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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 N_{60} 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 (Dirsė, 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 nitrogen doses, and choosing optimum growing intensity in general. Although a number of studies have been devoted to interactions between nitrogen and water in wheat, in cooler areas of temperate zone this issue still needs research efforts.

Models have already been produced by a number of research groups to predict the changes in plant growth, development, and productivity in a given environment and thus to help in the management of resources such as fertilizers and water (Hirel et al., 2007). Crop models have been increasingly used to explore and design options for plant growth, farming, and regional land use systems. Significant efforts have been made in the Netherlands, at Wageningen, where LINTUL, WOFOST, MACROS and other agricultural models have been created (Van Ittersum et al., 2003). In USA the DSSAT (Decision Support for Agrotechnology Transfer) crop growth model, which integrates the effects of soil, weather, and management has been in use for more than 20 years (Jones et al., 2003). Still, in order to increase predictive capacity and applicability, sophisticated crop simulation models already used in basic and applied research should be further refined with a special emphasis on specific pedo-climatic conditions and technologies in different production regions.

The DSSAT model offers wide opportunities for studies of interactions between plants and ambient, nitrogen, plant varieties, irrigation, carbon (Thorp et al., 2008). Harnos and Kovacs (1999) used regional winter wheat yield data set from 1962 to 1989 from West Hungary and found that the DSSAT model's part CERES-Wheat gave the higher correlation between simulated and actual yields, than AFRCWHEAT2, SUCROS2 and CROPSIM models. Recently, the DSSAT model was tested against the results of observations of wheat yield in 141 experimental agricultural stations of China during 1980–2000 (Xiong et al., 2008). The findings of this study suggest that the model captures the spatial patterns of yield variability reasonably well when compared to observed field and census data. However, studies performed in cooler climatic conditions, gave rather controversial results. In the United Kingdom, a large – scale study on the feasibility of the DSSAT model to predict grain yield was performed on observed yields from well-managed and documented agricultural experiments carried out during the period 1976–1993 (Landau et al., 1998). The authors of this study concluded that more work is still needed before such yield predictions can be used with confidence in decision support or climate change assessment in the UK. Another study performed in the UK, where the model was validated also using historic crop performance data (Ghaffari et al., 2001), revealed that the calibrated and validated CERES-Wheat model can be used for the prediction of wheat growth and yield under West European conditions. Conversely, the results of the study on winter wheat grown under contrasting nitrogen management in North-Germany suggest that CERES-Wheat model is not applicable as a nitrogen management optimization tool under temperate-maritime environmental conditions (Langensiepen et al., 2008).

The DSSAT model can be used for a variety of tasks in simulating water regime. In India, the DSSAT-CSM-CERES-Wheat V4.0 model was calibrated using the historical weather data of a 36-year period (1970–2005) to estimate the long-term mean and variability of potential yield, drainage, runoff, evapo-transpiration, crop water productivity and irrigation water productivity (Timsina et al., 2008). The authors suggested that the model could be a useful decision support system for farmers and the validated model and the simulation results can also be extrapolated to other areas with similar climatic and soil environments.

In general, the results of the DSSAT model evaluations performed in different regions indicate that applicability for crop yield simulation is higher in a warmer climate, although in cooler areas of temperate zone the performance of the model is not very consistent.

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-Epihypogleyic 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 (N_{60}) 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 15^{th} of September in 1988, on the 9th of September in 1989 and on the 13th of September in 1990 and harvested in the end of July or beginning of August. The crop was sprayed with herbicide, growth retardant and fungicide.

The second series of the experiments was conducted during 2007–2009 with the winter wheat cv. 'Ada' under three levels of intensity: a) traditional, b) integrated and c) organic. Wheat under traditional system was applied with the fertilisers at a rate of $N_{110}P_{90}K_{140}$ calculated for target 6–7 t ha^{-1} yield, applied with herbicide, fungicide and insecticide. Under integrated system the crop received by 35–40% lower rates of $N_{70}P_{40}K_{60}$ fertilisers, and under organic system the crop was managed following the rules of organic agriculture without application of industrial N fertilisers and plant protection measures. Similarly to the experiments carried out during 1989–1991, winter wheat was sown at a density of 400 kernels m^{-2} on the 15th of September in 2006 and 2008 and on the 14th of September in 2007 and harvested in the end of July or beginning of August. Plants for biomass measurements were sampled six times per growing season from the beginning of spring till harvesting. Soil water availability was measured with soil moisture sensors "Watermark". The sensors were installed in the soil at the 20 and 40 cm depths in one place in each growth system.

