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The application of AgroMetShell model for the analysis and prediction of spring barley productivity in Lithuania

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Abstract

The study deals with the capability of the AgroMetShell model to analyse and predict the spring barley (*Hordeum vulgare* L.) productivity in the whole territory of Lithuania. The data used in this study covers the 2000–2009 period and represents observed meteorological and environmental variables as well as specific soil water balance parameters from the AgroMetShell model. Although the individual annual productivity differences between the actual and simulated values in different agroclimatic regions had opposite signs, the mean simulated productivity in Lithuania is slightly higher (~1.2%) than the actual. Minimum differences were found in agroclimatic region I, while region III shows the highest differences in productivity. The modelling results revealed that the variation range of the actual crop productivity is 1.2–2.4 times higher than the simulated one in all analyzed territory. It is assumed that these productivity simulation errors are influenced by the effect of the whole complex of meteorological factors, including those that are not related to the model input parameters. Nevertheless, the results presented in the paper led to the conclusion that the AgroMetShell model is applicable in various agro-climatic regions of Lithuania.

According to the regional CCLM (COSMO Climate Limited-area Model) output data obtained from the two greenhouse gases emission scenarios A1B and B1, the plausible changes of spring barley productivity during the 21st century were modelled with the AgroMetShell model. Under both scenarios, by the end of the century the productivity of spring barley is expected to increase in larger part of Lithuania, except Tel iai, Utena and Vilnius districts where the highest fluctuation in productivity is expected to occur till 2030, however in later years the rate of changes will slow down.

Key words: AgroMetShell model, *Hordeum vulgare*, climate change, Lithuanian crop simulation, multiple regressions, environment monitoring.

Introduction

Due to limited water resources, arable land and pasture quality degradation, desertification, deforestation and pollution the global food supply safety is becoming an increasing challenge for both the United Nations and countries of specific regions (Minamiguchi, 2004; Challinor et al., 2005; Narendra, 2008). While some countries are still producing too much food, many others, especially less developed ones with a large population suffer from permanent food and other essential commodity shortage.

The development of agricultural monitoring and modelling systems was mostly associated with food security and nutrition policy (Vecchia et al., 2007). The high variability of environmental conditions has prompted development of the agroclimatic models that help to maintain a normal level of crop productivity in many parts of the world. An increase in frequency of weather extremes and interannual crop productivity in Lithuania confirms the necessity of the climate and crop productivity complex research.

Most of the papers concerning this research topic were prepared by the scientists from the Lithuanian Institute of Agriculture and the Lithuanian Institute of Agrarian Economics (Juščenko et al., 2001; Povilaitis et al., 2008; Kriščiukaitienė et al., 2009; Povilaitis et al., 2009). The Decision Support System for Agrotechnology Transfer model DSSAT v4 has been widely applied in different countries for crop productivity simulation and prediction for more than 20 years, particularly in the areas where irrigation is seen as the crucial measure to intensify cropping systems (Lhomme, Katerji, 1991; Araya, 2005; Sau et al., 2004).

The research done at the Lithuanian Institute of Agriculture (2006–2007) showed that DSSAT model in its hindcast overestimated the spring barley grain weight and produced a large deviation of simulated productivity from its actual range. Therefore, the scientists decided that the effectiveness of the model depends on the additional examination of the soil characteristics (Povilaitis et al., 2009).

Developed in the end of the 20th century and regularly improved global climate models allow prediction of many hydro-meteorological characteristics. Furthermore, fast developing computing technology and increasing awareness about climate systems changes are able to produce more accurate climate predictions (Rimkus et al., 2009). The downscaling of the climate predictions for Lithuanian territory was already applied in the last decade of last century.

Agroclimatic models are still heavily used in Lithuanian agrometeorological research. Specialists responsible for agriculture business and economy development in Lithuanian institutions as well as policy makers and scientists are very interested in how agricultural business can be adapted to regional climate. This paper focuses on the problem concerning extreme weather impact on crop productivity.

