect. Thus, we reduced the number of soil horizons to five by merging morphologically similar horizons in order to ensure comparable simulations results. First, the B- (0.80−0.97 m) and BCk-horizons (0.97−1.10 m) were merged into one B-horizon (0.80−1.10 m), because only the content of limestone particle size (> 2 mm) differed between the two horizons. Similarly, the Ckg- (1.10−1.30 m) and Ck-horizons (1.30−1.55 m) were merged into a Ck-horizon (1.10−1.55 m), because of similar hydraulic characteristics of these horizons and minor differences regarding stagnation in the Ckg-horizon.

Soil hydraulic parameters such as permanent wilting point (PWP), field capacity (FC), volumetric water content or saturation (θ_s or SAT), and saturated hydraulic conductivity (K_{sat}) were calculated from the retention curve measured by the HYPROP® data, whereby FC was assumed to be the water content at a pressure head of pF 2.2 158.5 cm. Additionally, the AgroC calibrated K_{sat} was used.

For both models, the same meteorological data were used for the two consecutive years 2015 and 2016. In simulating yield potential in both models, it is assumed that all factors (temperature, water content in soil, fertilization, management) are non-limiting for optimal grain maize growth and development. For the calculation of yield potential in AgroC, the base temperature was set to 0 °C, and the reduction factor of the maximal light assimilation rate was set to 1 (no reduction due to low temperature). The water stress in the model was turned off. For the yield potential calculation in AquaCrop, cold stress, which is characterized as affected crop transpiration, was not considered as well as water stress.

3. Results

3.1. Field observations

During the two years of the experiment, the maize growing period was quite similar, with 158 growing days in 2015 and 156 days in 2016. Irrespective of the nearly similar growing period over the two years, grain yield differed substantially, with 6.85 ± 0.20 and 9.02 ± 0.71 t ha^{-1} for 2015 and 2016, respectively, indicating that the overall environmental conditions were contrasting between the years. The key differences were the average air temperature and the amount of precipitation during the vegetation period. In 2015, the average air temperature from 8th May to 12th October was 14.7 °C (sum of GDD, 1193 °C), which was almost the same as the climatic normal but close to the minimum value of the 2000–2016 period. In 2016, the average temperature for the period from 10th May to 10th October was slightly higher, with 15.9 °C (sum of GDD, 1340 °C), which was close to the maximum value for the 2000–2016 period. The higher air temperature in 2016 resulted in faster development of the plants, especially in the vegetative stage, which was approximately more than 10 days shorter than in 2015 (Table 2). It should be noted that at the beginning of June (V5 growth stage), the leaves turned purple in the majority of maize plants (50–70%) in both years. It is likely that the change to purple colour was caused by a change of the leave pigments (anthocyanin) as a genetic response of the early hybrid variety to cool nights, because during that period air temperatures dropped below 8 °C. Approximately 14 to 18 days later, the leaves fully recovered to a green colour and no further growth effects were detected. Additionally, soil moisture conditions during the maize growing seasons were also contrasting. In 2015, the precipitation sum over the maize growing period was only 194.2 mm, while 378.4 mm were recorded in 2016. In particular, the dry August in 2015, with only 5.6 mm of precipitation, influenced and slowed down maize growth during the R1 growing stage, whereby the lowest three to four leaves started to turn brown until they finally withered. On the other hand, the weather conditions in 2016 were favourable for maize growth in terms of temperature and rainfall regime, which could become typical for Lithuania in the forthcoming decades due to climate change. In contrast, the relatively cool and droughty weather conditions recorded in 2015 are typical for the current Lithuanian climate. In the following text, the season of 2015 is referred to as 'cool and dry' and the season of 2016 as 'warm and wet'.

Table 2 Maize growing stages and growing degree days (GDD °C) for the growing seasons 2015–2016

		Growth Stage						
	Year	VE	V2	V5	V10	VT/R1	R2	R6
Days after planting	2015	14	21	36	64	88	118	158
	2016	11	18	26	55	77	109	156
GDD (°C)	2015	41	76	164	408	615	966	1193
	2016	53	106	208	482	702	1032	1340

Vegetative stages: *VE* – emergence, V_n – n^{th} leaf, *VT* – tasseling; Reproductive stages: *R1* – silking, *R2* – blister, *R6* – physiological maturity

3.2. Soil data and hydraulic properties

A pronounced vertical heterogeneity of soil texture was found at the test site. In general, the sand content increases from the Ap-horizon (sand = 55%) to more than 70% in the underlying E-horizon. Below that, the Bt-horizon is lower in sand content (35%) before it increases again to more than 54% in the B- and Ck-horizons. Accordingly, the silt content varies between the horizons but to a lesser extent, and therefore clay is also quite variable over depths with the highest clay contents in the Bt-horizon (29.3%) and the lowest in the E-horizon (6.2%) (Table 3).

