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Simulated potato crop yield as an indicator of climate variability and changes in Estonia

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1. Introduction

During the recent decades, global climate change has been at the centre of quite many scientific studies. Although the consensus is that climate is changing on a global scale, change on a regional or local scale is often more subtle and variable. 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. 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.

Interactions between the biosphere and the atmosphere are obvious and have long been studied by several disciplines (e.g. Budyko, 1971, 1984; Fritts, 1976; Bolin, 1977; Tooming, 1977, 1984; Semenov and Porter, 1995; Scheifinger et al., 2002; Menzel, 2003; Aasa et al., 2004; McPherson, 2007). It has long been recognized that climate decides what can be cultivated, whereas soils indicate mainly to what extent climatic opportunities can be realized. The crops that continue to be grown in a particular location will primarily be determined by the changes in climate, and the seasonal distribution of rainfall and temperature that they experience. The main effect of temperature derives from the control of the growing period duration (Woodward, 1988), but also other processes linked with the accumulation of dry matter (leaf area expansion, photosynthesis, respiration, evapotranspiration etc.) are affected by temperature. Rainfall and soil water availability may affect the duration of growth through leaf area duration and the photosynthetic efficiency. These general climatic constraints on agricultural production are modified by local climatic constraints. In Northern countries the length of growing season, late spring and early autumn frost and solar radiation availability are typical climatic constraints, limiting the productivity of crops. For example, in Germany the growing season is one to three months longer than in Scandinavian countries (Mela, 1996).

Not surprisingly, also the reverse relation is true – biological and agricultural data can be used in climate assessments. Several biology-related indicators have been used by several scientists to assess past and present climate, its changes and variability, such as Palmer Drought Severity Index (e.g. Makra et al., 2002; Szep et al., 2005; Burke et al., 2006; Mpelasoka et al., 2007), growth season beginning and length (e.g. Menzel and Fabian, 1999;

Chmielewski & Köhn, 2000; Schwartz & Reiter, 2000; Sparks & Tryjanowski, 2007), dates of phenological phases (e.g. Ahas et al., 2004; Badeck et al, 2004; Chuine et al., 2004; Donnelly et al., 2004), etc. One of the complex variables, integrally describing summer weather conditions, is the biological production of plants and yield of agricultural crops. In this chapter, the potentiality of using the biological production and yield of agricultural crops as an indicator of summer climate variability and possible change is discussed. This approach is based on the postulate that the primary requirement for the success of a plant in a particular area is that its phenology would fit the environment. The signals of climate change usually occur more clearly in species growing at the borders of their distribution areas (Pensa et al., 2006) or whose growth is strongly influenced by climate, such as many arable crops (Hay & Porter, 2006).

Trends in individual climate variables or their combination into agro-climatic indicators show that there is an advance in phenology in large areas of North America and Europe, which has been attributed to recent regional warming. In temperate regions, there are clear signals of reduced risk of frost, longer growing season duration, increased biomass, insect expansion, and increased forest-fire occurrence that are in agreement with regional warming. Still, no detectable change in crop yield directly attributable to climate change has been reported for Europe (IPCC, 2007). Experimental studies of climate change through plant productivity are complicated indeed, as it is hard to distinguish the impact of climate variability or change from the effects of soil, landscape, and management. The worldwide trends in increasing productivity (yield per hectare) of most crops over the last 40 years, primarily due to technological improvements in breeding, pest and disease control, fertilisation and mechanisation, also make identifying climate-change signals difficult (Hafner, 2003). Thus, although the yield of agricultural crops is a quite commonly measured value, there is usually no long homogeneous time series of field crop yields. Therefore, the use of a simulated time series of crop yields, computed with dynamic plant production process models, is a more convenient and efficient way to draw climate estimations. These models are compiled from our knowledge of the different physiological processes in plants, and integrate different daily or more frequent weather data, calculating the development of plant production step-by-step. Traditionally, crop models are useful tools for translating climate forecasts and climate change scenarios into changes in yield, net returns, and other outcomes of different management practices. Additionally, those results can be turned backward and model-calculated yields can be used as an indicator to describe climate resources. In this chapter the concept of meteorologically possible yield (MPY) - the maximum yields under given meteorological conditions - is applied to derive qualitatively new information about climate variability. We will describe series of weather-reliant potato yields based on real existing meteorological series. Trends and variability changes within the series are assessed and compared to variability in the series of meteorological data. Probable range of temperature and precipitation in years 2050 and 2100 is applied to construct possible distribution of MPY in those years; future changes in mean values and variability are examined.