According to several studies (Hughes, 2000; Lenoir et al., 2008), the climate change has already induced the crop vegetation response. Changes in the amount and pattern of precipitation may result in flooding and drought. Other effects may include changes in agricultural yield, addition of new trade routes; reduced summer stream flows, species extinctions, and increases in the range of disease vectors (Understanding…, 2008). Although the consensus is that climate is changing on a global scale, the change on a regional or local scale is often more subtle and variable (Aasa et al., 2004; Bukantis, Bartkevičienė, 2005). Global climate change is mostly evaluated using the changes of annual average ambient temperature indicators; however, regional climate scenarios are not always consistent with global indicators (Saue, Kadaja, 2009). Consequently, the search for, and identification of, clear and unambiguous indicators of the impact of global climate change at a regional or local level is of vital importance.

The changing climate impact on agricultural crops in Lithuania was first discussed in a scientific paper of Bukantis and Rimkus (1996). Other studies have revealed that the increase in temperature during the vegetation period can significantly reduce the productivity of spring barley (Kriščiukaitienė et al., 2009). However, the real effect of changing climate on Lithuanian agricultural crops is still not clear.

The main task of this study was to test the AgroMetShell model for the spring barley productivity prediction in the territory of Lithuania.

Materials and methods

Data. The research involves environmental data and meteorological data obtained form 16 Lithuanian meteorological stations for the period 2000–2009. As required by the model's characteristics, ten-day meteorological data were used: mean ten-day air temperature, absolute ten-day air temperature minimum and maximum, absolute ten-day wind speed, ten-day precipitation amount etc. (Table 1).

Table 1. Environmental and meteorological data used in the AgroMetShell model

Environmental data	Meteorological data
1) soil water holding capacity, mm	1) mean, minimal and maximal air temperature, °C
2) the productivity of spring barley, kg ha^{-1}	2) precipitation amount, mm
3) phenological phase dates of spring barley phenological phases	3) potential evapotranspiration, mm
(initial, vegetative, flowering and ripening)	4) mean and maximal wind speed, m s^{-1}
	5) sunshine duration, hours
	6) relative humidity, %

The spring barley was selected for the investigation because it is the main summer cereal species in Lithuania (Agroclimatic manual, 1999). Yield information for each region was taken from the Lithuanian Department of Statistics. The species suitable for Lithuanian climatic condition and resistant to frost are: 'Aura DS' (developed in Lithuania), 'Beatrix', 'NFC Tipple' and 'Kangoo'.

AgroMetShell model. The AgroMetShell model is a joint collaboration product developed by the Agrometeorology Group, Environment and Natural Resources Service, Food and Agriculture Organization of the United Nations Regional Early Warning System (Mukhala, Hoefsloot, 2004). It is a regional crop forecasting toolbox mostly applied over large administrative units in various countries. The model allows calculation of the crop water balance and estimation when crop can suffer from the shortage of water which eventually leads to reduction in crop yield based on rainfall, evaporation and yield data.

The growth of the AgroMetShell began in 1980 trying to create a tool which may help to calculate the crop yield for early warning purposes. At that time this model was called FAOINDEX, but over the time it was developed and finally got the AgroMetShell name (Mukhala, Hoefsloot, 2004).

The 30 years of experience shows that the AgroMetShell model is able to transform pure meteorological observations into value-added indices (like the water satisfaction index – WSI) for crop (maize, millet, sorghum, beans, wheat and two species of rice) productivity forecasting. The essence of WSI is the calculation of specific soil water balance (Grieser et al., 2006).

For example, in Turkey the AgroMetShell model was used to calculate WSI and to create a total yield forecast map. The high statistical relationship (correlation coefficient $r^2 = 0.9067$) between forecasted and actual yield was obtained. Probably due to the high forecast verification the AgroMetShell model has been used in Turkey till now (Simsek et al., 2007). Moreover, the AgroMetShell model is widely applied in different climatic conditions and was successfully adapted and used for crop production modelling in Africa (Malawi, Kenya, Zimbabwe), Asia (Bangladesh, Cambodia, Azerbaijan, Georgia, Armenia) and Europe (Turkey, Italy) (Rojas, 2007).

Recently the AgroMetShell model has been introduced in research by the scientists of the Lithuanian Institute of Agriculture for converting solar luminosity to solar radiation (Povilaitis et al., 2008). The research on crop productivity simulation applying the AgroMetShell model described in this paper has been done for the first time in Lithuania.