Grain yield and biomass were subjected to analyses of variance, and significance of treatments' effects was assessed with F criteria. Treatment means and standard deviation are presented in the article. Calculation of liner regression and correlation were performed in the way conventional for crop science (Clewer, Scarisbrick, 2001).

Modelling. In this study the computer model DSSAT v4.0.2.0 was used to simulate winter wheat yield and water stress effects. The required weather data set was obtained from the Dotnuva (daily maximum and minimum air temperature, precipitation) and Kaunas (radiation) weather stations. Soil input data were derived from the Valinava experimental site and the crop management parameters from the individual field experiment treatments. Genetic coefficients were selected from the models' data base, designed for the Western Europe winter wheat type.

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

Experiments performed in 1989–1991. 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

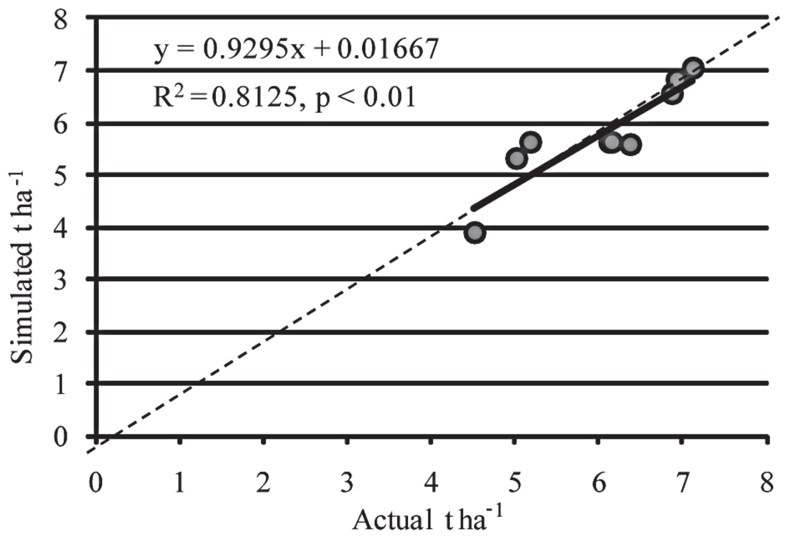
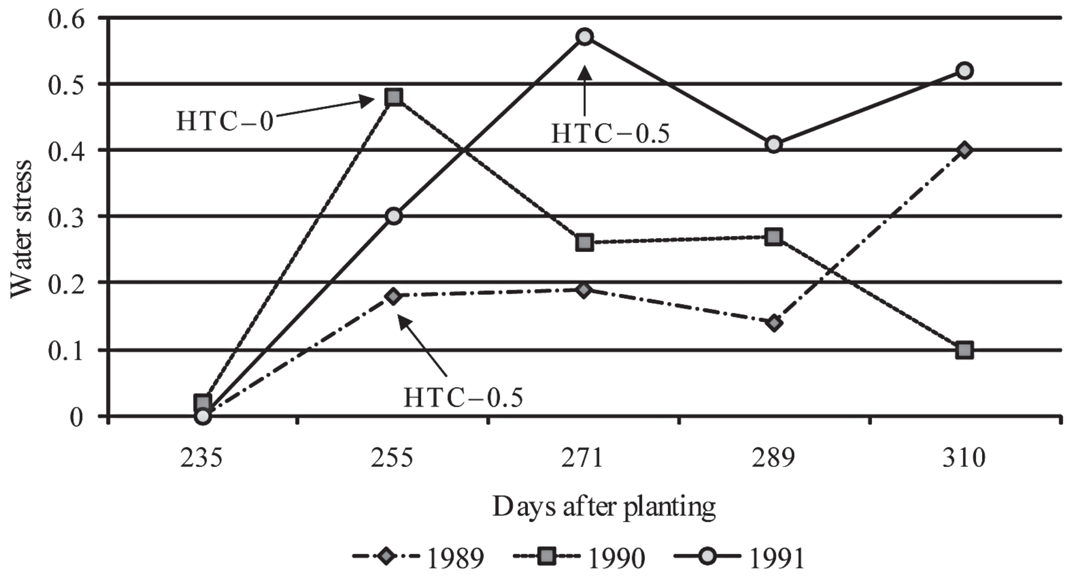


