Effect of climate change on sowing and harvest dates of spring barley and maize in Poland**

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Abstract. Climate change and projected temperature increase is recognised to have significant impact on agricultural production and crop phenology. This study evaluated the climate change impact on sowing and harvest dates of spring barley and maize in the boundaries of two largest catchments in Poland – the Vistula and the Odra. For this purpose, an agro-hydrological Soil and Water Assessment Tool has been used, driven by climate forcing data provided within the Coordinated Downscaling Experiment – European Domain experiment projected to the year 2100 under two representative concentration pathways: 4.5 and 8.5. The projected warmer climate significantly affected the potential scheduling of agricultural practices, accelerating the occurrence of sowing and harvest dates. The rate of acceleration was dependent on the time horizon and representative concentration pathways scenario. In general, the rate of sowing/harvest advance was accelerating in time and, also from representative concentration pathways 4.5 to 8.5, reaching 23 days for spring barley and 30 days for maize (ensemble mean for the far future under representative concentration pathways 8.5).

Keywords: SWAT and EPIC models, phenology, heat units, temperature

INTRODUCTION

Climate change is widely recognised to have substantial impact on water quality (Glavan et al., 2015; Marcinkowski et al., 2017) and various economic sectors, including agriculture, which is highly vulnerable to temperature and precipitation changes (Albic et al., 2017; Gil et al., 2017; Møller et al., 2017). According to International Phenology Gardens (IPG), there is an average trend in Europe for particular phases to advance by approximately 2 days/decade from 1959 to 1996 (Menzel, 2000, 2006). Crop phenology is assumed to be one of the most important features involved in the final yield assessment and the adaptation of crops to the changing environmental conditions. The assessment of cropping systems response to a warmer climate plays a crucial role in the evaluation of future agricultural production potential, and the investigation of crop phenology response is a key stage for a better formulation of adaptation policies (Duchene and Schneider, 2005; Lipiec et al., 2013; Sadras and Monzon, 2006; Wolfe et al., 2005).

The occurrence of consecutive crop phenological phases may be assessed using numerical models of crop growth (Ma et al., 2012; Olesen and Bindi, 2002). In general, three groups of phenological models can be distinguished i.e. theoretical, statistical and mechanistic (Kozyra, 2013). The latter have become the most popular due to their usefulness for quantitative assessments of different environmental factors (e.g. temperature and precipitation change) impact on the timing of phenological phases (Cleland et al., 2007).

The objective of this paper is to provide a model-based assessment of the impact of projected climate change on sowing and harvest dates of spring barley and maize in Poland. The study looks into projected changes for two future time horizons within the 21st century (2021-2050 and 2071-2100) under the Representative Concentration Pathways (RCPs) 4.5 and 8.5, using an ensemble of nine bias-corrected EURO-CORDEX model scenarios. The Soil and Water Assessment Tool (SWAT) model incorporating the modified Erosion-Productivity Impact Calculator (EPIC) crop growth sub-model was used in this paper in order to analyse spatio-temporal variability in sowing and harvest dates.

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MATERIALS AND METHODS

This study is concentrated on the agricultural land within the Polish parts of two largest river basins in Poland, the Vistula and Odra basins (VOB), covering 87% of the Polish territory (Fig. 1). It investigates two important crops for Polish agriculture: spring barley and maize. Spring barley is the most common spring cereal in Poland. According to Agricultural Census Data (2002), spring cereals and maize accounted for 36% of cultivated area in Poland, of which, cereals occupied 31%. Maize has undergone tremendous change in terms of cultivated area: in the interval from 1996 to 2015, its area increased by an order of magnitude (from 69 000 to 670 000 ha). In this study, early ripening varieties of maize cultivated for silage were considered due to the lower risk of the loss of yield under the climatic conditions of Poland (Zaliwski and Hołaj, 2006).

SWAT is a process-based, continuous-time agro-hydrological model which simulates the movement of water on a catchment scale with a daily time step (Arnold et al., 1998). It integrates hydrological processes with the plant growth component based on a simplified version of the EPIC model (Williams et al., 1982). In EPIC, phenological plant development is based on daily accumulated heat units (growing degree days). In this study, we build upon the existing, extensively calibrated and validated SWAT model of the VOB (Piniewski et al., 2017).

In this study, SWAT model simulations were conducted in two steps. The first step included calibration and validation of the model as driven by interpolated meteorological data from the Polish and European monitoring network (Berezowski et al., 2016). In the second step, the climate projections data derived from Mezghani et al. (2017) were used as a forcing for both historical and future periods.