To test AgroMetShell model and specific soil water balance module suitability, the territory of Lithuania was divided into three agroclimatic regions, shown in Figure 1. The first agroclimatic region is considered to be the coolest, the second – moderate and the third – the warmest. Subregions (a), (b), (c), (d) and (e) are less different in climate and in this research were not analyzed separately.

Figure 1. Agroclimatic regions of Lithuania

Because of the high spatial variability of the simulated crop productivity within one agroclimatic region, for future crop productivity analysis AgroMetShell model and its modules were applied for different meteorological stations which represent an exact region – Utena, Vilnius, etc.

Specific soil water balance data computed with the AgroMetShell model was used for Principal Component Analysis (PCA) – this function is built in the AgroMetShell model. PCA is a useful statistical technique which selects the most important components between crop productivity and selected meteorological variable (correlation coefficient has to exceed |0.7|). Selected components were used for making multiple regression equations (1–3 formulas) to forecast the spring barley productivity for each agroclimatic region:

$$Y_{I} = (-1,449 \cdot WEX_{flow}) + (-5,851 \cdot WEX_{tot}) + (58,908 \cdot ETA_{flow}) + (-37,185 \cdot ETA_{tot}) + (0 \cdot DEF_{veg}) + (50,059 \cdot DEF_{rip}) + (-13,100 \cdot DEF_{flow}) + (-0,133 \cdot DEF_{tot}) + (14,959 \cdot WSI) + 3810,600 \quad (1),$$

$$Y_{II} = (-3,888 \cdot WEX_{tot}) + (39,744 \cdot ETA_{flow}) + (19,604 \cdot ETA_{veg}) + (-17,461 \cdot ETA_{tot}) + (-25,900 \cdot DEF_{flow}) + (11,053 \cdot DEF_{tot}) + (-20,529 \cdot WSI) + 2466,110 \quad (2),$$

$$Y_{III} = (2,838 \cdot WEX_{rip}) + (-0,721 \cdot WEX_{flow}) + (-3,534 \cdot WEX_{tot}) + (-3,393 \cdot ETA_{rip}) + (4,470 \cdot ETA_{flow}) + (2,567 \cdot ETA_{tot}) + (-36,765 \cdot DEF_{veg}) + (-1,891 \cdot DEF_{rip}) + (1,767 \cdot DEF_{flow}) + (29,324 \cdot WSI) - 1897,800 \quad (3),$$

where *Y* – productivity of spring barley (kg ha^{-1}) in first (I), second (II) and third (III) agroclimatic region, *WSI* – water satisfaction index, *DEF* – water deficit (mm), *ETA* – total actual evapotranspiration (mm), *WEX* – total water surplus (mm). The corresponding index values: *tot* – characteristic length of the total growing season, *ini* – of initial phase, *flow* – of flowering stage, *veg* – of vegetation stage, *rip* – of ripening stage. Ten year period was chosen to highlight the differences in growing seasons with different meteorological conditions (Table 2).

The sensitivity test was made for the productivity of spring barley artificially increasing and reducing the following input variables: a) soil water holding capacity, b) precipitation amount, c) mean air temperature.

The simulation of spring barley productivity for 2001–2100 was made following CCLM model's output data: mean monthly air temperature and monthly precipitation amount. These characteristics were used as input data in the AgrometShell model. The CCLM is a nonhydrostatic regional climate model, developed in the German Weather Service in 1999, which is still being used as the basis for Lokal modell (Domms, Schättler, 2002; Steppeler et al., 2003). The model is constantly being improved by COSMO (The Consortium for Small-scale Modelling) consortium, which includes weather services from seven European countries. CCLM is used for climate diagnostics and climate change analysis in Germany since 2005. These kind of models can dynamically increase the resolution of global models output grid. In order to better reveal the changes of meteorological parameters, the 21st century was divided into three periods (2001–2030, 2031–2060, 2061–2100). The productivity was assessed using differences between anomalies of spring barley productivity using 2000–2009 data.

