VARIABILITY OF POTATO WATER USE IN THE NORDIC CONDITIONS (ESTONIA) AND THE FREQUENCY OF EFFECTS FROM REGULATION

JÜRI KADAJA, TRIIN SAUE
Estonian Crop Research Institute, J. Aamissepa 1, 483 09 Jõgeva, Estonia

The crop water demand, defined as the amount of water loss through evapotranspiration (ET), refers to a crop grown under optimal conditions. We used the principle of maximum plant productivity and concept of meteorologically possible yield (MPY – maximum yield conceivable under the existing irradiance and meteorological conditions) to model and analyse such situation. Potato crop MPY and ET were calculated with model POMOD for two varieties and three agroclimatic regions of Estonia – all with and without natural outflow. Mean growing period potato water demand – ET in optimal water conditions (corresponding to two-way water regulation) – was from 286 to 333 mm, varying from 180 to 410 mm and being higher in marine climate, southward and for late variety. In natural water conditions ET was 10-32 % lower.

Although water deficit exists in some extent in 71-97 % of years and water excess in 38-81 %, irrigation or drainage water amounts less than 50 mm had practically no effect on yield. Therefore, at least some yield gain from irrigation may be expected in 28-86 % and from drainage in 3-50 % of years. Despite the more often positive effect from irrigation, the maximum yield gain from drainage exceeded yield increase from irrigation approximately twice.

Keywords: evapotranspiration, meteorologically possible yield, potato, water demand, water regulation

INTRODUCTION

Water is one of the most limiting factors of crop production throughout the world. Usually, only irrigation is considered in mitigation studies of soil water impact, since drought is globally the most common risk in agriculture. However, on a regional rather than global scale, there are areas where excess water may be as or even more important. Nordic countries, including Estonia, are represented in this group. In Estonia the annual amount of precipitation exceeds evaporation by a factor of two, however, there are considerable differences in precipitation between regions and years as well as within growing seasons. Frequent alternating of drought and excessive wet periods, often during the same growing period, turns the mitigation to non-optimal water conditions quite complicated. Commonly, these cases are imputed as comparable causes of failure in Estonian agriculture (Tammets, 2007; Ingver et al., 2010). However, traditionally more attention have been paid on the drainage than on the irrigation measures.

Potato (*Solanum tuberosum*) is one of the most sensitive crops to water stress. At the global scale, the potato yield gap (difference between potential and actual yield) has been quantified at approximately 20–30 $t.ha^{-1}$ (Supit et al., 2010). To a great extent, this difference is a consequence of non-optimal water conditions.

This study was implemented applying the crop model POMOD (Kadaja and Tooming, 2004) to explain potato water demand and accordance of real conditions to it, to evaluate the frequency, magnitude and influence of water deficit and excess, and assess the frequency for getting yield gain from ameliorative measures in different agroclimatic regions of the country.

MATERIALS AND METHODS

Model POMOD and required input

The POtato MODel POMOD (Sepp and Tooming, 1991; Kadaja and Tooming, 2004) is based on the principle of maximum plant productivity (Tooming, 1967, 1970, 1988) and derived from it the concept of reference yields (Tooming, 1984, 1993, 1998; Zhukovskij et al., 1989; Sepp and Tooming, 1991; Kadaja, 1994; Kadaja and Tooming, 2004).

From the reference yields, reflecting limits between the influences of agro-ecological groups of factors, the meteorologically possible yield (MPY) is applied in this study. MPY is the maximum yield attainable under the existing irradiance and meteorological conditions with optimal soil fertility and agrotechnology.