The characterization of the soil profile in terms of hydraulic properties is relevant, since the estimated water stress is related to these properties. Furthermore, a sound estimation of the water stress is required to quantitatively separate the effects of water stress and cold stress. Volumetric soil water contents were measured occasionally in both years at three depths (10, 30 and 60 cm). The largest changes in SWC were observed for the 10 cm soil layer (Fig. 2), which was expected because this layer is exposed to the atmosphere with resultant precipitation and evaporation. The estimated Mualem-van Genuchten parameters that form the HYPROP® data are listed in Table 4. The saturated water content, θ_s, increases from 0.30 cm^3 cm^{-3} in the Ap-horizon to 0.34 cm^3 cm^{-3} in the underlying E-, Bt-, and B-horizons and declines substantially to 0.25 cm^3 cm^{-3} in the compact Ck-horizon. The larger porosity or saturated volumetric water content in the E-horizon can be explained by the larger sand fraction and in the Bt- and B-horizon by a secondary pore structure due to aggregation effects. In contrast, the Ap-horizon showed intermediate sand contents, and the secondary pore structure might have been destroyed due to the tillage and management practice. Because FC and PWP are calculated from the retention curve, compared to θ_s the same tendencies over depth were observed with a lower FC in the Ap-horizon and larger values in the E-, Bt-, and B-horizons. Again, the Ck-horizon showed the lowest FC.

Table 3 Soil horizons, texture, and hydraulic properties of the field experiments

Horizon description	Particle size %			Textural class	Bulk density g cm^{-3}	SWC (cm^3 cm^{-3}) at			TAW cm^3 cm^{-3}	K_{sat} cm day^{-1}
	Sand	Silt	Clay			PWP	FC	SAT		
Ap (0–0.30 m)	55	31.9	13.1	Sandy loam	1.81	0.023	0.289	0.300	0.277	0.6
E (0.30–0.60 m)	70.4	23.4	6.2	Sandy loam	1.70	0.069	0.354	0.358	0.289	2.2
Bt (0.60–0.80 m)	35	35.7	29.3	Clay loam	1.73	0.122	0.317	0.342	0.220	6.1
B (0.80–1.10 m)	57.5	22.6	19.9	Sandy loam	1.68	0.083	0.343	0.351	0.268	62.0
Ck (1.10–1.55 m)	54.4	31.6	14	Sandy loam	1.96	0.062	0.234	0.245	0.183	3.2

SWC = soil water content; *PWP* = permanent wilting point; *FC* = field capacity; *SAT* = saturation; *TAW* = total available water; K_{sat} = saturated hydraulic conductivity; **horizon description:** *Ap* = mineral surface horizon with an accumulation of humified organic matter; *E*= mineral horizon in which the main features is loss of silicate clay; *Bt* = mineral illuval horizon with accumulation of silicate clay; *B* – mineral illuval horizon, *Ck* = initial horizon with accumulation of pedogenetic carbonates.