Table 2. Phenological and meteorological characteristics of analysed years

2000
The beginning of the vegetation season in all agroclimatic regions was 2.2–3.2°C warmer than normal. Summer was slightly cooler. Precipitation amount in I agroclimatic region was below the 1961–1990 climatology (92%), in II and III – above climatology (115% and 150%, respectively). The productivity of the spring barley was close to normal.
2001
The vegetation season in all agroclimatic regions was warmer (1.0–2.0°C) and wetter (125%) and sunnier (120%) than normal. The productivity of spring barley was slightly below the average (2000–2009).
2002
The beginning of the vegetation season was very dry. The vegetation season in all agroclimatic regions was quite warmer (3.5°C) and sunnier than normal. The precipitation sum deviations from climatology in regions were smaller. Such meteorological conditions caused favourable conditions for drought in many regions of Lithuania.
2003
The vegetation season in all agroclimatic regions was warmer (1.0–1.3°C) and sunnier than normal. The precipitation sum deviations from climatology in all agroclimatic regions were smaller. Such meteorological conditions caused relative higher productivity level of spring yield.
2004
The vegetation season in I agroclimatic region was the coolest, the driest and the sunniest one. In II region – less cool and wetter, but least sunny, while III region was moderately cool, sunny and wet in comparison with 1961–1990 climatology. The highest spring barley productivity in I and II regions was the highest throughout the analysed period.
2005
There were no significant insolation and air temperature deviations from climatology, however spatial and temporal differences in precipitation were high: precipitation amounts only 70% of all vegetation season norm, while 96% amounts in II and 147% – in III agroclimatic region.
2006
Comparatively high soil and air temperature, the lack of precipitation and high incoming solar radiation inflow caused favourable conditions for drought in many regions of Lithuania. Poorest productivity of spring barley throughout analysed period.
2007
The vegetation season in I agroclimatic region was the wettest one. In II and III regions there were no significant precipitation amount anomalies. The air temperature and the insolation were close to the climatology.
2008
The vegetation season in all agroclimatic regions was warmer (1.5–2.0°C) and sunnier than normal. The precipitation sum deviations from climatology in agroclimatic regions were quite different – 80% of all vegetation season precipitation amount in I agroclimatic region, 100% – in II and 150% – in III.
2009
The vegetation season in all agroclimatic regions was slightly warmer (1.0°C), wetter (125%) and sunnier (120%) than normal. In II agroclimatic region it was the year with the highest spring barley productivity.

Results and discussion

The spring barley simulation results. The analysis of the AgroMetShell model simulated and actual spring barley productivity, firstly, shows that model simulated productivity differs from actual. The smallest differences between actual and simulated productivity are in I agroclimatic region: the differences account for 10% of the average productivity which is very low, whereas the interannual actual spring barley productivity in this district fluctuates in about 50% according to 2000–2009 mean productivity. In II agroclimatic region, the differences between actual and model simulated productivity is about 32%, while annual actual productivity varies in 47%. Finally, in III region the consistence between simulate and actual is 42% and 63%, respectively.

Although the annual differences between the actual and model simulated productivity in different agroclimatic regions had opposite signs, the average model simulated productivity in Lithuania is a little higher (~1.2%) than the actual. The smallest differences were in I agroclimatic region (0.3%), while the highest were in III region (2.8%).

Analyzing the differences between actual and AgroMetShell model simulated productivity of spring barley, the attention was drawn to the droughts in Lithuania (2002 and 2006): in all agroclimatic regions model simulated productivity was higher than actual. During drought, at high temperatures the rainfall efficiency declines (plants cannot use the rain water because of rapid evaporation). Moreover, the territory where rain falls can differ in size from the territory used for yield simulation. In contrast, in relatively wet and warm years (2004 and 2009) the model simulated productivity was lower than actual (Fig. 2 a–c). Furthermore, the difference of actual spring barley productivity between agroclimatic regions is 1.2–2.4 times larger than the simulated difference (first region differs by 1.2 times, second by 2.2 and third by 2.4 times). This means that under the extreme weather conditions the AgroMetShell model underestimates the productivity of spring barley.