In SWAT, two different methods of agricultural operations scheduling are available. The first one is based on the Julian calendar and the model user has to define exact dates of each operation. The second method is based on heat unit theory (Bernard, 1948). This postulates that each plant has its own temperature range for growth. Crop growth is triggered once the daily average temperature exceeds the crop-specific minimum temperature. The growth rate gradually increases with temperature until the maximum temperature is exceeded which ceases the growth. According to the theory, the timing of the operations are expressed as fractions of user-defined potential heat units (PHU/PHU₀), which is the total number of heat units required for plant maturity. In this study, the heat unit method was used for agricultural operations scheduling.

Heat unit-based simulation of sowing and harvest dates in SWAT can be interpreted as an approximation of the corresponding phenological stages: beginning of growth and achieving crop maturity, respectively. The relationship between simulated dates and phenological phases is straightforward: crop emergence begins several days after sowing, whereas harvest takes place several days after reaching maturity. Projected changes in sowing dates can, therefore, be interpreted as proxies of changes in crop emergence, whereas changes in harvest dates act as proxies of changes in maturity.

In the current setup of the SWAT model created for the VOB, agricultural management calendars were defined for spring barley and maize (Piniewski et al., 2017). Base temperatures for heat unit calculation (T_BASE) were set to 5°C for spring barley and 8°C for maize, whereas the total number of heat units needed to bring plant to maturity (PHU_PLT) was set to 1 230 for spring barley and 1 200 for maize. In the heat unit method, the exact date of operation occurrence is varied from year to year, depending on the thermal conditions. Therefore, the crop-specific fraction of PHU and PHU₀ for a particular operation needs to be adjusted iteratively until reasonable and satisfactory occurrence dates are achieved. In the VOB, the fraction index was assumed satisfactory when at least 75% of observed sowing and harvest dates fell into crop-specific optimal dates range resulting from literature review (Dragańska et al., 2008; Kruczek and Sulewska, 2005; Sulek, 2009).

Fig. 1. Spatial distribution of selected crops in Poland (Agricultural Census, 2002) expressed as fractions of arable land cover at powiat level. Black line denotes the border of the Vistula and Odra basins. A – spring cereals, B – maize.
In order to analyse the correlation between the pheno-
logical phases and temperature, average temperature in-
dices were calculated in a crop-specific and development
stage-specific manner. For example, for spring barley, usu-
ally sown in March/April in Polish climatic conditions,
a pre-sowing average temperature for February–April
was calculated. Harvest of spring barley typically occurs
in July/August, so that the average temperature was cal-
culated for April–July. For maize, the temperatures were
calculated for February–May (pre-sowing) and June–
October (pre-harvest).

In this paper, SWAT is driven by climate forcing data
from the CHASE-PL Climate Projections: 5 km gridded dai-
ly precipitation and temperature dataset (CPLCP-GDPT5)
(Mezghani et al., 2017), consisting of nine bias-corrected
GCM-RCM runs provided within the EURO-CORDEX
experiment projected to the year 2100 under two RCPs: 4.5
and 8.5. The RCPs are families of scenarios dependent on
various assumptions about future socio-economic develop-
ment and greenhouse gases concentrations (Moss et al.,
2010). RCPs 4.5 and 8.5 correspond to two targeted radi-
ative forcing levels in year 2100 relative to pre-industrial
values: +4.5 and +8.5 W m⁻², respectively. These two RCPs
were selected because they are the most commonly used
in impact studies worldwide. A bias correction procedure
was based on the quantile mapping method developed by
the Norwegian Meteorological Institute (Gudmundsson et
al., 2012), and it concerned three time periods: 1971-2000,
2021-2050, and 2071-2100. The corresponding time hori-
zons will be hereafter referred to as historical period (ACT),
near future (NF) and far future (FF), respectively. Future
changes in planting and harvest dates were estimated as a
difference (in days) between respective future periods and
the historical (control) period. The model runs were carried
out assuming constant land use, in order to illustrate pure
climate change effect.

Projected mean annual temperature in Poland is expect-
ed to increase by approximately 1.1°C in NF and 2°C in
FF following the RCP4.5 according to the ensemble mean.
Comparing the seasonal variation, the highest change is
expected to occur in winter (2.5°C) and lowest in sum-
mer (1.7°C). Following the RCP8.5 emission scenario, the
temperature increase rate seem to accelerate substantially
in the second half of the century, reaching on average 3.6°C
in FF, whereas in NF, it is quite similar to RCP4.5 (1.3°C
vs. 1.1 °C).

