Winter wheat productivity in relation to water availability and growing intensity

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Abstract
The study was aimed at water availability effects on productivity of winter wheat in relation to growing intensity, including preliminary testing of the DSSAT v4.0.2.0 model. For this purpose we analysed research material on winter wheat (Triticum aestivum L.) performance in the field experiments carried out at the Lithuanian Institute of Agriculture in Dotnuva, Kėdainiai, Central Lithuania during the periods 1989–1991 and 2007–2009. The soil of the experimental site is light loam, Endocalcari-Epihypogleyic Cambisol (CMg-p-w-can).

Comparison of simulated and measured grain yield values in three cropping seasons 1989, 1990 and 1991, involving the results from the treatments where winter wheat cv. ‘Širvinta 1’ had been applied with N60 in spring, showed a good match judging from the correlation ($R^2 = 0.81$) and data scatter according to 1:1 line. However, on the plots without N fertilisation the grain yield was underestimated. A series of experiments carried out on the winter wheat cv. ‘Ada’ during 2007–2009 involved three levels of growing intensity – traditional, integrated and organic. Soil moisture availability was measured with “Watermark” sensors and water stress was simulated by the DSSAT v4.0.2.0 model. The DSSAT model and soil moisture sensors produced comparable estimations of water shortage and can be considered as useful tools for monitoring water availability status in winter wheat crops. Winter wheat biomass accumulation and grain yield in field experiments were influenced by the growing intensity and water availability during the growing season, and likely, by the interaction between these two factors. Winter wheat yield was well predicted by the DSSAT v4.0.2.0 model in the treatments applied with N fertilisers in the years devoid of severe water stress. However, the accuracy of estimations declined in the seasons with longer droughty periods and in the treatments without N application.

Key words: grain yield, DSSAT model, water stress, biomass, growing intensity.

Introduction
Environmental concerns are gearing farm production towards less intensive and more sustainable farming. A number of research studies have been devoted to organic and low-input cropping systems as alternatives to chemical and synthetic fertiliser-based systems with a view toward developing more environmentally friendly, ecologically sound and economically profitable agricultural practices (Poudel et al., 2001). However, well tailored to local nature conditions, environmentally friendly, resource efficient and resilient to climate change wheat production system is still a task for research.

In general, crop yields are closely related to the available water and nitrogen supply levels. Under temperate climate, nitrogen is a key limiting factor of winter wheat growth and yield. However, due to the climate change, drought is becoming a factor to consider also in temperate zone. Climate change affects water availability not only by changing regional precipitation levels and temporal variability, but also by affecting water flows and soil moisture dynamics (Holsten et al., 2009). This also applies for Lithuania, which belongs to the zone of periodical surplus of moisture, however, with periodical droughts (Diršė, 2001). For this reason, monitoring of water availability during the growing period of winter wheat is becoming an important issue, relevant for yield prediction, correcting nitro-
The aim of this study was to highlight the effect of water availability on the productivity of winter wheat and to test the DSSAT v4.0.2.0 model against the data from winter wheat under different growing intensities.

**Material and methods**

**Site description.** The study refers to the field experiments with winter wheat (*Triticum aestivum* L.) carried out at the Lithuanian Institute of Agriculture in Dotnuva, Central Lithuania during the periods 1989–1991 and 2007–2009. The soil of the experimental site is light loam, *Endocalcari-Epiphytoge-lycan Cambisol (CMg-p-w-can)*, neutral, rich in humus, relatively rich in potassium and phosphorus. The mean annual precipitation is 656 mm and the mean annual temperature is 6.5°C.

**Field experiments.** The first series of the experiments was conducted during 1989–1991 with the winter wheat cv. ‘irvinta 1’ applied with ammonium nitrate (N₆₀) at different growth stages (from the beginning of the vegetation in spring until the beginning of heading). Winter wheat was sown at a density of 400 kernels m⁻² on the 15th of Septem-
The DSSAT model is a collection of independent programs that operate together; crop simulation models are at its centre. The databases describe weather, soil, experimental conditions and measurements, and genotype information for applying the models to different situations (Jones et al., 2003). The model describes the progress through the crop lifecycle using degree-day accumulation. The duration of growth stages in response to temperature and photoperiod varies between species and cultivars, and genetic coefficients are used as model inputs to describe these differences. The model simulates phonological development, biomass accumulation and grain growth, and the soil and plant water and N balance from planting until harvest maturity based on daily time steps (Singh et al., 2008). The software helps users prepare these database and compare simulated results with observations to give them confidence in the models or to improve accuracy (Jones et al., 2003).