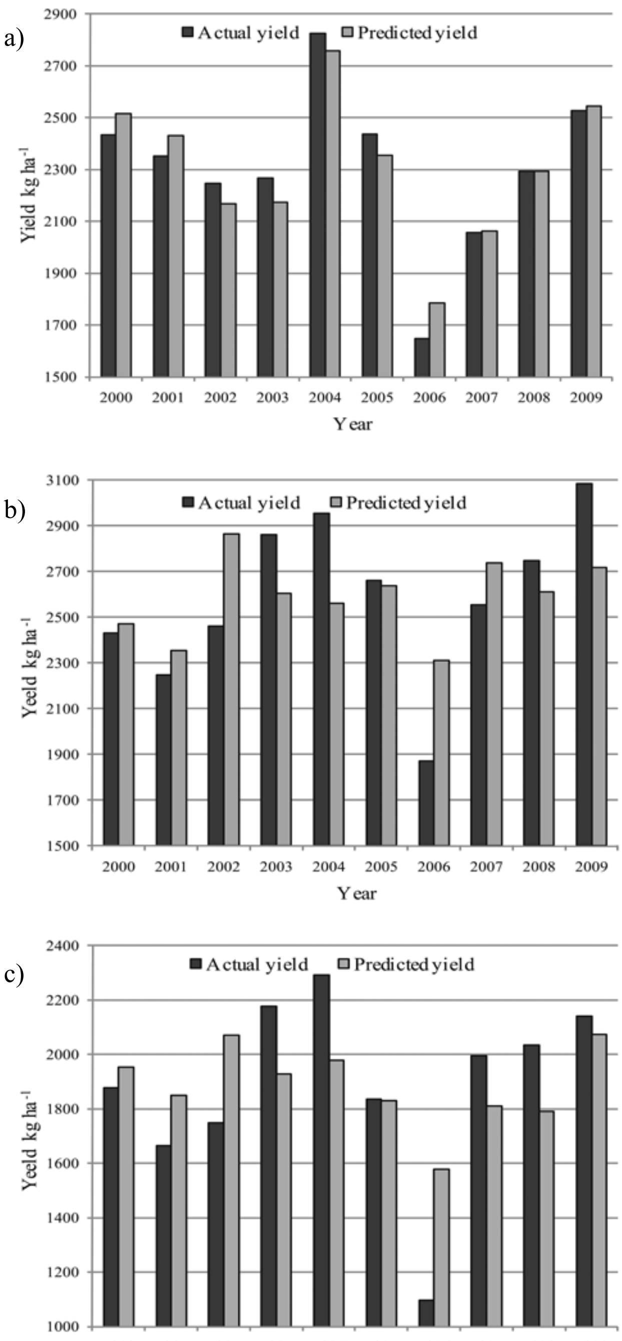


Figure 2. Simulated by AgroMetShell model and actual spring barley productivity in all agroclimatic regions (a – I, b – II, c – III)

It is well known that positive precipitation and negative air temperature anomaly negatively affect crop productivity, while moderately humid and warm season increments the crop productivity. This theory is clearly visible in the column of 2006 – in dry year, higher rainfall ensures adequate moisture for crops and thereby increases productivity (Fig. 3). It shows the differences between the actual and simulated spring barley productivity in separate agroclimatic regions. Two additional simulations were done with artificially increased and decreased amount of precipitation (±5 mm). However, in dry year the AgroMetShell model still simulated higher productivity of spring barley than the actual. Also, there were found large productivity differences between agroclimatic regions, when the temperature was artificially corrected in the model. Therefore, the analysis showed that the effect of separate meteorological and geographical characteristics on crop productivity is ambiguous in all agroclimatic regions – it is possibly influenced by a whole complex of meteorological elements (intensity of solar radiation, air humidity, wind speed, soil temperature, etc.).

The simulation of spring barley productivity for 2001–2100. The future spring barley productivity modelling is based on the A1B and B1 emission scenarios, where B1 is a low-emission scenario (considered to be the 'best case') and A1B is a relatively high-emission scenario (Rimkus et al., 2011; Veriankaitė et al., 2010). Simultaneous studies using greenhouse gasses scenarios (A1B and B1) output data were also done in other countries of the world (Mearns et al., 1999; Southworth et al., 2000; Stone et al., 2003).

According to CCLM model's output data the sum of precipitation in Lithuania is going to grow during the 21st century (Rimkus et al., 2007). If the emission of greenhouse gases varies depending on the A1B scenario, the precipitation sum will increase by 5–22% till the end of the 21st century, and if it changes according to the B1 scenario, it will increase by 5–17%: the largest changes are expected in the coastal area, while the least ones in the south-western part of Lithuania.