3.3. Models calibration and validation

3.3.1. Soil Water Content

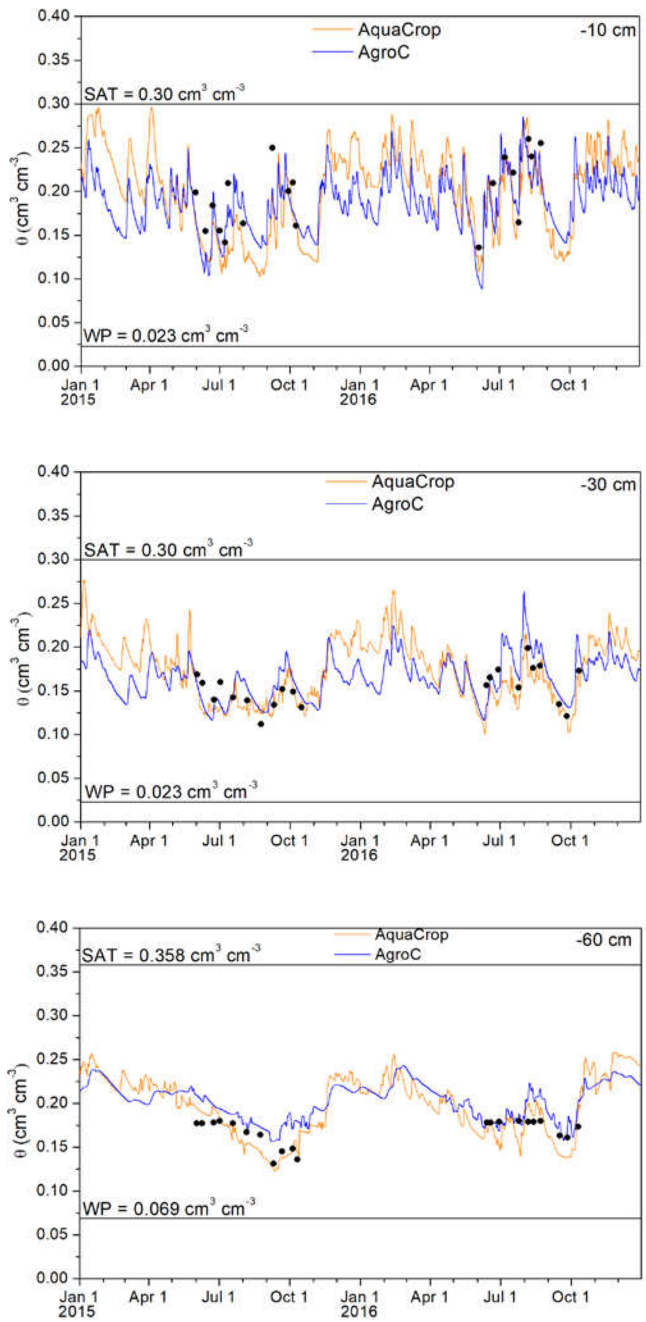

Fig. 2 Comparison between observed (dots) and simulated (lines) volumetric soil water content, θ, (cm^3 cm^{-3}) at 10, 30 and 60 cm depths. *SAT* is the saturated water content, *WP* is the wilting point, and *SAT-WP* is the plant available water (all in cm^3 cm^{-3}).

The measured SWC for the three depths and the two experimental periods (2015 and 2016) are depicted in Fig. 2. Additionally, the SWC estimated by AquaCrop and AgroC is shown. AgroC matched the SWC dynamics quite well for both years for the measurements at 10 and 30 cm depths in the dry and wet seasons. In contrast, the AquaCrop model underestimated SWC at 10 and 30 cm depths. Although both models produced SWC levels similar to the measurements, some peaks of soil moisture were not captured in the lower profile at the 60 cm depth. Over the dry season in 2015, AquaCrop simulated higher SWC during the vegetation stage (VE–V8 stages) and lower SWC during the reproductive stage (R1–R2), whereas the AgroC model overestimated SWC during the entire growing season of 2015. It can also be seen that in the wet season 2016 the measured SWC at the 60 cm depth varied over a small range during the vegetation period, which is in contrast to the modelling results, where pronounced variations were estimated.

The statistical measures, R^2 and RMSE, showed that the SWC simulated by AgroC were slightly better at 10 and 30 cm depths in both years in comparison to the AquaCrop model (Table 5). The calculated error for the AgroC model for the calibration period (2015) was quite low and increased on average only slightly for the validation period (2016). For the validation period, the RMSE for 60 cm depth even decreased. The RMSE values for AquaCrop model were higher than for AgroC for the calibration period (except 60 cm depth) and for the validation period. The calculated R^2 values were quite similar to those of the AgroC model, with 0.41 to 0.78 in 2015, and 0.53 to 0.66 in 2016. In general, the results listed in Table 5 and the visual inspection of Fig. 2 indicate that the AgroC estimates of the soil water content variations are slightly more in agreement with the measurements.

Table 4 Soil hydraulic properties (θ_r = residual water content; θ_s = saturated water content; α = inverse air entry pressure; n = shape parameter; K_{sat} = saturated hydraulic conductivity)

Horizon description	Thickness (m)	θ_r ($cm^3\ cm^{-3}$)	θ_s ($cm^3\ cm^{-3}$)	α (cm^{-1})	n (-)	K_{sat} ($cm\ day^{-1}$)
Ap	0–0.30	0.000023	0.300	0.0016	1.78	0.6
E	0.30–0.60	0.000020	0.358	0.0007	1.68	2.2
Bt	0.60–0.80	0.000010	0.342	0.0034	1.26	6.1
B	0.80–1.10	0.000184	0.351	0.0011	1.51	62.0
Ck	1.10–1.55	0.000011	0.245	0.0019	1.41	3.2