Results and discussion


In the first stage of the study, the DSSAT v4.0.2.0 model was tested against the data of the experiments with winter wheat cv. ‘Širvinta 1’ carried out during period 1989–1991. It involved a comparison between grain yield measurement data and outputs generated by the model. Simple linear regression was computed to determine $R^2$ value between observed and simulated data. Comparison of simulated and measured grain yield values in three cropping seasons, involving results from the treatments where winter wheat was applied with N fertilisers in spring, showed good match judging from the correlation ($R^2 = 0.81$) and data scatter according to 1:1 line (Figure 1). However, on the plots without N fertilisation a good fit between measured (3.69 t ha$^{-1}$) and simulated (3.57 t ha$^{-1}$) values was demonstrated only in 1990, when crop stand severely thinned out during the winter, while in 1989 and 1991 the grain yield was markedly underestimated. In the field experiments, winter wheat was grown after red clover, so was able to utilise additional quantities of nitrogen which probably were not properly computed by the model. Such assumption concurs with the suggestion of Gisman et al. (2002) that model well calculates only one type of recently added soil organic matter. Another likely reason can be associated with water stress, which is in general a source of uncertainty in crop growth simulation, as an accurate simulation of crop available soil water is difficult. Eitzinger et al. (2003) reported, that model underestimated yields in years with relatively low winter wheat yields and overestimated years with high yields, and pointed, that the impact of groundwater on the rooting zone considerably affected yield level. Singh et al. (2008) found, that model DSSAT underestimated the interaction.
of nitrogen and water, and simulated lower biomass yield than was actually measured in field experiments on the semi-arid and subtropical climate. In order to highlight the effect of water availability on the yield of winter wheat we used the DSSAT model to generate estimations of water stress of winter wheat crop. The DSSAT v4.0.2.0 model calculates evapo-transpiration of crop on daily bases according to Penman-Monteith formula, which is FAO reference method. The model simulates water stress in the main growing stages of plants and grades it according to scale from 0 to 1 point, where 0 – no stress, 1 – the maximum stress.

Water stress simulation showed that winter wheat plants experienced water shortage in 1990 and 1991 (Figure 2). In 1991, in the first half of June the simulated water stress level reached 0.5 (hydrothermal coefficient of Selianinov (HTC) for the first half of June was 0.58) and water shortage continued until the end of vegetation. No significant water stress was recorded in 1989 and it is likely, that the difference in grain yield 0.83 t ha\(^{-1}\) in the plots applied with N fertilisers between these two years resulted from the difference in water availability. In 1990, winter wheat experienced water stress in the first half of May, estimated by

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y = 0.9295x + 0.01667 \\
R^2 = 0.8125, \ p < 0.01
\]

**Figure 1.** The relationship between actual and simulated grain yield of the winter wheat cv. ‘Širvinta 1’

**Figure 2.** The simulated water stress of the winter wheat cv. ‘Širvinta 1’

Note. 1 – maximum stress, 0 – no stress; HTC – hydrothermal coefficient of Selianinov.
the model as 0.5 points (HTC of the first two weeks of June was 0), which along with thinned out crop stand resulted in the lower yield level than 1989 and 1991.

**Experiments performed during 2007–2009.**

In the second stage of this study, the DSSAT model was used as an additional research tool to analyse the results of the field experiments with the winter wheat cv. ‘Ada’ performed during 2007–2009. In the field experiments, winter wheat was grown according to three different levels of intensity – traditional, integrated and organic.

In order to provide additional information on water availability, soil moisture sensors “Watermark” were installed at the end of May in all growing systems – two sensors (one at 20 cm, the other at 40 cm depth) in each system. The “Watermark” meter performs well when the soil temperature is above 16°C. The soil moisture sensors are usually used in irrigated crops such as coffee (Lin, 2010) or vegetables; however, they can be a useful tool for soil moisture measurements and water stress predictions also in other crops. The study of Brian et al. (2003) showed that sensors are able to follow the general trends of water requirement successfully as soil water content changes during the growing season.

In 2007, simulated by DSSAT v4.0.2.0 model, water stress occurred early in spring, but was short (Figure 3). Severe stress re-occurred in the beginning of June, when soil moisture sensors readings reached 120 centibars, the level at which the soil becomes too dry to support maximum rate of growth. This period of stress lasted for 20 days. The end of winter wheat growing season was not very dry according to soil moisture meters, but the model’s simulations showed a severe water stress.

In 2008, soil moisture sensors were installed in the third ten-day period of May and showed water shortage from the first until the last measurements before harvesting, with readings mainly above 150 centibars (Figure 4). The simulation of water stress suggests that in the winter wheat crop water stress occurred even before the installation of soil moisture sensors. Although the DSSAT v4.0.2.0 model simulated three short periods with less severe water stress, while soil moisture sensors showed stable high water shortage, we can assume that in general both methods provided relevant information regarding water availability for winter wheat.