According to the A1B scenario, CCLM model predicts high positive temperature changes (up to 3.8°C compared with 1961–1991 climatology) till the end of the 21st century, while changes up to 2.5°C are expected under B1 scenario (Fig. 4). Future precipitation changes will have different signs in the coastal area and the rest of the territory of Lithuania during vegetation season. Therefore, increase in air temperature and decrease in precipitation in a large part of Lithuania will produce unfavourable crop growing conditions (Rimkus et al., 2007).

Model simulation under A1B scenario revealed the permanent decline of spring barley productivity at the end of the 21st century. However, the lowest changes in productivity are simulated in the middle part of Lithuania or in II agroclimatic region (absolute values vary from 2% to 8% compared with 2000–2009 climatology), while the highest productivity loss is expected in Šilalė, Šiauliai and Biržai regions (up to 14–22%).

Simulated changes under B1 scenario show significant increase in spring barley productivity during all 21st century in Tel iai, Utena and Vilnius regions (10–18%). However, expected crop productivity increase trend appears to be varied in different periods: the highest productivity of spring barley should be expected in 2031–2060, and latter it will slightly decrease (Fig. 5). Other regions (Kaunas, Kėdainiai, Panevėžys, Raseiniai, Šiauliai, Šilalė, Ukmergė, Varėna and Vilkaviškis) show small differences of crop productivity (1–8%), while significant decrease is expected only in Biržai region (up to 14%).

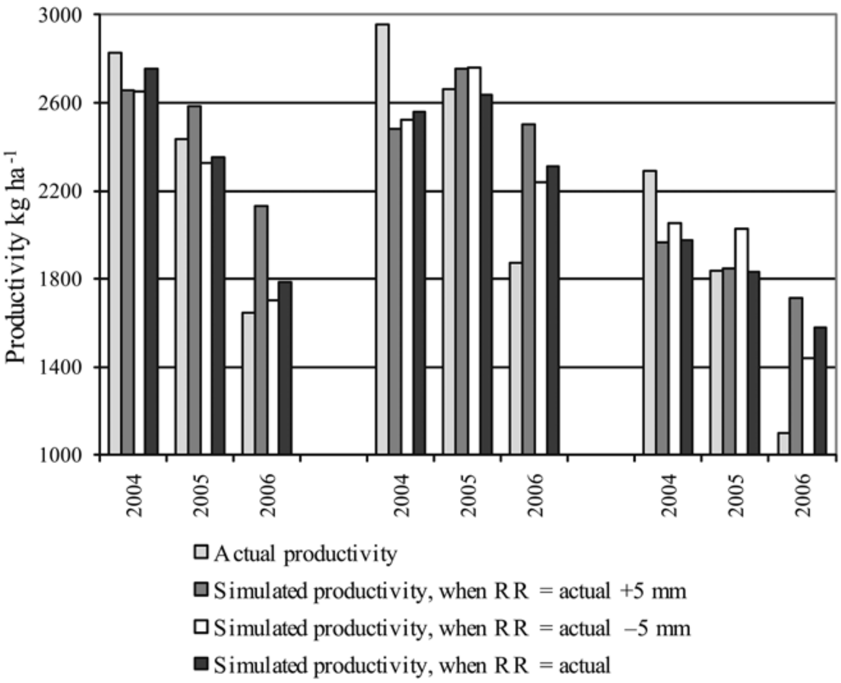
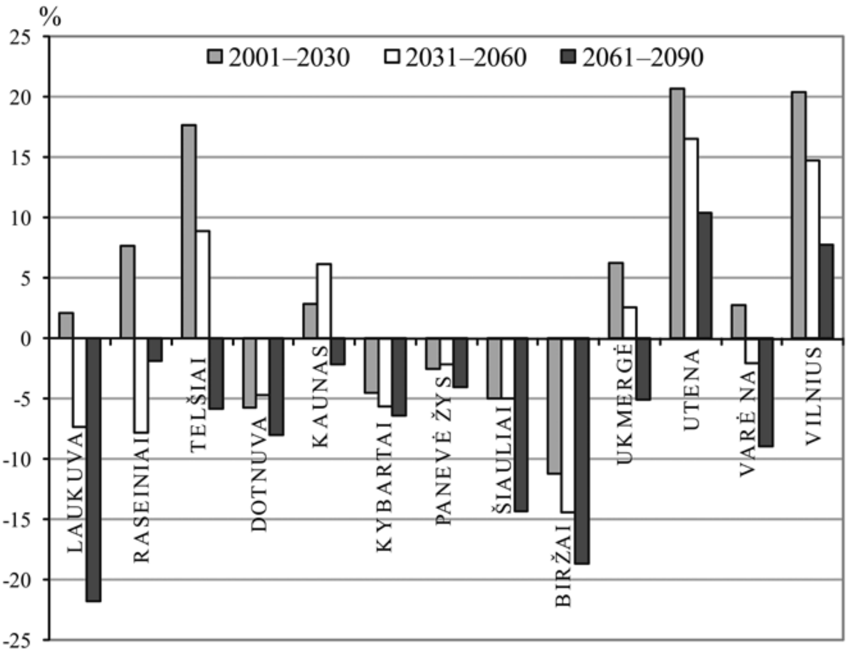