Figure 1. The relationship between actual and simulated grain yield of the winter wheat cv. 'Širvinta 1'
Dotnuva, 1989–1991



Note. 1 – maximum stress, 0 – no stress; HTC – hydrothermal coefficient of Selianinov.

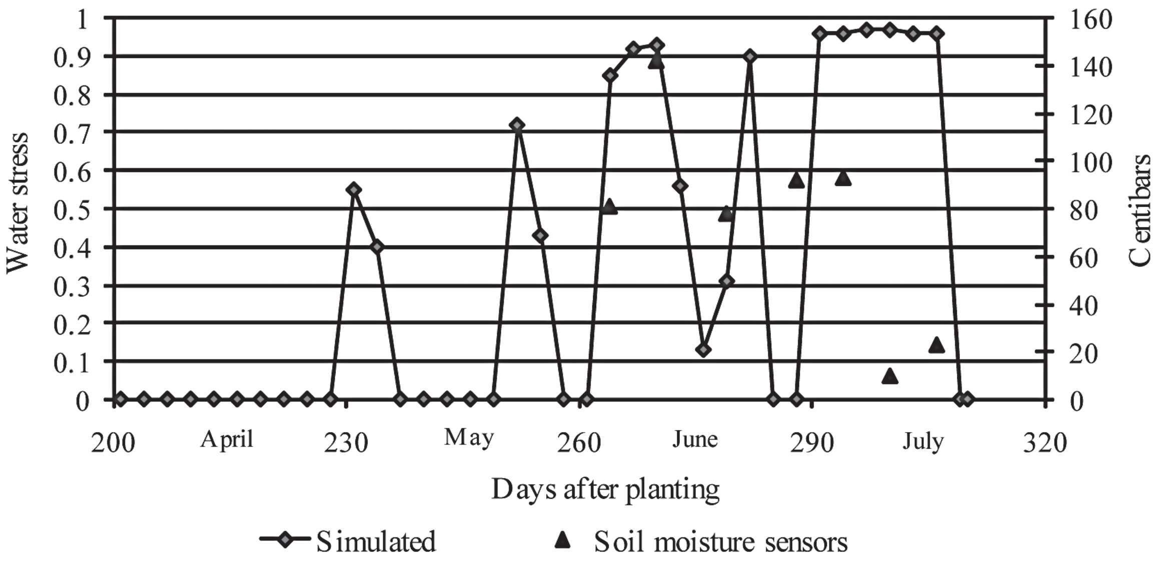
Figure 2. The simulated water stress of the winter wheat cv. 'Širvinta 1'
Dotnuva, 1989–1991

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.



Note. 1 – maximum stress, 0 – no stress.