2. Material and methods

2.1 The model and the category of meteorologically possible yield

Plant productivity and thus the yields of field crops depend on many different closely interrelated factors. To introduce all of them into the model simultaneously is complicated. In our approach, the concept of the separation of factors, the principle of reference yields (Tooming, 1984; Kadaja & Tooming, 2004) was applied based on the principle of maximum plant productivity: such adaptation processes take place in a plant and plant community which are directed towards providing the maximum productivity of net photosynthesis possible under the existing environmental conditions (Tooming, 1967, 1970, 1977, 1984, 1988). Proceeding from this principle, maximum plant production is observed under different limiting factors, which can be divided into agroecological groups: biological, meteorological, soil, and agrotechnical groups. These groups of factors are included separately in the model, step by step, starting from the optimal conditions for the plant community (Tooming, 1993, 1998; Kadaja, 1994). Because the conditions specified as optimal involve no limitations, no input information regarding their optimal and limiting ranges is necessary. The corresponding categories of reference yields, as limits between the aforesaid groups, are in descending order: potential yield (PY), MPY, practically possible yield, and commercial yield (Fig. 1).

This concept is applied in the dynamic model POMOD to model the potato production process and yield (Sepp & Tooming, 1991; Kadaja & Tooming, 2004). In the present state, POMOD allows the computation of the PY and the MPY. The PY is the maximum yield of a given species or variety possible under the existing conditions of solar radiation, with all the other environmental and agricultural factors considered to be optimal. Therefore, PY is determined by the biological properties of the variety and the solar radiation available for utilization, and it expresses the radiation resources in units of biomass produced. The MPY is the maximum yield conceivable under the existing irradiance and meteorological conditions, with optimal soil fertility and agrotechnology, the levels of soil nutrients and the agrotechnology used do not limit production, and the effects of plant diseases, pests, and weeds are excluded. Only those soil properties related to the determination of the soil water content are applied.

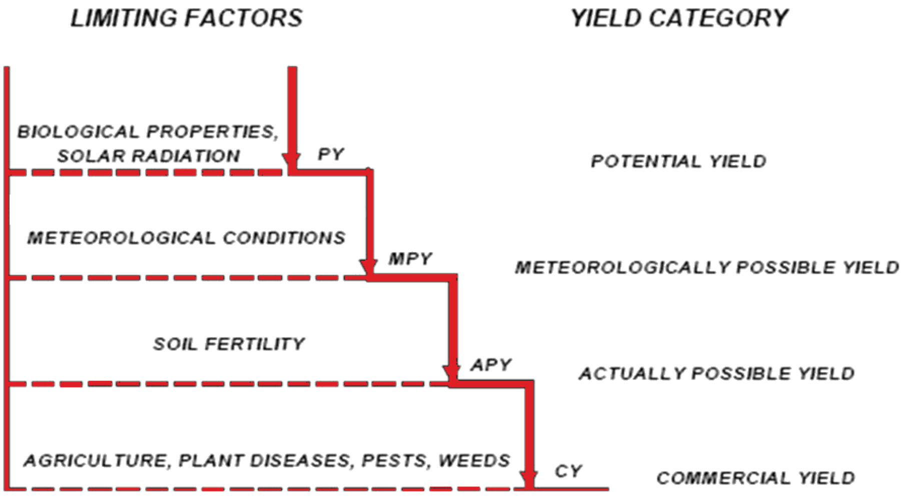

Fig. 1. The concept of yield limiting factors and corresponding reference yields (Zhukovsky et al., 1989).

As a result, MPY expresses agrometeorological resources, while its mean value and variability distribution over a long period characterize the agroclimatic resources in yield units. Using the category of MPY and the model of crop production, we can transform the complex of meteorological conditions into their yield equivalent and easily assess the agrometeorological resources of different years and the agroclimatic resources at different locations.

The underlying parameters of POMOD are the total biomass and the masses of plant organs (leaves, stems, roots, and tubers) per unit ground area (Kadaja & Tooming, 2004). The total growth of the plant biomass is calculated as the difference between the gross photosynthetic and respiration rates, integrated over time and leaf area index. The gross and net photosynthetic rates are expressed by equations derived from the principle of maximum plant productivity (Tooming, 1967). The meaning of parameters of gross and net photosynthesis irradiance curves are illustrated in Fig. 2. The initial slope *a* is the slope of tangent to the gross photosynthesis irradiance curve drawn from the origin of co-ordinates. R_a is the PAR flux density at the tangential point of net photosynthesis irradiance curve and its tangent drawn from the origin of co-ordinates. The intensity of photosynthetically active radiation (PAR) in the canopy is calculated from the total radiation and the leaf area above a particular level. The distribution of the total increase in biomass between different plant organs is determined using growth functions (Ross, 1966), which are given in the model as functions of accumulated positive temperatures. MPY is calculated taking into account the impact of meteorological factors on photosynthesis and respiration, and the influence of temperature on development rate.