POMOD is a dynamic model with daily time steps. The equation for the rate of photosynthesis is derived from the principle of maximum plant productivity (Tooming, 1967; Tooming and Nilson, 1967), and its potential values are determined by the distribution of the intensity of photosynthetically active radiation (PAR) in the canopy. The distribution of newly formed biomass among different plant organs is determined using growth functions (Ross, 1966), which are expressed as a function of the thermal time (accumulated positive temperatures). MPY is calculated by taking into account the impact of air temperature and soil moisture on photosynthesis and the impact of temperature on respiration. A general description of the model structure and governing equations can be found in Kadaja and Tooming (2004); however, soil water handling procedures have since been upgraded (Kadaja, 2004b, Saue and Kadaja, 2014).

Model input data can be divided into four groups: daily meteorological data, annual information, site parameters and crop parameters of the variety.

Daily meteorological data include air temperature, precipitation and solar radiation.

Annual information includes information for determining the planting time in the spring, the initial soil moisture, the dates of the last and first night of frost (≤ -2 °C), and the date of the permanent drop in temperature to < 7 °C in autumn.

Sites are characterized by their geographical latitude and soil hydrological parameters: wilting point, field capacity and maximum water capacity.

Crop parameters, which are variety-specific, include the initial slope of the photosynthesis irradiance curve, the irradiation density of adaptation, the photosynthesis and respiration rates at the saturated PAR density, and the growth functions for the distribution of the newly formed biomass among different plant organs.

The locations for the calculations were chosen to represent the different climatic regions of Estonia. Data from the Tartu (58°16´N, 26°28´E) and Tallinn (59°24´N, 24°36´E) meteorological stations were considered to represent the climatic region of Mainland Estonia (Jaagus and Truu, 2004), but fall into different climatic subregions. Tallinn, which is characteristic of the regions near the Gulf of Finland, is a typical semicontinental subregion where the continental influence prevails, but is also significantly influenced by the Baltic Sea. Tartu is located in the far hinterland in the continental subregion, with practically no climatic effect from the sea.

Kuressare (58°15´N, 22°29´E), a station on the island of Saaremaa, was selected to represent the maritime climate characteristic of the west coast of Estonia. The sums of the growing season precipitation indicate much drier conditions in this region (Jaagus et al., 2010; Saue and Kadaja, 2014).

Following the World Reference Base for Soil Resources (WRB, 2006), the soils can be characterized as Albeluvisol at Tartu and as Skeletic Regosol at Tallinn and Kuressaare. All of the soils are sandy silt loam, with quite similar hydrological parameters estimated by Kitse (1978).

Daily meteorological data up to 2011 were extracted from the archives of the Estonian Meteorological and Hydrological Institute. For Tartu, such data were available from 1901, for Tallinn from 1920, and for Kuressaare from 1923 to 2000. For this latter site data, 2001–2011 were reconstructed on the basis of data from adjacent stations. Because direct measurements of global radiation were only recorded since 1954 in Tartu and since 2004 in Tallinn, the missing daily sums of the global radiation were computed from sunshine duration.

The data for the soil water status in spring were collected from reports of the agrometeorological network. For the earlier period (up to the end of the 1940s) and for some later years when the agrometeorological network was not working, the data were derived from the meteorological data at the stations (Saue and Kadaja, 2011).

The early variety ‘Maret’ (Tsahkna et. al, 2003) and late variety ‘Anti’ (Sarv and Koppel, 1995), both bred for Estonian conditions, were considered in the study. The variety-specific crop parameters of the two varieties were determined from field experiments (Kadaja, 2004a) or specified in the model by calibration using experimental data (Saue, 2006).

For this study, eight different model runs concerning water limitation and its regulation were conducted. The cumulative requirements for irrigation and/or drainage and resulting potential changes in yield were calculated.

1) Reference – baseline run of MPY, limited by both water excess and deficit.
2) Irrigation – water deficit was calculated daily and added simultaneously as irrigation water to the water balance equation.
3) Drainage – excessive water was calculated and removed as ameliorated drainage water from the balance equation.
4) Two-way regulation – both water deficit and excess (as defined in the previous points) were calculated simultaneously. Corresponding amounts of irrigation and/or drainage water were added/removed.