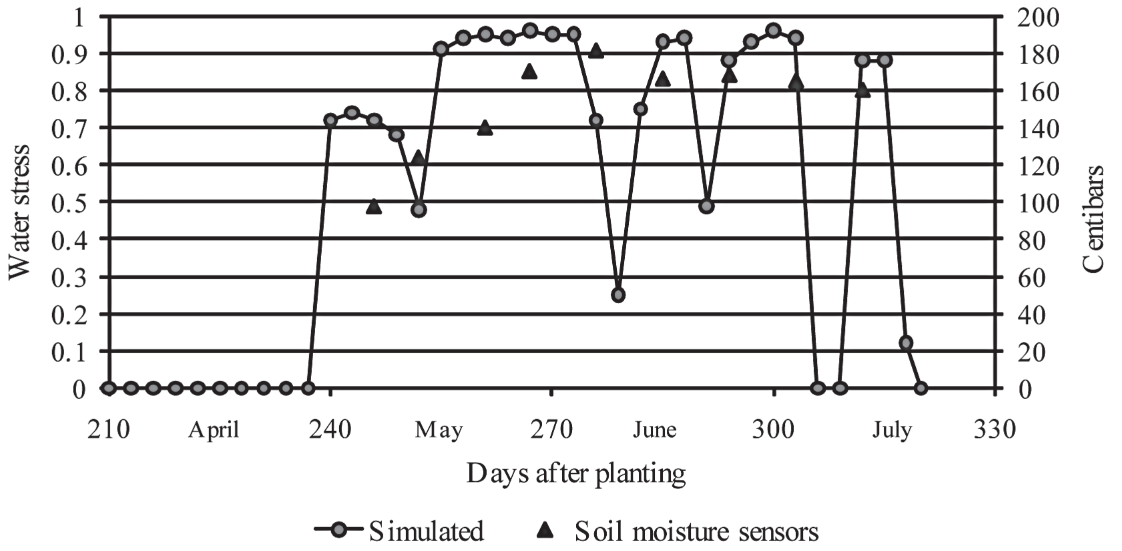
Figure 3. Simulated water stress and soil moisture sensors in the winter wheat cv. 'Ada' in the traditional growing system

Dotnuva, 2007

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 moistures 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 moisture sensors "Watermark" ceased exhibiting water shortage.

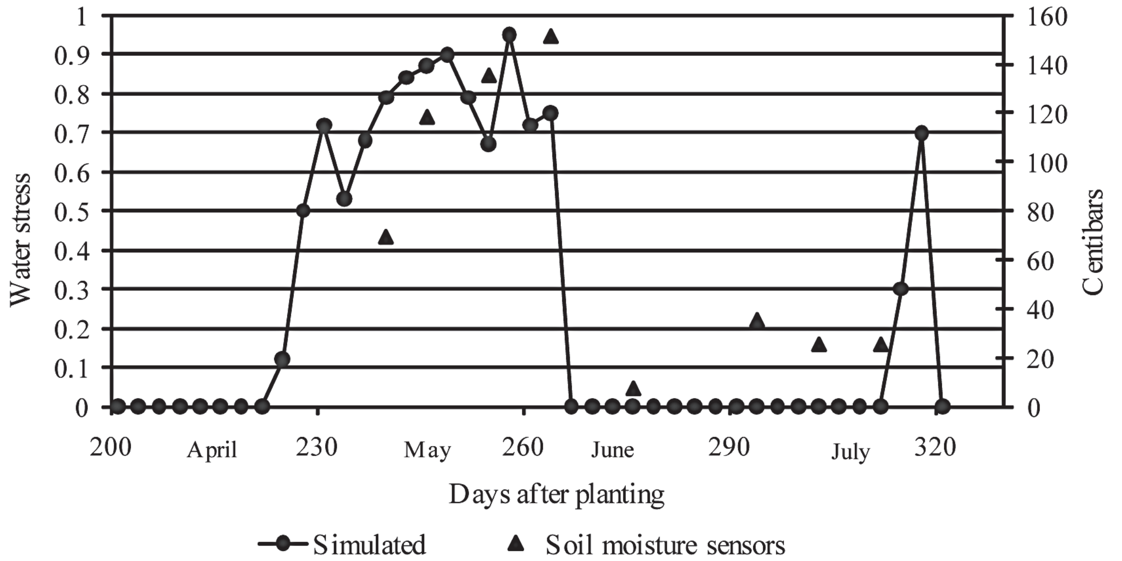
Water availability is a highly relevant factor in the formation of winter wheat yield; however, it is not always easy to correlate it directly with actual grain yield level. In field experiments of Behera and Panda (2009) with winter wheat grown under different levels of NPK fertilisers and irrigation 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.



Note. 1 – maximum stress, 0 – no stress.

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

Dotnuva, 2008



Note. 1 – maximum stress, 0 – no stress.

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.