3.3.2. Canopy cover

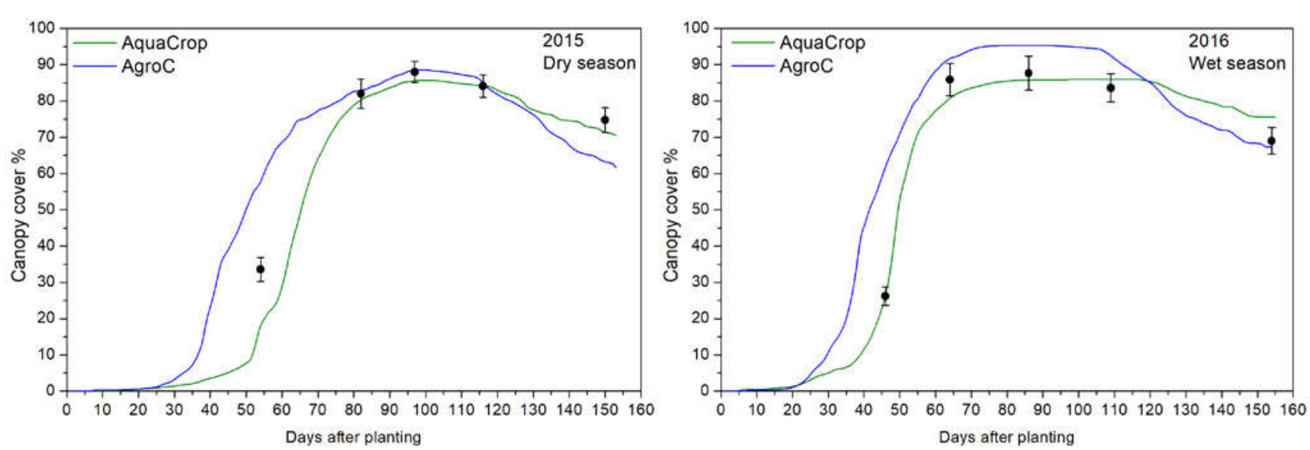

Fig. 3 Comparison between the observed (dots) and simulated (lines) canopy cover for the two contrasting maize growing seasons 2015 (calibrated) and 2016 (validation).

The agreement between the simulated and observed canopy cover (CC) for the two contrasting maize growing periods are presented in Fig. 3 and Table 5. AquaCrop is characterized by the fact that it does not simulate LAI, and therefore the foliage development is expressed as CC, the fraction of the soil surface covered by the canopy, whereas for AgroC model, CC was converted according to Equation 1 using the simulated LAI. Without model calibration (using default plant parameters), the simulated CC provided much lower values than the measured CC for both models. The reason for the mismatch can be found in the phenological response of maize to the specific environmental conditions, particularly to the impact of climatic factors, such as temperature, precipitation, and light (Liu et al. 2013). With increasing latitudes, the sum of GDD required for maize to reach a specific crop development stage is much lower, as standard default values might suggest, due to the early season varieties planted. Therefore, plant-specific parameters had to be adjusted considerably for adequate CC simulations. After calibration for the year 2015, both models showed much better prediction of the CC for both periods, whereby the AgroC model simulated higher CC percentages than observed at the beginning of each maize vegetation period. In comparison, the AquaCrop simulated CC was lower than observed for the year 2015 and matched the observation in 2016. For later growing stages, both models were able to capture the CC development in the year 2015, whereby AgroC was slightly closer to the observations than AquaCrop. Only for the last measurement in 2015 CC was substantially underestimated by AgroC, whereas AquaCrop was in agreement with the measurements. This changed for 2016, where AgroC was able to match the last measurement, whereas AquaCrop could not, but AgroC dropped down from a higher level of CC for the mid-season. Basically, both models simulated the seasonal trends in CC fairly well, whereby for AquaCrop the RMSE for the dry and wet seasons were 7.0 and 4.0% (R^2 = 0.99 and 0.97), respectively, and for AgroC the RMSE was slightly higher with 11.7 and 17.0% (R^2 = 0.71 to 0.76).

Table 5 Statistical values between the simulated vs. measured data for the calibration and the validation period for rainfed maize at Akademija

Parameters	Observed	Simulated		RMSE		R^2	
		AgroC	AquaCrop	AgroC	AquaCrop	AgroC	AquaCrop
Calibration period							
CC (%)				11.7	7.02	0.71	0.99
TAB (t ha^{-1})	14.53±0.65	15.27	14.05	0.86	0.69	0.97	0.98
Leaf (t ha^{-1})	1.21±0.18	1.99	–	0.53	–	0.69	–
Stalk (t ha^{-1})	2.37±0.21	3.54	–	0.79	–	0.56	–
Storage organs (t ha^{-1})	4.1±0.38	2.81	–	0.96	–	0.95	–
Grain yield (t ha^{-1})	6.85±0.59	6.93	6.90	0.44	1.01	0.98	0.92
SWC at 10 cm (cm^3 cm^{-3})				0.023	0.032	0.61	0.52
SWC at 30 cm (cm^3 cm^{-3})				0.016	0.021	0.48	0.41
SWC at 60 cm (cm^3 cm^{-3})				0.026	0.012	0.58	0.78
Validation period							
CC (%)				17.02	4.01	0.76	0.97
TAB (t ha^{-1})	18.52 ± 0.75	18.97	18.02	0.54	1.33	0.99	0.97
Leaf (t ha^{-1})	2.26 ± 0.16	2.51	–	0.68	–	0.86	–
Stalk (t ha^{-1})	4.56 ± 0.44	4.52	–	0.42	–	0.91	–
Storage organs (t ha^{-1})	2.68 ± 0.41	2.93	–	0.61	–	0.31	–
Grain yield (t ha^{-1})	9.02 ± 0.71	9.01	8.93	0.35	0.89	0.99	0.98
SWC at 10 cm (cm^3 cm^{-3})				0.031	0.056	0.78	0.53
SWC at 30 cm (cm^3 cm^{-3})				0.018	0.023	0.69	0.66
SWC at 60 cm (cm^3 cm^{-3})				0.017	0.019	0.54	0.55

CC = canopy cover; TAB = total aboveground biomass; SWC = soil water content.