Figure 3. Actual and simulated spring barley productivity in different agroclimatic regions (I region is on the left, II – in the middle, III – on the right) of 5 mm higher and lower total precipitation for each ten-day period (marked RR in the legend)

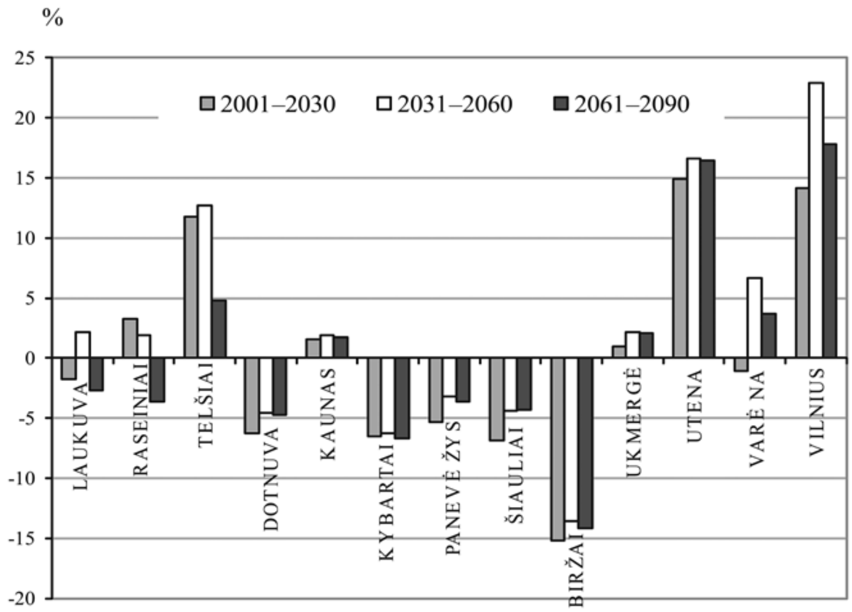


Note. The changes were calculated on the basis of CCLM and AgroMetShell output data.

Figure 4. The AgroMetShell model simulated changes (in percent of 2000–2009 climatology) of spring barley productivity using A1B scenario for the 21st century (I agroclimatic region – Laukuva, Raseiniai, Telšiai, II – Dotnuva, Kaunas, Kybartai, Panevėžys, Šiauliai, III – Biržai, Ukmergė, Utena, Varėna, Vilnius)

All the regional differences in spring barley productivity can be determined by different soil characteristics and microclimate features.

Earlier studies showed similar results (Kriščiukaitienė et al., 2009; Saue, Kadaja, 2009). Higher temperature of the growing season and rainfall deficiency significantly reduce spring barley productivity, because higher air and soil temperature accelerates the development of separate parts of plants, shortens the duration of phenological phases and finally reduces biomass production.



Note. The changes were calculated on the basis of CCLM and AgroMetShell output data.