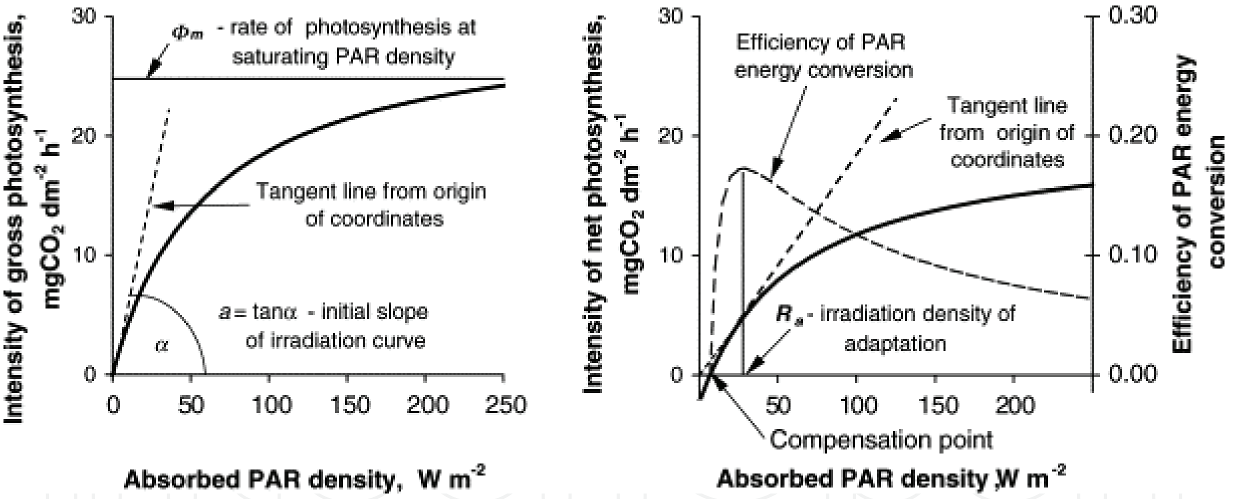

Fig. 2. Gross and net photosynthesis irradiance curves and their characteristics (Tooming, 1984).

The biological parameters of the potato varieties were determined on the basis of field experiments, not limited by nutrient deficiency, properly cultivated, weed and pest free, and regularly protected from late blight (Sepp & Tooming, 1991; Kadaja, 2004). The computed yields have proved similar to the real yields under these conditions, if the reduction in leaf area from late blight, not totally avoidable by protection, is included in the model. Differences in the real and computed yields did not exceed 5% in independent data collected under extremely good and bad growing conditions (Sepp & Tooming, 1991). Further verification of the model has been made on the basis of 20-year yield series at four stations of the Estonian Variety Control Network, with relatively stable cultivation and soils maintained during the period. Significant correlations between actual yields and calculated MPY were verified at three stations, whereas at the fourth, the correlation was not significant because of an increased level of plant diseases, grown without crop rotation.

2.2 Locations

To simulate time series of meteorologically possible yield, we compiled series of meteorological and agrometeorological data from the archives of the Estonian Meteorological and Hydrological Institute. We used the data from two stations: Tartu (58°15´N, 26°27´E) and Kuressaare (58°15´N, 22°29´E). These stations are located in regions with different local climates. Local climatic differences in Estonia result from, above all, the proximity of the Baltic Sea, which warms the coastal zone in winter and cools it especially in spring. According to the climatic classification of Estonia based on its air temperature regime, as proposed by Jaagus & Truu (2004), Tartu is located in the Mainland Estonia climatic region, characterized by a more continental climate and practically no climatic effect of the Baltic Sea, and Kuressaare is located in the Island Estonia region, with a much more maritime climate. Spring is much warmer in Tartu and summer starts earlier. In addition to different temperature regimes, there are considerable differences in precipitation between the two stations (Fig. 3). Furthermore, climate change effects appear to be different in the continental and coastal areas (Jaagus, 2006). For instance, because of the direct influence of the sea, the evident increase in annual mean temperature (1.0-1.7 °C at the different stations in Estonia during the second half of the 20th century) is less intense in spring in Kuressaare compared to that in Tartu. A significant increase in winter precipitation has also taken place in Estonia, but is much lower on the westernmost coast. In the same period, precipitation has increased remarkably in the coastal region in spring.