3.3.3. Partitioning of total above-ground biomass and grain yield

The measured TAB in dry matter weight along with the simulated TABs from AquaCrop and AgroC are presented in Fig. 4 for the two maize growing seasons 2015 and 2016. Both models reproduced the total above-ground biomass development over time quite well. In 2015, the RMSE for AquaCrop was 0.69 t ha^{-1} (R^2 = 0.98) and for AgroC the RMSE was slightly larger with 0.86 t ha^{-1} (R^2 = 0.97). In 2016, the corresponding values were 1.33 t ha^{-1} (R^2 = 0.97) and 0.54 t ha^{-1} (R^2 = 0.99) for AquaCrop and AgroC, respectively, indicating a better correspondence for AgroC for the validation period compared to the calibration period. In 2015, at harvest, the observed TAB was 14.53 ± 0.65 t ha^{-1}, which was slightly underestimated by AquaCrop, with a simulated TAB of 14.05 t ha^{-1} (3.3% underestimation) and slightly overestimated by AgroC, with a simulated value of 15.27 t ha^{-1} (5.1% overestimation). In the more favourable season for maize growth in 2016, the observed biomass was

18.52 ± 0.75 t ha^{-1}, which was again slightly underestimated by 2.7% by AquaCrop (18.02 t ha^{-1}) and overestimated by 2.4% by AgroC (18.97 t ha^{-1}). Grain yields observed from field experiments in the dry season of 2015 and the wet season of 2016 were 6.85 ± 0.59 and 9.02 ± 0.71 t ha^{-1}, respectively (Table 5). Similarly to the total above-ground biomass measurements, grain yield differences between the two contrasting seasons were evident and can be partly explained by high rainfall, particularly during the grain filling stages, and a higher sum of GDD in 2016. This indicates that the climatic conditions, mainly water availability, plays an important role in this region for maize growth. In both seasons, grain yield simulated with AgroC (6.93 t ha^{-1} in 2015 and 9.01 t ha^{-1} in 2016) was slightly higher than those simulated by AquaCrop (6.90 t ha^{-1} in 2015 and 8.93 t ha^{-1} in 2016). Despite rather contrasting growing conditions, the performance of both models in terms of simulation of total above-ground biomass and grain yield can be considered as reasonably well. Unfortunately, AquaCrop does not provide further insight of the development of different organs (e.g., stem, leaves) over the growing season, whereas AgroC provides detailed information of the different maize organs, which helps to identify model parameters of the maize variety planted in the experiment. Under favourable growing conditions in 2016, the observed final weights of observed biomass components corresponded quite well with the AgroC simulated results. The observed leaf weight (on dry mass basis) was 2.26 ± 0.16 t ha^{-1} and the simulated weight was 2.51 t ha^{-1}. The observed stalk weight was 4.56 ± 0.44 t ha^{-1}, corresponding to a simulation result of 4.52 t ha^{-1}. The weight of the storage organs (cob) was 2.68 ± 0.41 t ha^{-1} and AgroC predicted 2.93 t ha^{-1}. Unfortunately, in the unusually dry season of 2015, the correspondence between observed and simulated values of final weights of individual components was not as good as in 2016. In 2015, the weight of maize leaf blades reached the maximum at the end of the vegetative period in August and started to decrease steadily due to increasing water shortage. At the VT growth stage, the lowest 2 to 4 plant leaves lost their green colour and withered, and thus their weights were not included to the total leaf weight. On the other hand, in 2016, the soil moisture availability was adequate to crop requirements and the leaves kept their green colour and did not wither. Therefore, their total weight did not decrease until the end of the growing period. In 2015, the weight of the stalk reached the maximum at the beginning of the reproductive period at the end of August, and then started to decrease steadily, probably due to reallocation of carbon and nitrogen compounds from the stalk to the developing ear, whereas, in 2016, the stalk and leaf weights did not decrease. In the wet season of 2016, the share of storage organs (cob, husk) in the total biomass was only 14.5%, whereas in the dry season of 2015 it was much larger, with 28.3%. This may be explained by the fact that in 2015 the majority of plants produced several cobs. However, only one cob per plant reached an adequate size and physiological maturity. We added non-matured cobs to the sum of storage organs. These separate inconsistencies of biomass components could not be reproduced by the AgroC simulation, which were only based on the differences in meteorological conditions in those contrasting seasons and do not include compensation effects between organs or the loss of leaves after withering due to water stress conditions.