Figure 5. The AgroMetShell model simulated changes (deviations from 2000–2009 climatology) of spring barley productivity using B1 greenhouse gases emission scenario for the 21st century (I agroclimatic region – Laukuva, Raseiniai, Telšiai, II – Dotnuva, Kaunas, Kybartai, Panevėžys, Šiauliai, III – Biržai, Ukmergė, Utena, Varėna, Vilnius)

Conclusions

1. The AgroMetShell model is applicable for large administrative units for crop-yield predictions on the national level; it is inexpensive to implement and to adapt to local conditions. It represents an essential tool for assessing the impact of climatic conditions on crops, climatic risk analysis and for regional crop yield forecasting.

2. According to 2000–2009 data, the differences between the actual and model simulated productivity in different Lithuanian agroclimatic regions had opposite signs, the model simulated productivity on average was slightly higher (~1.2%) than the actual. The amplitudes of simulated spring barley productivity are 1.2–2.4 times lower than those of the actual productivity: 1.2 times lower in the first agroclimatic region, 2.2 times – in the second and 2.4 times lower in the third region. This suggests that the model is unable to simulate the effect of extreme agrometeorological conditions on the spring barley productivity.

3. The analysis of the effect of the individual meteorological and environmental characteristics on simulated crop productivity showed the irrelevant relationship between the analysed characteristics in all agroclimatic regions and led to the implication that crop productivity is an outcome of the whole complex of meteorological elements.

4. The loss of spring barley productivity at the end of the 21st century is expected using the A1B scenario, particularly in Šilalė, Šiauliai and Biržai. Minor changes are expected in Middle Lithuanian Lowland (Kaunas, Kėdainiai, Panevėžys and Vilkaviškis). According to the B1 scenario, the AgroMetShell model simulates a significant increase in spring barley productivity in particular regions of Tel iai, Utena and Vilnius, while the rest of Lithuania's territory will experience insignificant changes.

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Modelio „AgroMetShell“ taikymas vasarinių miežių derlingumui modeliuoti Lietuvoje

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Santrauka

Vasarinio miežio (*Hordeum vulgare* L.) derlingumo modeliavimo ir prognozavimo modeliu „AgroMetShell“ galimybių tyrimai atlikti visai Lietuvos teritorijai, remiantis 2000–2009 m. meteorologiniais bei gamtiniais-geografiniais ir modelio „AgroMetShell“ savitojo dirvos drėgmės balanso išvesties rezultatų duomenimis. Nors kasmetiniai faktinio ir modeliu prognozuoto derlingumo skirtumai įvairaus agroklimato rajonuose turi priešingus ženklus, vidutinis prognozuotas analizuojamo laikotarpio derlingumas visoje Lietuvoje yra nedaug (~1,2 %) didesnis už faktinį. Faktinio ir prognozuoto derlingumo mažiausi skirtumai yra I agroklimato rajone, didžiausi – III. Nustatyta, jog faktinio derlingumo svyravimų amplitudė visuose agroklimato rajonuose yra 1,2–2,4 karto didesnė nei prognozuoto modeliu „AgroMetShell“. Darytina prielaida, kad šį derlingumo skirtumą lemia kompleksinis visų meteorologinių veiksnių, įskaitant ir nesančius modelio įvesties parametruose, poveikis. Nepaisant to, straipsnyje pateikiami rezultatai leidžia daryti išvadą, kad modelis „AgroMetShell“ gali būti taikomas įvairiuose Lietuvos agroklimatiniuose rajonuose.

Remiantis regioninio CCLM (COSMO Climate Limited-area Model) modelio išvesties duomenimis, gautais dviejų šiltnamio dujų emisijų scenarijų A1B ir B1 pagrindu, modeliu „AgrometShell“ sumodeliuoti tikėtini vasarinių miežių derlingumo pokyčiai XXI a. Abiejų scenarijų duomenimis, vasarinių miežių derlingumas iki XXI a. pabaigos turėtų didėti visoje Lietuvoje, išskyrus Telšių, Utenos ir Vilniaus rajonus, kuriuose didžiausia derlingumo kaita laukiama iki 2030 m., o vėliau pokyčių tempas lėtės.

Reikšminiai žodžiai: modelis „AgroMetShell“, *Hordeum vulgare*, derlingumo prognozavimas Lietuvoje, klimato kaita, tiesinė regresija, vasariniai miežiai, aplinkos stebėsena.