This set of four runs was implemented for two cases, where the natural outflow exists and where it was omitted. The last case corresponds to a situation when filtration into deeper ground is prevented by compactness of soil, or by limestone or clay layers, and surface runoff is blocked by the relief character.

From the output of the model, the yield gain or loss due to irrigation, drainage and two-way regulation and the amount of added/removed water were calculated for each year.

RESULTS

It is customary to express crop water demand in terms of evapotranspiration in optimal water conditions, i.e. under conditions not limited by water deficit or excess. This situation corresponds to the case of two-way amelioration. Potato evapotranspiration was calculated by summing it from planting to harvest. On average, potato water demand under optimal conditions is quite similar across different locations (Fig.1.). The differenced could be explained by longer growing periods in Tartu and Kuressaare, which is more valid for late variety ’Anti’, and mainly by a higher level of solar radiation in Kuressaare. In the case of early variety ’’Maret“, the influence of longer period in Tartu and higher solar radiation in seaside Tallinn balance each other. In Fig. 1., potato water demand is compared with total evapotranspiration from reference calculations to estimate differences in water demand and water use in non-regulated conditions. Under non-regulated conditions the mean total water use is 11–14 % less than demand in Tallinn and Tartu; in Kuressaare the difference is 30–32 %, being lower for early variety.

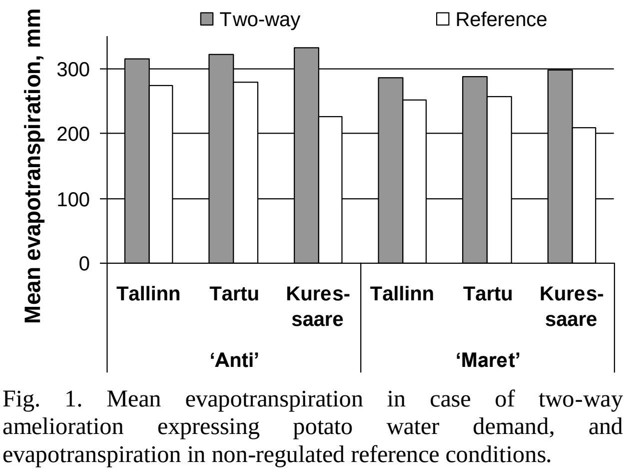

Fig. 1. Mean evapotranspiration in case of two-way amelioration expressing potato water demand, and evapotranspiration in non-regulated reference conditions.

Although the spatial variation of mean long-term water demand is small, from 286 to 333 mm, its temporal variability, depending on weather conditions, is great, from 180 to 410 mm (Fig. 2). Either in case of water demand or evapotranspiration in natural conditions, Kuressaare differs from other localities. Water demand is higher there, but real evapotranspiration is markedly lower than for other stations. Reason is in higher solar radiation and lower precipitation in this location. Small differences between Tartu and Tallinn appear mainly in the range of low evapotranspiration. Responding for these differences are cool summers with low radiation and/or short growing period. In such years, shorter growing period in Tallinn limits yield more compared to Tartu.

Water demand of the early variety is 6-14 % lower compared to the late one. In the case of non-changed water regime the differences in evapotranspiration between the varieties are somewhat lower.

Both, water deficit and excess are frequent and the frequency varies by sites. In Kuressaare there is a water deficit in almost every year (Table 1), while in Tallinn and Tartu water deficit was found in 71-78 % of years.