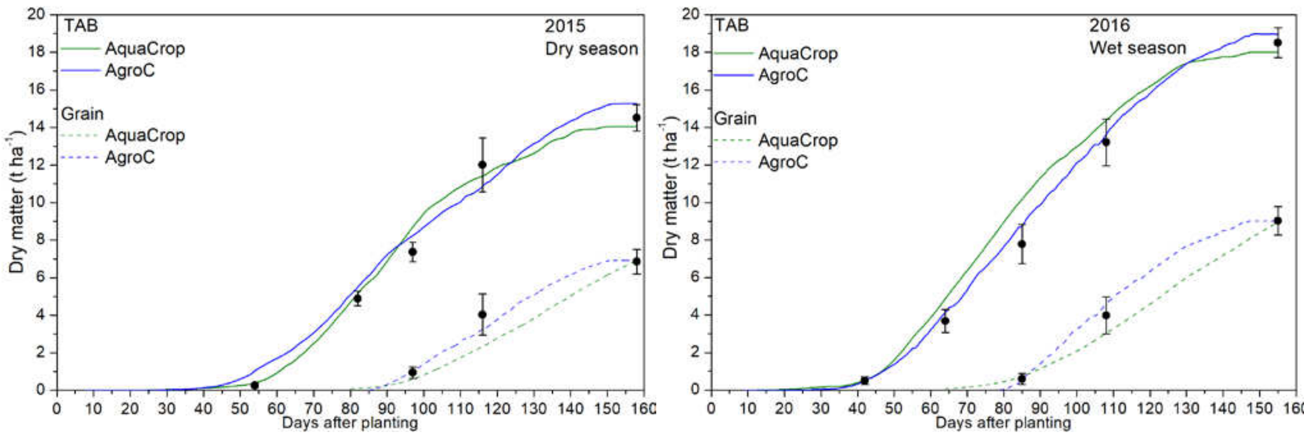

Fig. 4 Comparison between observed (dots) and simulated (lines) total above-ground biomass (TAB) and grain as dry matter for the seasons 2015 (calibrated) and 2016 (validation).

3.4. Cold stress and water stress

The results of water stress simulation in the two contrasting growing seasons for both models are shown in Fig. 5. In both years, the occurrence of water stress and its intensity reflect the precipitation distribution over the growing season. In 2015, during the vegetative stage, the amount of precipitation was 126.8 mm, thus only a temporary water shortage occurred during the maize development period. The comparison of simulated water stress intensity suggests that the two models provided comparable results but interpreted the occurrence of water stress in somewhat different ways. AquaCrop results indicated mild water stress during emergence-tasselling stage (VE–VT growing stages), expressing it as up to 12% reduction in leaf expansion. Water stress simulated by the AgroC model, which is defined as the ratio between actual and potential transpiration, was within the range of 0–27%. Precipitation during the reproductive stage was as low as 67.4 mm causing significant water shortage in maize. Both models provided a similar pattern of water stress occurrence with peaks at the R2 stage and comparable scores of stress intensity (~42% in AquaCrop and ~49% in AgroC).

In 2016, the amount of precipitation was adequate during the entire maize growing cycle (211 mm in the vegetative and 167.4 mm in the reproductive stage), thus only mild water stress occurred occasionally. During the vegetative period, the AquaCrop model indicated up to 11% water stress mainly at early growth stages, whereas AgroC simulated somewhat higher levels of water stress (2–30%). During the reproductive period, no water stress was predicted by the AquaCrop model and only short episodes of mild water stress were simulated by the AgroC model (0–11.3%).

In the next step, the simulated yield for the two contrasting years was compared to potential yield without water stress. The grain yield losses due to water shortage in 2015 were substantial. AquaCrop indicated a yield gap between potential and actual yield of 0.81 t ha^{-1}, and AgroC estimated an even larger gap of 1.93 t ha^{-1} (Table 6). Even in the growing period with favourable climatic conditions (2016), grain yield losses due to water shortage were still detectable but clearly lower than in the dry year of 2015. The calculated yield gaps for AquaCrop and AgroC were 0.48 and 0.94 t ha^{-1}, respectively.