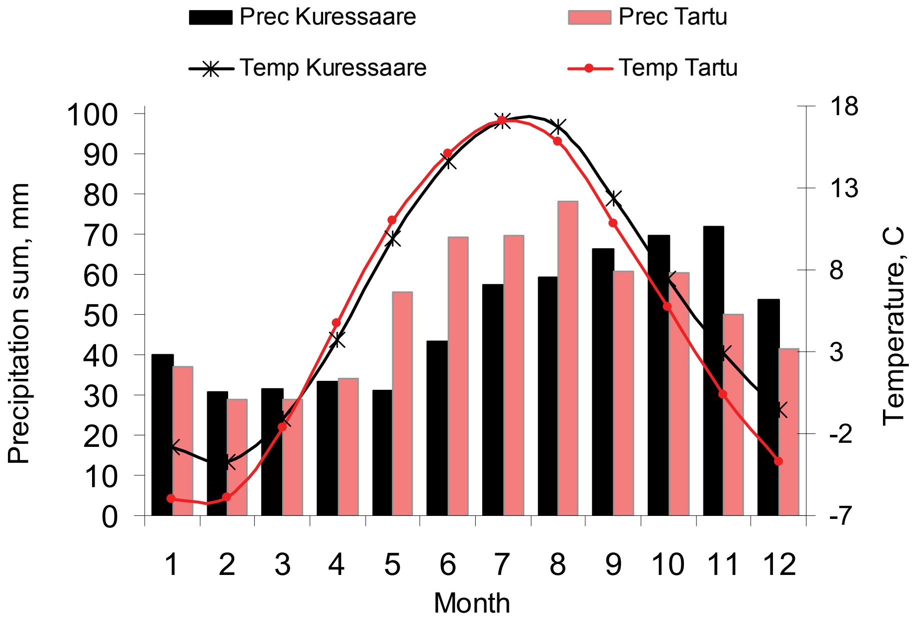

Fig. 3. Monthly mean temperatures (lines) and precipitation sums (bars) in Kuressaare and Tartu in 1965-2006.

2.3 Input data: calculations with current climate

The input information for the model can be divided into four groups: daily meteorological data, annual information, parameters of location, and biological parameters of the potato variety (Kadaja & Tooming, 2004).

The first group includes daily data on global radiation, air temperature, and precipitation for the growing period. For Tartu, meteorological data were available from 1901, for Kuressaare from 1923. Calculations were carried out up to 2006. As Kuressaare meteorological station was closed in 2001, the data for last years were calculated there on the basis of an adjacent station (Virtsu, Sõrve, Vilsandi, or Ristna, depending on which had the highest correlation for a particular factor or period). Direct measurements of global radiation have only been made since 1954 in Tartu. We computed the missing daily sums of global radiation from sunshine duration, using regression equations established separately for every month in Tartu.

Annual information included the year, the date and the value of the initial water storage in the soil (or the date when the soil moisture fell below the field capacity), the date of the permanent increase in temperature to above 8 °C in the spring, the dates of the last and first night frosts (≤ -2 °C), and the date of the permanent drop in temperature to below 7 °C in autumn. The initial soil moisture value is used as a basis for further calculations of soil moisture progression throughout the vegetation period. The dates of the temperature transitions are used as 'planting' and 'harvesting' dates for potatoes. We obtained the dates of night frosts and temperature transitions from the meteorological data sets of the stations. The data for the soil water status in spring was collected from the reports of the agrometeorological network using observations at Tartu-Erika (adjacent to Tartu) and at Karja on the island of Saaremaa (for Kuressaare). 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.

The locations are characterized by their geographical latitudes and the hydrological parameters of the soil, such as the wilting point, field capacity, and maximum water capacity. We used the parameters of the field soils (Kitse, 1978) prevalent at the locality. For Tartu, the parameters of a region with Albeluvisol (World Reference Base for Soil Resources) were used; for Kuressaare, the Skeletic Regosol prevails. All the soils are sandy silt loam, with quite similar hydrological parameters.

As parameters of variety, the model requires the parameters for photosynthesis, respiration, and the growth functions. We used the parameters of the early variety 'Maret' and the late variety 'Anti', both bred for Estonian conditions. The variety-specific photosynthesis variables, the initial slope of the photosynthesis irradiance curve a (kg CO_2 $s^{-1}W^{-1}$), the irradiation density of adaptation R_a (W m^{-2}), and the photosynthesis and respiration rates at the saturated PAR density given per unit mass of leaves, σ_1 and σ_2 respectively (kg CO_2 kg^{-1} s^{-1}), were estimated initially from the literature and adjusted for the specified varieties by a calibration method from experimental field data (Saue, 2006). Parameters σ_2 and α were considered constant throughout the vegetation period, while σ_1 and R_a were studied as variables. To associate parameters amongst each other, measured data of specific leaf weight of leaves, μ, were used. Specifically, different values were given to the maximum value of σ_1 and to the parameters describing its change within the temperature sums. The scope of change of σ_1 were first estimated by literature data (Tooming, 1977). R_a was calculated through σ_1, α and μ . To find the most optimal σ_1 value, relative errors between measured and modelled data at different σ_1 values were calculated. Data of leaf area index and the biomass of all organs at all measurement dates were used.

Growth functions (Fig. 4) were determined on the basis of field experiments made from 2001 to 2006 (Kadaja, 2004, 2006).

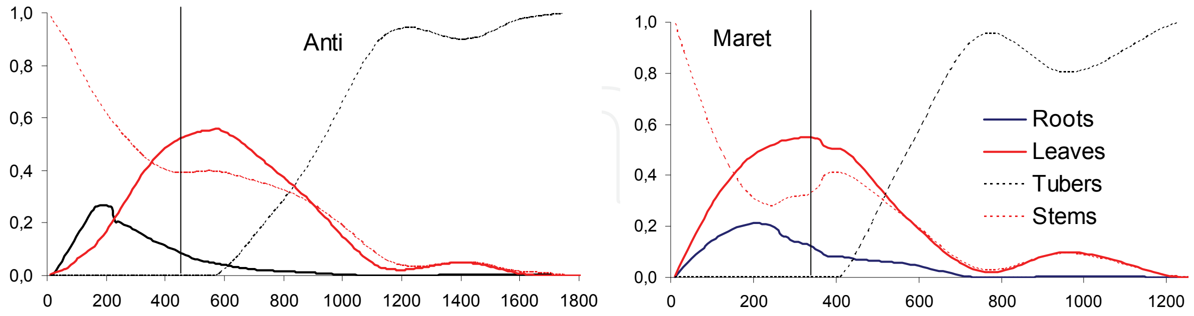

Fig. 4. Experimentally determined growth functions of late potato variety 'Anti' and early variety 'Maret'. Vertical lines denote the beginning of calculations.