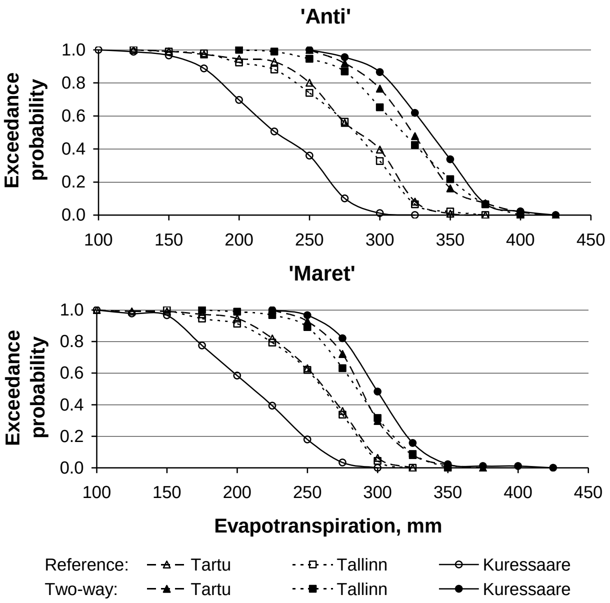

Fig. 2. Distribution of potato water demand (evapotranspiration of two-way ameliorated crop) and evapotranspiration of non-ameliorated crop (reference).

In Tallinn and Tartu the percentage of years with excess water periods is even higher than that for water deficit. However, the appearance of water excess is more frequent in the very beginning and end of the growing season, and therefore its direct impact on potato yield is not so evident in most years of its appearance as that of water deficit limiting mostly during the intensive growing period. Although there is a water excess in Kuressaare in up to 40 % of years, its negative effect on yield is small, even opposite, its existence decreases the water deficit in subsequent dry periods.

Table 1. Percentage of years with water deficit and excess, and with both existing during the same year.

Cultivar	Water status	Tallinn	Tartu	Kuressaare
‘Anti’	Deficit	75.0	77.5	96.6
	Excess	78.3	80.2	39.3
	Excess and deficit	53.3	57.7	36.0
‘Maret’	Deficit	70.7	73.9	95.5
	Excess	78.3	81.1	38.2
	Excess and deficit	48.9	55.0	33.7

The average need for irrigation water is 30–45 mm for the early and 47–58 mm for the late variety per growing period in continental locations, but twice as high for insular Kuressaare. In continental stations the need for drainage is around 30–40 mm for both varieties in addition to normal outflow, but 20–25 mm more if outflow is restricted. In Kuressaare, the mean amount of excess precipitation is only 9–20 mm.

The dependence of the yield change on the amounts of irrigation water is presented in Table 2 for the case with normal outflow, and dependence on drainage water for the case without it, so, for the conditions where the measure is more needful. Rise of these dependences is accelerating and can be described by a second order polynomial. If the water deficit is less than 50 mm per growing period, providing the lacking amount of water to the crop does not produce an essential result. Effect from removing of water excess less than 50 mm is rather negative.

In continental sites, the percentage of years exceeding the 50 mm deficit level is 37-49 % and 28-40 % for the late and early varieties, respectively, while in Kuressaare, this limit is achieved in 76-86 % of years (Table 3). Water excess more than 50 mm can be found in continental sites in 22-59 % of years, in island region this number remains below 20 %.

Table 2. Mean change of yield corresponding to different amount ranges of added or removed water.

Variety	Means	Amount of water	Mean change of yield		
			Tallinn	Tartu	Kuressaare
Anti	Irrigation, with normal outflow	0-50	0.40	0.38	0.66
		50-100	3.56	4.01	5.57
		100-150	12.60	12.44	11.44
		150-200	24.35	19.55	25.36
		200-250	17.25	36.15	36.60
	Drainage, without outflow	0-50	-0.70	-1.23	-0.82
		50-100	3.10	4.13	-1.09
		100-150	11.54	14.98	-11.97
		150-200	36.80	25.74	-
		200-250	51.23	-	-
		250-300	-	54.00	-
Maret	Irrigation, with normal outflow	0-50	0.38	0.14	0.61
		50-100	2.54	3.28	4.89
		100-150	9.79	6.79	10.86
		150-200	16.61	20.50	20.11
		200-250	-	-	23.72
	Drainage, without outflow	0-50	-0.39	-0.58	-0.47
		50-100	2.40	2.90	-0.34
		100-150	12.32	10.19	0.57
		150-200	20.48	14.28	-
		200-250	29.37	26.18	-
		250-300	-	43.19	-

Table 3. Percentage of years when water deficit or excess overcomes 50 mm.