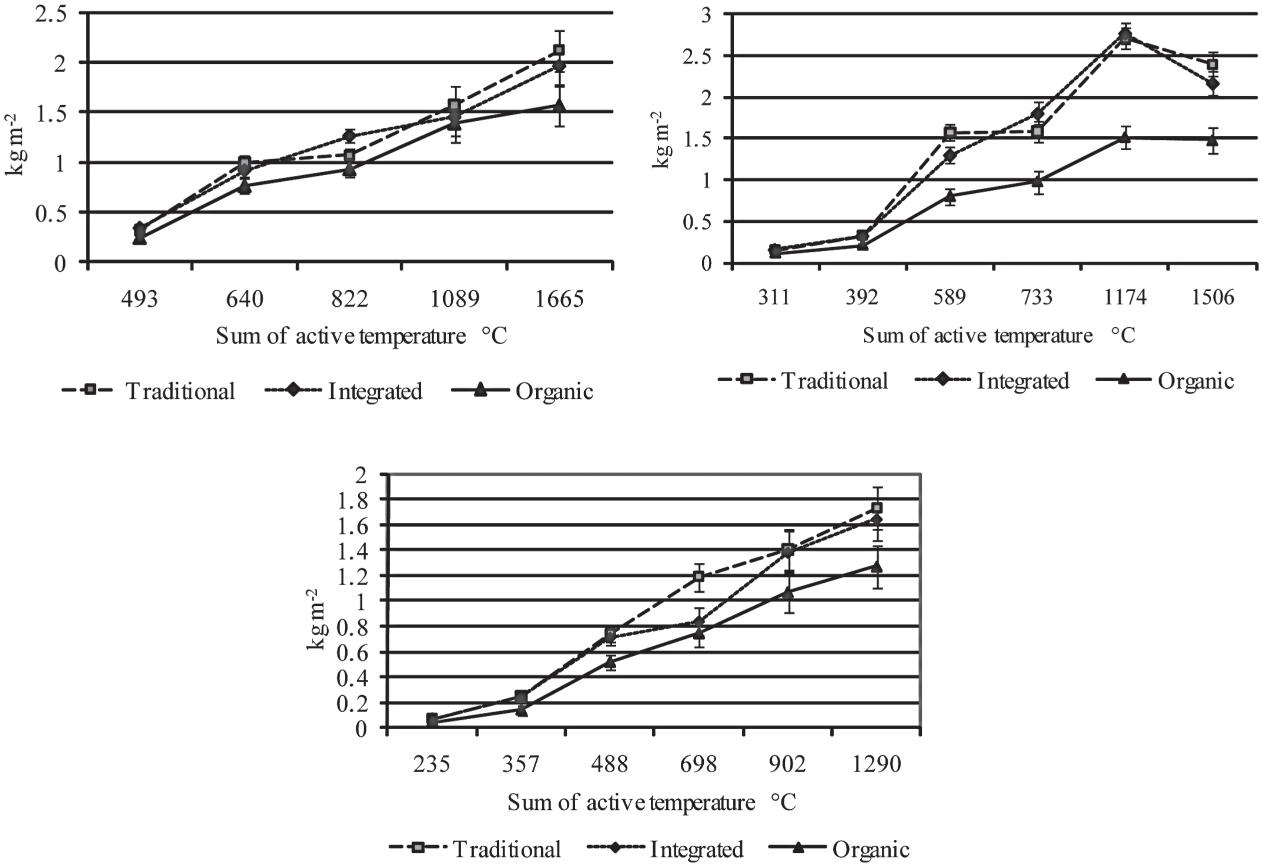


Figure 6. The accumulation of biomass of winter wheat cv. 'Ada' in different growing systems
Dotnuva, 2007–2009

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.