2.4 Input data: calculations with future climate

Climate change could considerably affect the growth and yield of most crops (Adams et al., 1990; Easterling et al., 1992a, b). For model simulations of future potato production, future weather data were required. To achieve temperature and precipitation data for the years 2050 and 2100, climate change scenarios were generated for Estonia using a simple coupled gas-cycle/climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) that drives a spatial climate-change scenario generator (SCENGEN). MAGICC has been one of the primary models used by IPCC since 1990 to produce projections of future global-mean temperature and sea level rise; we used the 5.3 version of the software, which is consistent with the IPCC Fourth Assessment Report (http://www.cgd.ucar.edu/cas/wigley/magicc/UserMan5.3.v2.pdf).

Because projections of climate change depend heavily upon future human activity, climate models are run against scenarios. There are over 40 different scenarios, each making different assumptions for future greenhouse gas pollution, land-use and other driving forces. Assumptions about future technological development as well as the future economic development are thus made for each scenario. Four alternative illustrative emission scenarios were used in our study to generate climate change scenarios for Estonia: A1B, a scenario of an integrated world with rapid economic growth, slowing population increase and a quick spread of new and efficient technologies with a balanced emphasis on all energy sources; A2, a scenario of a more divided world with continuously increasing population and an emphasis on family values and local traditions; B1, scenario of a world of "dematerialization" and introduction of clean technologies with rapid economic growth and increasing population; B2, a scenario of a world with an emphasis on local solutions to economic and environmental sustainability, with moderate economic growth and slowed population increase (Nakićenović & Swart, 2000). The highest climate warming is projected by A2; the lowest by B1. The year 1990 is used as the reference year in MAGICC/SCENGEN, all the climatic changes are calculated with respect to this year.

Data of changes in mean monthly air temperature and precipitation, averaged over 18 GCM experiments available on SCENGEN were applied. The idea of averaging more than one

GCM experiment and constructing a composite pattern for future climate change was first introduced by Santer *et al.* (1990); later Hulme *et al.* (2000) reported the clear supremacy of the technique over just only one model. The data are displayed in MAGICC/SCENGEN in a grid resolution of 2.5° latitude/longitude, thus the Estonian territory is covered by three grid boxes, with medium coordinates 58.8°N/21.3°E, 58.8°N/23.8°E and 58.8°N/26.3°E. Kuressaare and Tartu fall into two outermost boxes. However, the direct use of the SCENGEN output is not possible, because these predictions are available as changes in monthly means, but the crop model depends on daily time-series of weather as one of its main inputs. To calculate the future values of MPY, we used observed daily weather data in those stations during the baseline period 1965-2006. This shorter period is applied instead of previously used longer periods, since in climate change calculations it is necessary to use data outside the heretofore growing period. Global radiation was assumed not to change. Future daily temperatures and precipitation were calculated by adding the predicted monthly corrections to the observed series of daily data. This way, not just the one average predicted future value for temperature and precipitation, but 41 possible series of those meteorological elements were obtained for the two target years, suggesting the possible future weather distribution. Such setup also leads to the variability in the future climates being almost identical to the variability of the historical climate. Although the variability of climate in the future may alter (Rind et al., 1989; Mearns, 2000), inducing possible decrease in mean crop yields (Semenov & Porter, 1995; Semenov et al., 1996), some researchers (Barrow et al., 2000; Wolf, 2002) have reported that for potato, changes in climatic variability in northern Europe generally resulted in no changes in mean yields and its coefficient of variation.

Thus converted future weather data series are employed to calculate the date and the value of the initial water storage in the soil (or the date when the soil moisture falls below the field capacity), the date of the permanent increase in temperature to above 8 °C in the spring, the dates of the last and first night frosts (≤ -2 °C), and the date of the permanent drop in temperature to below 7 °C in autumn for each individual year of the new series. For determination of the soil water status in spring a relationship between radiation balance R_{fc} from permanent transition of temperature over 0° C to soil moisture fall below the field capacity, and meteorological data was derived using 30-year data of 13 stations of the Estonian Agrometeorological Network. To calculate R_{fc} , incoming global radiation and evaporative energy of precipitation (precipitation multiplied by latent evaporative heat) were accounted. The strongest correlations of R_{fc} were achieved with temperature sums from March to April $T_{3\text{-}4}$ and precipitation sums from February to April $U_{2\text{-}4}$:

$$R_{fc} = 468.2 - 1.587\, T_{3\text{-}4} - 0.517\, U_{2\text{-}4} \qquad r = 0.66 \tag{1}$$

To apply relationship (1) into the future dataset, a submodel calculates R_{fc} as well as permanent date of temperature rise over 0° C for each year of the new weather data series for 2050 and 2100. Next, from that date, the running radiation balance is summarized day-by-day. The date when the running radiation balance exceeds R_{fc} is counted as the date of achieving the soil field capacity and it is considered as the 'first possible' planting date. Additionally, 'optimal planting date' is applied – the date achieved by postponing the day of planting in model calculations day-by-day until the maximum yield is obtained. To prevent staying to a side maximum this postponing is conducted until the MPY drops below 70% of its maximum value, or until the date of summer equinox.