Variety	Location	Deficit > 50 mm		Excess > 50 mm	
		With outflow	Without outflow	With outflow	Without outflow
Anti'	Tallinn	48.9	40.2	22.8	40.2
	Tartu	44.1	36.9	26.1	49.5
	Kuressaare	86.5	82.0	3.4	12.4
Maret'	Tallinn	40.2	33.7	25.0	44.6
	Tartu	30.6	27.9	28.8	49.5
	Kuressaare	80.9	76.4	4.5	18.0

Despite the equal or more often positive effect from irrigation, the maximum yield gains are obtained from drainage in continental sites and soils without natural outflow (Table 4).

Table 4. Maximum yield gains from amelioration measures during the whole observed period.

Variety	Site	Irrigation	Drainage, with outflow	Drainage, without outflow
Anti'	Tallinn	31.4	12.4	62.0
	Tartu	36.2	40.7	63.0
	Kuressaare	41.6	0.1	1.7
Maret'	Tallinn	17.5	15.8	37.0
	Tartu	22.9	28.7	43.2
	Kuressaare	26.4	0.3	2.6

CONCLUSION

In Estonia, located between latitudes 57° and 60° N, annual precipitation overcomes evapotranspiration. However, in summer period both deficit and excess of water are factors decreasing potato yield. Calculations indicate great differences in the direction from East to West, from continental to marine climate. Potato water demand is higher in marine climate, but its real evapotranspiration is much lower there. As a reason, more sunshine and less precipitation in seaside areas in summer play the role. Markedly less differences, observable from South to North, are mainly caused by shortening of the duration of growing period limited by late spring and early autumn night-frosts.

Water deficit as well as water excess present themselves in more than 70 % of years in the continental regions. Approximately in half of years, excluding insular and coastal regions, both, water deficit and excess exist during the same summer. However, the calculations indicate that both water deficit and excess less than 50 mm have not essential increasing influence on yield and do not need applying of ameliorative measures. Therefore, effect from each of amelioration measures can be expected in 40-50 % of years, except insular regions exemplified by Kuressaare, where need for irrigation is high and for drainage is absent. Water deficit and excess, existing in the same year, may together impact the crop more hardly, but may also decrease influences of each other. In this case, excluding one of these limiting factors reinforces decrease of the yield, which was often a result of drainage in Kuressaare.

Acknowledgement

The research was supported by the projects of applied research: PA1-RUP-018 “Agrometeorological forecasts and reviews” and PA1-RUP-019 “Influence of climate change on field crops” which are funded by the Estonian Ministry of Agriculture, and the COST project EURO-AGRIWAT.

LITERATURE

Ingver, A., Tamm, I., Tamm, Ü., Kangor, T., Koppel, R., 2010, The characteristics of spring cereals in changing weather in Estonia. Agronomy Research 8 (Special Issue III): 553-562.

Jaagus, J., Briede, A., Rimkus, E., Remm, K. 2010. Precipitation pattern in the Baltic countries under the influence of large-scale atmospheric circulation and local landscape factors. Int. J. Climatol. 30: 705--720.

Jaagus, J., Truu, J., 200,. Climatic regionalisation of Estonia based on multivariate exploratory techniques. Estonia. Geographical studies 9: 41-55.

Kadaja, J., 1994., Agrometeorological resources for a concrete agricultural crop expressed in the yield units and their territorial distribution for potato. In: Vilu, H., Vilu, R. (Eds.). Proceedings of the GIS – Baltic Sea States 93. Tallinn Technical University, Tallinn, pp 139-149.

Kadaja, J., 2004a, Influence of fertilisation on potato growth functions. Agronomy Research 2: 49-55.