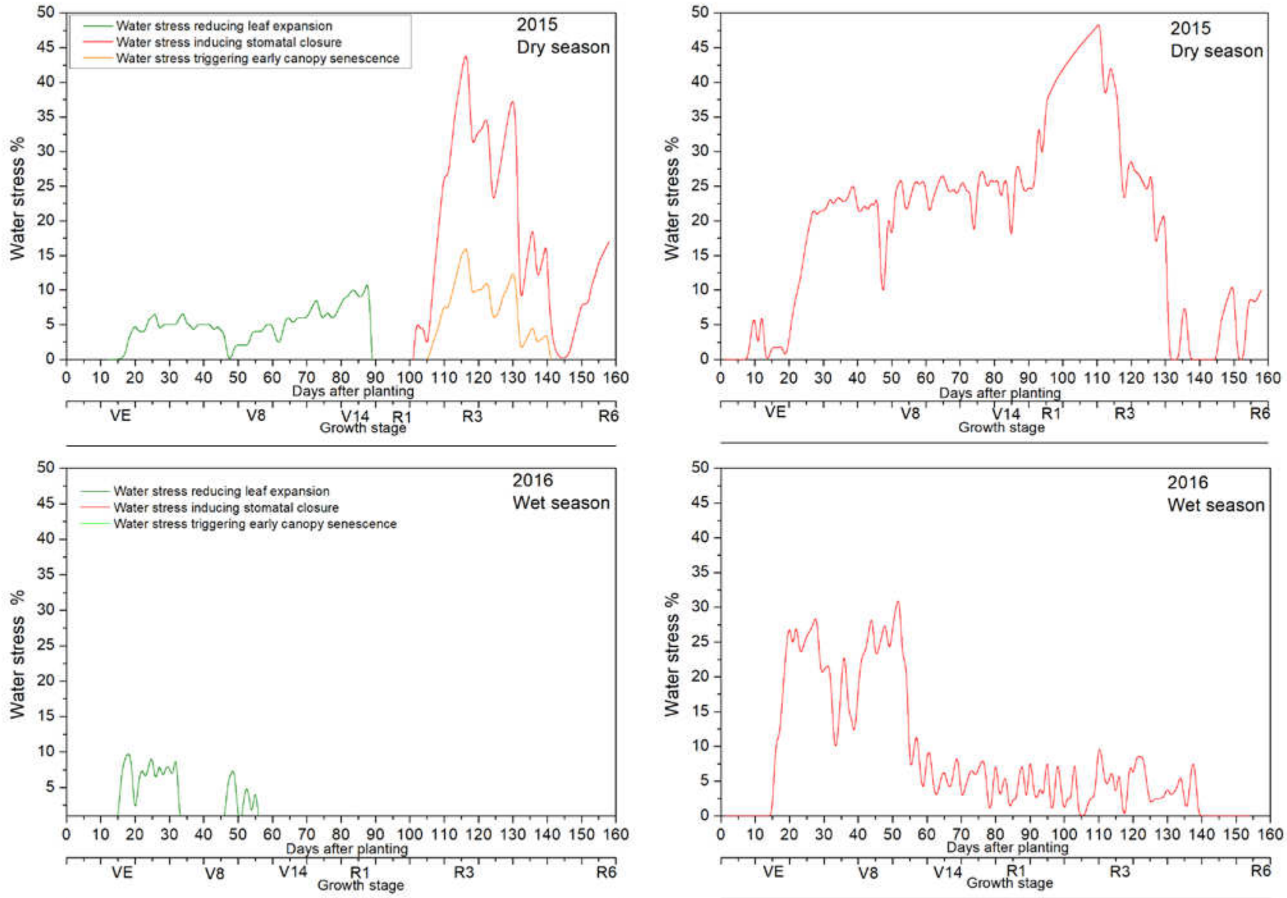

Fig. 5 Estimated water stress intensity using AquaCrop (left) and AgroC (right) models in two contrasting growing seasons

As expected for these high latitude regions, low air temperature (lower than 8 °C) can be an important limiting factor of maize growth and development. In 2015, days with average temperature below 8 °C accounted for 28.2 and 24.6% of the days during vegetative and reproductive stages, respectively. In accordance with the yield gap caused by water stress, the yield gap caused by low temperatures was also calculated. The results showed that yield losses due to low temperatures in the season of 2015 were 2.60 and 2.39 t ha^{-1}, for AquaCrop and AgroC, respectively. In 2016, days with low temperatures accounted for only 18% during the vegetative stage but stayed nearly the same (25.3%) during the reproductive stage compared to 2015. As a consequence, potential grain yield losses in 2016 were lower than in 2015, with only 1.54 and 1.90 t ha^{-1} for AquaCrop and AgroC, respectively. This indicates that temperature stress during the vegetative stage is the dominant factor for potential yield losses at this location.

Table 6 Simulated potential and actual grain maize yields and relative loss for the contrasting growing conditions in 2015 and 2016

	2015		2016	
	AquaCrop	AgroC	AquaCrop	AgroC
Simulated yield				
Potential yield (t ha^{-1})	10.31	11.25	10.95	11.85
Water-limited yield (t ha^{-1})	9.50 (-7.9%)	9.32 (-17.2%)	10.47 (-4.4%)	10.91 (-7.9%)
Temperature-limited yield (t ha^{-1})	7.71 (-25.2%)	8.86 (-21.2%)	9.41 (-14.1%)	9.95 (-16.0%)
Water/temperature limited yield (t ha^{-1})	6.90 (-33.1%)	6.93 (-38.4%)	8.93 (-18.4%)	9.01 (-24.0%)
Average farmers yield in Lithuania				
Farmers yield (grain maize + cob mix) (t ha^{-1})	4.81		6.94	

The combined water/temperature stress yields in comparison to potential yield indicate that AquaCrop predicts a slightly smaller yield reduction due to water and temperature stress, with 3.41 and 2.02 t ha^{-1} for 2015 and 2016 compared to AgroC with 4.32 and 2.84 t ha^{-1}, whereby this gap is mainly caused by higher potential yields predicted by AgroC.