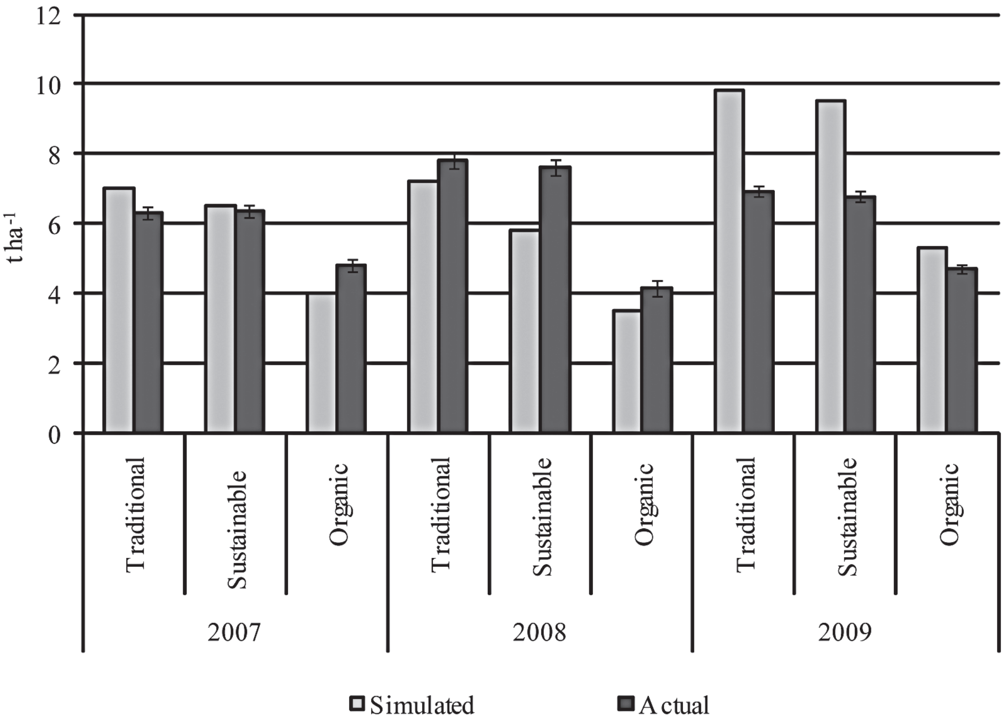


Figure 7. Simulated and actual grain yield of the winter wheat cv. 'Ada' during 2007–2009

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.

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Žieminių kviečių produktyvumas priklausomai nuo drėgmės pasiekiamumo ir auginimo intensyvumo

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Santrauka

Tyrimo tikslas – ištirti drėgmės pasiekiamumo reikšmę skirtingu intensyvumu augintų žieminių kviečių produktyvumui ir įvertinti modelio DSSAT v4.0.2.0 tinkamumą. Buvo atlikta 1989–1991 ir 2007–2009 m. Lietuvos žemdirbystės institute, Dotnuvoje, vykdytų žieminio kviečio (*Triticum aestivum* L.) lauko bandymų duomenų analizė. Dirvožemis – lengvo priemolio rudžemis (RDg8-k2).

Modelio apskaičiuotas ir lauko bandymuose išaugintų veislės ʽŠirvinta 1’ žieminių kviečių, pavasarį patręštų N_{60} trąšų, grūdų derlius 1989, 1990 bei 1991 m. parodė stiprų koreliacinį ryšį (determinacijos koeficientas $R^2 = 0,81$) ir gerą duomenų sklaidos atitikimą 1:1 linijai. Tačiau azotu netręštuose laukeliuose modelis apskaičiavo mažesnį nei faktinis grūdų derlių.

2007–2009 m. atliktų bandymų metu veislės ʽAda’ žieminiai kviečiai auginti nevienodu intensyvumu, taikant tradicinę, tausojamąją ir ekologinę žemdirbystės sistemas. Dirvožemio drėgmei matuoti buvo įrengti dirvos drėgmės sensoriai „Watermark“, vandens stresas apskaičiuotas modeliu DSSAT v4.0.2.0. Tyrimai parodė, kad modeliui apskaičiavus vandens stresą ir dirvožemio drėgmės sensoriams užfiksavus dirvos drėgmės stygių gautas panašus vertinimas, tad šios priemonės gali būti naudingos vandens pasiekiamumo žieminių kviečių pasėliuose stebėsenai. Žieminių kviečių biomasės kaupimasis ir lauko bandymų grūdų derlius priklausė nuo auginimo intensyvumo bei drėgmės išteklių vegetacijos metu ir šių veiksnių sąveikos. Modelis DSSAT v4.0.2.0 gerai apskaičiavo azotu patręštų žieminių kviečių grūdų derlių tais metais, kai reikšmingo vandens streso nenustatyta. Tačiau azotu netręštuose pasėliuose ir metais, kai vyravo ilgesni sausringi periodai, modelio skaičiavimo tikslumas sumažėjo.

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