RESULTS

Area-averaged sowing and harvest timing variability is
presented in box plots for each crop (Fig. 2A). The great
majority of simulation results falls in the threshold rang-
es for both operations. In some cases, they go beyond the
range, which is mainly caused by extremely cold and hot
years, which explicitly determines either delay or accelera-
tion of sowing and harvest. The lowest temporal variability
in the occurrence of phenological phases, and, consequent-
ly, the highest accuracy of simulation is noted for spring
barley. Slightly worse, but still satisfactory results were
obtained for maize. It should be noted that other authors
reported a very high inter-annual variability in maize matur-
ity and harvest stages in Poland, reaching even 6 weeks in
a 15-year long period (Dragańska et al., 2008). This sup-
ports a high variability in Fig. 2A (maize harvest date).

Spatial variability of sowing and harvest dates occur-
rence expressed as a mean value for the entire simulation
period at sub-basin level is presented in Fig. 2B. In general
terms, strong regionalisation of the occurrence of sowing
dates with an increasing gradient towards the north-east is
noted. It perfectly reflects the thermal conditions of Poland,
where in the north-east, the temperatures are lower due to
the influence of the continental climate and slightly higher
in the west, conditioned by the milder maritime climate.
The crop-specific range of the sowing dates across the
country spans for 30 days and occurs earlier for spring bar-
ley (80-110) and significantly later for maize (110-140).
Fairly similar trends are observed for the harvest which
occur earlier in the south and south-western part of Poland
and later in the north-eastern sub-basins. Regional diffe-
rences in harvest dates, likewise for sowing, span for 30
days reaching ranges 210-240 and 230-260, for spring bar-
ley and maize, respectively, which is in accordance with
general trends in literature.

Simulated multi-annual variability of area-averaged
sowing and harvest dates strongly correlates with tempe-
trature (R² ranging from 0.7 to 0.9) (Fig. 2C and D). High
variability in the timing of sowing and harvest is visible,
however, all fluctuations strongly follow thermal condi-
tions of crop-specific critical period in a given year.

Climate change is expected to advance sowing operation
of spring crops and harvest of the crops under considera-
tion (Fig. 3). The rate of sowing acceleration is diverse and
increases with the time horizon, reaching 4 days (NF) and
8 days (FF) for maize and 7 days (NF) to 16 days (FF) for
spring barley under RCP4.5. With RCP8.5, the signal of
change gets stronger and the acceleration of spring barley
sowing dates increases to 9 days (NF) and 22 days (FF).
For maize, the sowing advancement reaches 5 days and 10
days for NF and FF, respectively.

For harvest, the overall advance of its occurrence was
noted for both crops. Likewise for sowing, the effect of cli-
mate change increases with both time horizon and RCP. For
spring barley, under RCP4.5, the rate of acceleration reach-
es 8 days (NF) and 12 days (FF), whereas for maize – 13
days (NF) and 22 days (FF). The acceleration rate increases
under RCP8.5, reaching 10 days (NF) and 23 days (FF) for
spring barley, and 15 days (NF) and 30 days (FF) for maize.

Projected sowing and harvest dates of selected crops
indicate clear regionalisation of sowing and harvest which
follows the thermal conditions across the country (Fig. 4).
There is a strong gradient increasing from south-west to north-east describing the sowing dates acceleration, and from south to north for harvest. The signal of change increases in magnitude with time horizon and RCP, but maintains the spatial pattern. The overall acceleration of sowing and harvest in each horizon-RCP combination is comparable to the mean values presented in the box plots in Fig. 3.

**Fig. 2.** Box plots of spatially-averaged simulated sowing and harvest dates of selected crops. Green and yellow lines in panel A represent optimal ranges of sowing and harvest dates in Polish conditions. B - Spatial distribution of multi-annual mean sowing and harvest dates. White spaces in panel B correspond to low fractions of a given crop in particular areas (sub-basins). Mean annual sowing (green) and harvest (yellow) dates of spring barley (C) and maize (D). Red lines in panels C and D show inter-annual variability in mean temperature for crop-specific pre-sowing and pre-harvest periods.