Kadaja, J., 2004b, Water sub-model of a dynamic agroecosystem model and an empirical equation for evapotranspiration. In: Isemer, H. J. (Ed.). Fourth Study Conference on BALTEX. Conference Proceedings. International BALTEX Secretariat. pp. 184-185.

Kadaja, J., Tooming, H., 2004, Potato production model based on principle of maximum plant productivity. Agric. For. Meteorol. 127: 17-33.

Kitse, E., 1978. Soil Water (in Estonian). Valgus, Tallinn.

Ross, J. 1966. About the mathematical description of plant growth. Dok. Akad. Nauk. SSSR (in Russian) 171: 481-483.

Sarv, J., Koppel, M., 1995, Anti. http://www.etki.ee/index.php/ eng/2014-08-26-17-30-03/varieties2#anti [06.01.2015]

Saue, T., 2006, Site-specific information and determination of parameters for a plant production process model. Masters Thesis. Eurouniversity, Tallinn.

Saue, T., Kadaja, J., 2011, Possible effects of climate change on potato crops in Estonia. Boreal Environ. Res. 16: 203-217.

Saue, T., Kadaja, J., 2014, Water limitations on potato yield in Estonia assessed by crop modelling. Agric. For. Meteorol. 194: 20-28.

Sepp, J., Tooming, H., 1991, Productivity resources of potato (in Russian with English abstract). Gidrometeoizdat, Leningrad.

Supit, I., Van Diepen, C.A., De Wit, A.W., Kabat, P., Baruth, B., Ludwig, F., 2010, Recent changes in the climatic yield potential of various crops in Europe. Agricult. Syst. 103: 683-694.

Tammets, T., 2007, Distribution of extreme wet and dry days in Estonia in last 50 years. Proceedings of the Estonian Academy of Sciences. Engineering, 13, 252--259.

Tooming, H., 1967, Mathematical model of plant photosynthesis considering adaptation. Photosynthetica 1: 233-240.

Tooming, H., 1970, Mathematical description of net photosynthesis and adaptation processes in the photosynthetic apparatus of plant communities. In: Setlik, I. (Ed.). Prediction and Measurement of Photosynthetic Productivity. Pudoc, Wageningen. pp. 103-114.

Tooming, H., 1984, Ecological Principles of Maximum Crop Productivity (in Russian with English summary). Gidrometeoizdat, Leningrad.

Tooming, H., 1988, Principle of maximum plant productivity. In: Kull, K., Tiivel, T. (Eds.). Lectures in Theoretical Biology. Valgus, Tallinn. pp. 129-138.

Tooming, H., 1993, Evaluation of agrometeorological resources based on the potential productivity of crops. J. Agric. Met. 48: 501-507.

Tooming, H., 1998, Climate change and estimation of *ecologically founded yields. In: Kallaste, T., Kuldna, P. (Eds.), Climate Change Studies in Estonia. Stockholm Environment Institute Tallinn Centre–Ministry of Environment, Republic of Estonia, Tallinn, pp. 141--152.*

Tooming, H., Nilson, T., 1967, Basis of energetic adaptation of vegetation on light. In: Phytoactinometrical Investigations of Vegetation (in Russian with English summary). Tallinn, Valgus. pp. 35-63.

Tsahkna, A., Anderfeld, A., Koppel, M., 2003, Maret. http://www.etki.ee/index.php/eng/2014-08-26-17-30-03/varieties2#maret [06.01.2015]

WRB,. 2006, World Reference Base for Soil Resources. 2006. A Framework for International Classification, Correlation and Communication. World Soil Resources Report 103, FAO, Rome.

Zhukovsky, E.E., Sepp, J., Tooming, H., 1989, On the possibility of the yield and forecasting calculation. Vestn. S.–H. Nauki (Messenger of Agricultural Sciences) (In Russian with English abstract) 5: 68-79.