The dates of last and first night frosts in the future series are found on the basis of the earlier determined relationships between mean daily air temperature and ground level minimum temperature, dependent on the radiation sum of previous day.

3. Results

3.1 Time series of meteorological resources: current climate

Series of meteorologically possible yield were compiled for early and late maturing potato varieties in two different Estonian localities. In Table 1 we present long-term mean yields calculated with existing meteorological data series, using real and computed (both first possible and optimal) planting dates; the yields thus describe real, possible and optimal climatic resources for plant growth during given period.

With real planting dates, there was practically no difference in average values of the MPY between long and short (from 1965) series. As expected, the late variety produced higher yields at all locations. Overall, the MPY series showed only weak and insignificant trends (Fig. 5), although reliable trends are apparent for some shorter periods. The longest period with a significant ($P < 0.05$) decreasing trend was observed in Kuressaare from 1977 to 2006.

Generally, 'Anti' demonstrated higher variance in yields. For both varieties, the variability reached higher in Kuressaare. Variability increases in all cases when using computed planting dates instead of real dates.

Closer investigation of the MPY variability showed a significant increase in variance in Tartu since the early 1980s. In the MPY calculations contrived with real meteorological data, the standard deviation of MPY was significantly lower for 'Maret' in 1901-1980 compared to 1981-2006 ($P = 0.006$, according to F test); for 'Anti', the change was smaller yet significant ($P = 0.046$). When using shorter time series and optimal planting times, the same difference in yield variance was detected both for 'Maret' ($P = 0.002$) and 'Anti' ($P = 0.015$). The meteorological elements series revealed no similar changes in climate variability. Reliable dispersion differences were detected only in the precipitation series, but their significance was lower than that of the yields.

	ANTI				MARET			
	Tartu		Kuressaare		Tartu		Kuressaare	
	MPY	Var. coeff.	MPY	Var. coeff.	MPY	Var. coeff.	MPY	Var. coeff.
Real dates								
Long series to 2006	55.5	0.20	50.3	0.27	45.0	0.16	37.8	0.21
1965-2006	54.5	0.21	50.3	0.28	45.1	0.19	37.7	0.22
1901-1980	56.1	0.18			45.5	0.14		
1981-2006	53.9	0.25			43.5	0.22		
1923-1938			51.0	0.16				
1939-2006			50.1	0.29				
Computed dates								
1965-2006, first planting date	58.8	0.24	49.8	0.33	42.4	0.18	38.2	0.27
1965-2006, optimum planting date	58.9	0.23	50.2	0.32	44.0	0.19	39.3	0.26

Table 1. Mean values of MPY and corresponding coefficient of variation for different periods.

Therefore, the separate meteorological elements did not reflect the influence of their combined effect on the variability of biological production. Significant differences in yield variability, not identified in the meteorological series, were also observed for 'Anti' at Kuressaare, where the standard deviation was approximately two times lower before 1939 than in later periods ($P < 0.017$).