4. Discussion

Our study provides experimental evidence of potential maize grain yield levels above 9 t ha^{-1} (in dry weight) for a region 55°N in the Baltic area. This level of yield was observed in the season of 2016 with favourable meteorological conditions (temperatures and rainfall above current climatic normal) and adequate management (under non-limited nitrogen nutrition). This result is in line with current global observations in the area showing that poleward regions exhibit an increase in suitability for grain maize production (Ramirez-Cabral et al. 2017). Thus, farmers in cool climate regions are encouraged to expand the area used for maize grain production. However, the experiments also showed that the grain yield in dry seasons such as 2015 (with temperatures close to climatic normal of 1981–2010) was 24% lower in comparison to the favourable conditions in 2016. Observed differences in reported farmer's yields between the two years was 31% in Lithuania (Table 6), which agrees nicely to the findings of our study and indicates potentially large year to year variations. Liu et al. (2013) analysed phenological responses of maize grown at different latitudes in China and suggested that, in high latitude regions, short season varieties should be sown in order to adjust to limited heat resources. However, the understanding of genotype and environment interactions is essential to ensure high and stable yields under local conditions, especially where soils may add constraints regarding water and nutrient stress. It is not possible to separate low temperature and water shortage effects on yield through empirical data only. Our simulations indicate the importance of both factors, whereby cold stress appears to be the most important factor in the region. This finding is in agreement with the literature, which states that in northern Europe, cool temperatures, mainly caused by late frost in spring, may damage the crop stands irreversibly and that short growing seasons are the main limitations for grain maize. Nevertheless, drought events are also a concern (Olesen et al. 2011). Unfortunately, both models only account for cold stress but were not able to account for permanent damage to plant organs (e.g., leaves) induced by low temperature. Additionally, Reidsma et al. (2010) suggested that improving estimations of actual maize yield requires regional specific models that, besides cultivar coefficients, relate to the farm characteristics (intensity, size, land use) important in the region. It is also recognised that below-ground processes, such as water availability and variations within the soil profile, have largely been neglected by breeders when considering ways to increase the yield of major crops (Hall and Richards 2013).

Model accuracy must be discussed against the background that for both models the crop parameters were calibrated by hand. In this respect, the model results always reflect the decisions of the model user (Diekkrüger et al. 1995). In this model comparison, AquaCrop performed slightly better for the prediction of crop cover/LAI, whereas AgroC showed slightly better agreement in terms of the estimated water content. This improved simulation of water contents, which finally affects the estimation of root water uptake stress, is however linked to a higher cost in terms of the measurement and inversion of soil hydraulic parameters. In addition, the higher complexity in the outputs regarding the dry mass weights of plant organs provided by AgroC requires additional input parameters. The question of whether a more complex or a more simple model should be used relies on the availability of input data and measurements. In this study, a well-characterized experimental site accompanied by a large number of continuous measurements allowed the application of both model types. Complex and flexible models such as AgroC increase the spatial application range, permitting the analyses across a broader range of environmental conditions and crop traits. In addition, AquaCrop can be seen as an efficient tool to improve the understanding of fundamental biophysical mechanisms determining crop performance in water limited or cold stress conditions.

Both models agree in their results regarding the bigger effect of cold stress in relation to water stress. Of course, the quantification of this effect depends on the chosen simulation approaches. For example, in AgroC the estimated water stress depends on the estimated amount of potential evapotranspiration, on the crop conversion factors A_{kc} on the Feddes parameters and also on the soil hydraulic parameters, in addition to other parameters. Cold stress is affected by the choice of the base temperature, and estimated assimilation is also influenced by the temperature-dependency function. Notably, both models agree quite well in their response to cold and water stress, even though the two models differ substantially in their simulation approaches. This provides some confidence to our simulation results regarding the cold stress and water stress response of maize.

5. Conclusions

In this experimental study evidence of relatively high grain yield of short season maize variety in high latitude region ~55°N was obtained. However, potentially large year to year yield variation was evident, both in experiments and reported farmer's yields. In addition, the experimental results reveal that the grain yield under optimum management is about 2 t ha^{-1} higher than the average yield in Lithuania.

After calibration of soil and crop parameters, both, the AquaCrop and AgroC models, were suitable for simulating crop development and grain yield. In relation to water stress, the simulation results indicate a larger effect of cold stress on maize grain yield for a region 55°N in the Baltic area. According to the models applied in this study, the effect of low temperatures could be about twice as big as the effect of water stress, depending on the meteorological conditions over the growing period.

Acknowledgements

The German Federal Environmental Foundation funded the internships (01/03/2017–06/08/2017) at the Agrosphere Institute IBG-3 at the Forschungszentrum Juelich, Germany. The authors are grateful to Jonas Volungevičius (Lithuanian Research Centre for Agriculture and Forestry) for a detailed description of the soil profile.

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