In 2009, the period with shortage of water was shorter than in 2008 (Figure 5). Severe stress was simulated from the middle of April till beginning of June. The soil moisture sensors were installed in the middle of May. The readings reached a value of more than 100 centibars in a few days and were increasing in the course of the next few weeks. After the rainfall, in mid June both models simulated water stress, and the readings of soil

![Graph showing simulated water stress and soil moisture sensors](image-url)
moisture sensors “Watermark” ceased exhibiting water shortage.

Water availability is a highly relevant factor in the formation of winter wheat yield; however, it is not always easy to correlate it directly with actual grain yield level. In field experiments of Behera and Panda (2009) with winter wheat grown under different levels of NPK fertilisers and irrigation regimes, grain yield decreased with an increase in water stress severity. In the experiments of Yang et al. (2006) the effect of water stress on winter wheat varied depending on plant growth stage and duration of water stress. As a result, biomass accumulation by a crop during the growing period can be a useful indicator.

Figure 4. Simulated water stress and soil moisture sensors in the winter wheat cv. ‘Ada’ in the traditional growing system

Dotnuva, 2008

Figure 5. Simulated water stress and soil moisture sensors in the winter wheat cv. ‘Ada’ in the traditional growing system

Dotnuva, 2009
Biomass accumulation in relation to the sum of active temperatures (the sum of daily temperatures during the period with an average daily temperature above 10°C) in experiments 2007, with short water stress periods, showed relatively small differences between treatments, while in 2008, with long and severe water shortage periods, the differences between the treatments applied with nitrogen fertilisers and without nitrogen were rather high (Figure 6). In experiments 2009, with a shorter water stress period than in 2008, the differences between treatments were less marked. These results suggest that along with water stress severity and duration, the interaction between water and nitrogen availability is relevant for winter wheat biomass accumulation and yielding.

**Figure 6.** The accumulation of biomass of winter wheat cv. ‘Ada’ in different growing systems Dotnuva, 2007–2009

In the field experiments, the grain yield level was influenced not only by growing intensity and water availability, but, very likely, also by the interaction between these two factors. Winter wheat grain yield was significantly affected by year ($F$ value = 51.03, $p < 0.01$), growing intensity ($F$ value = 316.99, $p < 0.01$) and the interaction between these factors ($F$ value = 34.81, $p < 0.01$). Despite rather diverse water availability conditions and water stress, the variation of winter wheat yield among years was lower than among growing systems. The lowest and the most stable grain yield in a range of 4–5 t ha$^{-1}$ was produced under ecological growing, without the application of commercial nitrogen fertilisers (Figure 7). The DSSAT v4.0.2.0 model simulated yields in a range of 3.5–5 t ha$^{-1}$, with slight underestimation in 2007 and 2008 and overestimation in 2009. The highest grain yield in a range of 6.5–7.5 t ha$^{-1}$ was produced under traditional growing, where commercial nitrogen fertilisers were applied at the rate calculated for the yield level of 6–7 t ha$^{-1}$. The DSSAT v4.0.2.0 model underestimated yield level in 2008 and overestimated in 2007, however, in 2009 overestimation of yield was very high. Simulated yield level was close to 10 t ha$^{-1}$, higher than that we can normally expect with the application of 110 kg ha$^{-1}$ of nitrogen. On the other hand, the end of winter wheat vegetation occurs in the conditions of substantial water oversupply, which can be a reason for lower realisation of high simulated yield potential.


**Figure 7.** Simulated and actual grain yield of the winter wheat cv. ‘Ada’ during 2007–2009

**Conclusions**

1. Winter wheat grain yield was significantly affected by the year, growing intensity and the interaction between these factors. The lowest grain yield in a range of 4–5 t ha\(^{-1}\) was produced under ecological growing, the highest – 6.5–7.5 t ha\(^{-1}\) under traditional growing.

2. The yield of winter wheat was well predicted by the DSSAT v4.0.2.0 model in the treatments applied with N fertilisers in the years without severe water stress. However, the accuracy of estimations reduced in the seasons with longer droughty periods and in the treatments without N application.

3. The DSSAT model produced comparable estimations of general trends of water shortage with soil moisture sensors and can be considered as a useful tool for monitoring water availability status in winter wheat crops.

**References**


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Žieminių kviečių produktyvumas priklausomai nuo drėgmės pasiekiamumo ir auginimo intensyvumo

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Santrauka


Reikšminiai žodžiai: modelis DSSAT, biomasė, grūdų derlius, žemdirbystės sistemos, vandens stresas.