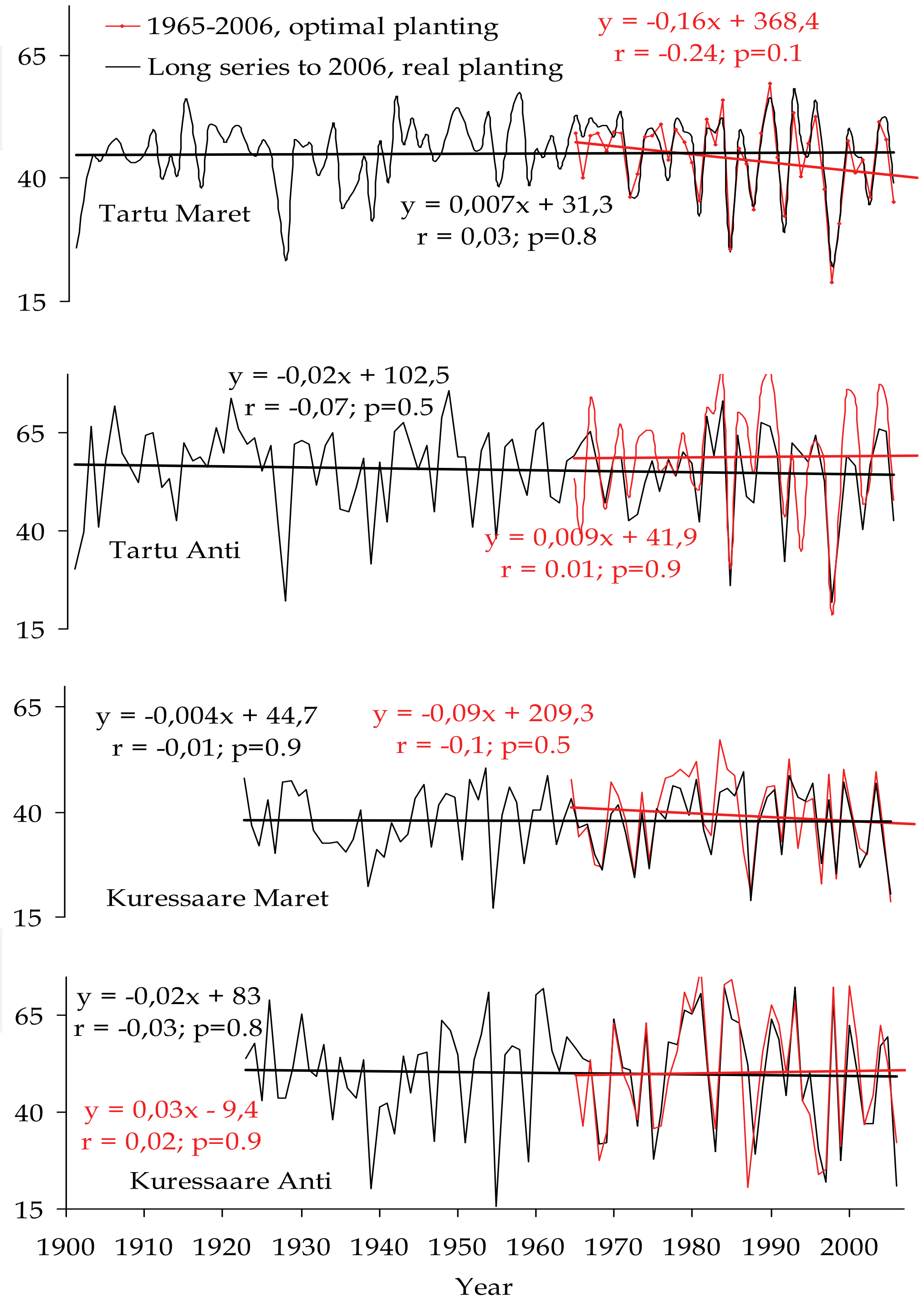

Fig. 5. Series of MPY of the early potato variety 'Maret' and the late potato variety 'Anti' in Tallinn and Kuressaare.

3.2 Relationships between MPY and other indicators

In Estonia, like elsewhere in temperate zone, crop yield variation is highly influenced by weather conditions (Carter, 1996; Karing et al.,1999). When using real, measured potato yield data, potato yield variance was found to be mostly dependent on weather conditions, while the impact of fertilization and soil management proved less significant and in interaction with weather (Saue et al., 2010). Of meteorological conditions, potato proved the most susceptible to spring temperatures, yielding higher in years with a warm spring; negative linear relation between yields and precipitation during the same period concurred. The positive influence of precipitation was expressed after flowering.

In this paragraph, we will compare simulated yields and direct meteorological series of precipitation, temperature and solar radiation, using accumulated values for those meteorological elements over different periods, in order to explain the extent to which individual factors allow us to describe the whole complex. Correlation analyses (linear and second-order polynomial) were performed.

In Tartu , linear correlations between MPY and the accumulated meteorological factors were weak, although they were significant in some cases since the series were long (Table 2). The correlations with temperature were slightly higher, but only for the early variety.

In Kuressaare, significant ($P < 0.01$) linear correlations were identified between MPY and all the accumulated meteorological factors in the selected periods: positive for precipitation and negative for solar radiation and temperature. In general, the period with the highest correlations began earlier for precipitation (from May for ‘Maret’ and from June for ‘Anti’), and later for temperature and radiation (from June and July, respectively). The results for Kuressaare are quite different from those for Tartu because its location on the island of Saaremaa in the western part of Estonia is characterised by a mild marine climate and dry summers. Low precipitation at the beginning of summer causes dry conditions, so water deficit is the main limiting factor there. The relationships between MPY and solar radiation and temperatures are largely indirect, and these factors correlate negatively with precipitation.

As a rule, if a curve with a maximum describable by a second-order polynomial is applied, better correlation will be apparent between MPY and the accumulated meteorological elements. This means that for all factors, the limitation derives from both deficit and excess. Again, the highest correlations occurred in Kuressaare: for ‘Anti’ with precipitation (June-August: r = -0.77, May-August: r = -0.76), and for ‘Maret’ with temperature from June to September (r = -0.71). The only exception, where the correlations are almost equal on the linear and polynomial curves, is the early variety in Kuressaare. There, the conditions are dry, especially in the first half of summer, so the limiting factor for the early variety in most years is a deficit of precipitation. For the late variety, the decrease in yield is occasionally caused by an excess of water. However, the latter is much more common in inland regions, represented by Tartu, where intense rainy periods produce soil moisture near its maximum content in June and July, causing the loss of soil aeration and a very significant reduction in yield.