**Fig. 3.** Box plots of sowing and harvest dates for NF and FF under RCP4.5 and 8.5. Variability in box plots represents multi-annual mean dates of nine ensemble members.

**DISCUSSION**

Simulated trends in sowing and harvest dates for the historical period in Poland are in line with studies reporting extension of the growing season and faster accumulation of the growing degree days (Graczyk and Kundzewicz, 2016; Wypych et al., 2017). A comparison of our results with similar studies reporting the impact of future climate
change on sowing and harvest dates is more difficult, however, as in every study different climate models, emission scenarios and time horizons are usually used. Olesen et al. (2012) investigated the impact of climate change on oats and maize using a statistical model driven by the ECHAM5 climate model under the A1B emission scenario for the years 2031-2050. The predicted advancement of sowing and harvest dates for Poland for this scenario was, in their study, in good agreement with the corresponding RCP8.5 NF scenario in our study. What is noteworthy, in both studies, fairly similar spatial variation of the sowing/harvest dates occurrence was noted, characterised by a clearly increasing gradient from south-west towards north-east. Rötter et al. (2011) conducted a similar study for spring barley in Finland, using the WOFOST model as driven by two emission scenarios: B1 and A1F1, for the years 2071-2100. They noted an acceleration of sowing dates reaching 14 days (B1) and 22 days (A1F1), which also corroborates our findings for corresponding scenarios RCP4.5 FF and RCP8.5 FF, respectively. Although our projections are in line with literature, the added value of our study is a higher spatial resolution, the use of a more recent emission scenario family (RCP instead of SRES) and a larger ensemble of climate models (nine instead of one and two in aforementioned studies).

Projections of changes in sowing and harvest dates in response to climate change are extremely important in the planning of agricultural production and adaptation and mitigation strategy (Kozyra, 2013). Significant shifts in the beginning and duration of growing season might significantly affect crop yields (Rötter et al., 2011). For example, Parker et al. (2016) reported that earlier sowing of maize in Germany under warming conditions might result in greater yields due to extended growing period. On the other hand, Eitzinger et al. (2013) revealed that yields are expected to decrease under climate change in Central and Eastern

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**Fig. 4.** Spatial distribution of the multi-annual mean sowing (A) and harvest (B) dates for the historical period (Act) and two future horizons, NF and FF, under RCP4.5 and 8.5, according to the ensemble mean. White spaces correspond to low fractions of a given crop in particular areas.
Europe if there is no adaptation strategy applied. They pointed out that adaptation should be related to altered production techniques that affect the water balance/demand of crops, the effective use of soil and water resources and the adapted crop timing and selection. Actually, adaptation of timing of management practices by farmers has already been noted in Poland (Blecharczyk et al., 2016). In general, since the expected future dynamics of changes in agroclimatic indices in Central and Eastern Europe is going to be very high, continuous, adaptive management should be a way forward (Trnka et al., 2009).

Among the several limitations of this study, one has to note that the applied model does not take into consideration precipitation conditions suitable for management operations (Eitzinger et al., 2013). Moisture conditions from the practical crop-cultivation point of view can significantly affect the start of sowing and harvest. Even if the thermal conditions were favourable for sowing, too wet soils might indispose entering tractors into the field to start the operation. Since future precipitation projections for Poland show high increases in spring (Mezghani et al., 2017), it is likely that performing sowing operation by farmers 2 or 3 weeks earlier than at present might be difficult or even impossible due to excessive moisture.

CONCLUSIONS

1. The analysing of historical patterns and model simulations correctly reflect the fluctuations of air temperature, showing high correlation between the sowing/harvest dates and crop-specific mean temperature of pre-sowing and pre-harvest periods.

2. Spatial variation was accurately reflected, showing delayed sowing/harvest in colder regions (north-east) and advanced sowing/harvest in warmer parts of the country (south-west).

3. Projected warmer climate significantly affected potential scheduling of agricultural practices, accelerating the occurrence of sowing and harvest dates. The rate of acceleration was dependent on the time horizon and representative concentration pathway scenario.

4. The rate of sowing/harvest advance was increasing from near future to far future and also from representative concentration pathway 4.5 to 8.5. The highest advancement was projected for far future under representative concentration pathway 8.5, reaching 23 and 30 days for spring barley and maize, respectively.

5. Spatially, future projections are fairly similar with the historical pattern, indicating congruous regionalisation with delayed (north-east) and advanced (south-west) sowing/harvest areas.

Conflicts of interest: The Authors do not declare conflict of interest.

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