The limiting from two sides and high variances between MPY and the cumulative meteorological elements allow us to conclude that, under our conditions, MPY gives qualitatively new information about climate variability in summer, especially regarding climatic favourableness, by integrating the effects of different weather factors. In conditions with one very dominant limiting factor, there is no need for such an indicator, e.g., near the

Polar Circle, where MPY correlates very well with temperature (Sepp et al., 1989) or in arid regions, where the dominant factor is water deficit. For the stations analyzed in our work, Kuressaare is the most likely to be affected by a single dominant limiting factor, but the variance is still quite high there.

Station	Meteo-element	Relation-ship	Early variety 'Maret'			'Late variety Anti'		
			May-Aug	June-Aug	May-Sept	May-Aug	June-Aug	May-Sept
Tartu	R	LIN	0,03	0,02	0.03	0,01	-0,03	0.02
		POL	**--0,36**	**--0,41**	**--0.31**	**--0,47**	**--0,52**	**--0.43**
	P	LIN	--0,07	--0,02	--0.13	--0,06	--0,12	--0.03
		POL	**--0,53**	**--0,40**	**--0.49**	**--0,64**	**--0,56**	**--0.40**
	T	LIN	**--0,26**	**--0,37**	--0.24	--0,04	--0,20	--0.03
		POL	**--0,35**	**--0,50**	--0.29	**--0,41**	**--0,55**	**--0.35**
		POL	--0,25	**--0,32**	**--0.26**	**--0,34**	**--0,35**	**0.34**
	P	LIN	0,19	**0,27**	0.05	**0,26**	**0,34**	0.10
		POL	**--0,31**	**--0,33**	**--0.34**	**--0,42**	**--0,46**	**--0.42**
	T	LIN	--0,17	**--0,41**	--0.24	0,14	--0,09	0.08
		POL	**--0,41**	**--0,52**	**--0.34**	**--0,46**	**--0,44**	**--0.41**
Kuressaare	R	LIN	**--0,50**	**--0,55**	**--0.51**	**--0,46**	**--0,56**	**--0.45**
		POL	**--0,50**	**--0,55**	**--0.51**	**--0,47**	**--0,57**	**--0.47**
	P	LIN	**0,65**	**0,61**	**0.64**	**0,65**	**0,72**	**0.61**
		POL	**--0,68**	**--0,66**	**-0.65**	**--0,76**	**--0,77**	**--0.69**
	T	LIN	**--0,56**	**--0,68**	**--0.61**	**--0,30**	**--0,44**	**--0.35**
		POL	**--0,58**	**--0,69**	**--0.62**	**--0,48**	**--0,57**	**--0.51**

Table 2. Correlation coefficients *r* for the linear (LIN) and polynomial (POL) relationships between meteorologically possible yield (MPY) and accumulated solar radiation (R), precipitation (P), and temperature (T) at two stations. Bold indicates significance levels of $P < 0.01$.

3.3 Climate Change

Most climate change scenarios project that greenhouse gas concentrations will increase through 2100 with a continued increase in average global temperatures (IPCC, 2007). Results of the four emission scenarios, each containing 18 General Circulation Models (GCM) experiments used in SCENGEN provide a wide variety of possible climate change scenarios (Table 3). In this paragraph we will look at the results by four illustrative emission scenarios, achieved by using the multi-model average for two locations in Estonia. All scenarios project the increase in annual mean temperature, the highest warming is supposed to take place during the cold part of the year (Fig. 6). During the plant-growth period (April to September), the increase of air temperature will be lower. Average annual precipitation is also predicted to increase (Fig. 7), however, changes in the annual range of monthly precipitation vary highly between models and scenarios and are less certain than changes in temperature. On average, the highest change in precipitation is predicted for January and

November; August and September are predicted a small increase or even a slight decrease. All the projected climatic tendencies have already been noted during the last century (Jaagus, 2006), indicating evident climate warming in Estonia. In previous analogous works (Keevallik, 1998; Karing et al., 1999; Kont et al., 2003), temperature rise has been predicted higher; however we believe that moderate warming is more realistic.

		Temperature change, ° C		Precipitation change, %	
Year	Scenario	Tartu	Kures-saare	Tartu	Kures-saare
2050	A1B	2.40	2.37	8.5	8.1
	A2	2.60	2.54	10.0	8.8
	B1	1.73	1.71	6.2	5.8
	B2	2.25	2.24	8.1	8.0
2100	A1B	4.65	4.64	16.2	16.3
	A2	5.78	5.72	20.7	19.5
	B1	3.11	3.14	10.7	11.2
	B2	4.13	4.13	14.7	14.4

Table 3. Changes in annual air temperature and precipitation calculated as a mean of experiments by 18 different GCM for four different emission scenarios.

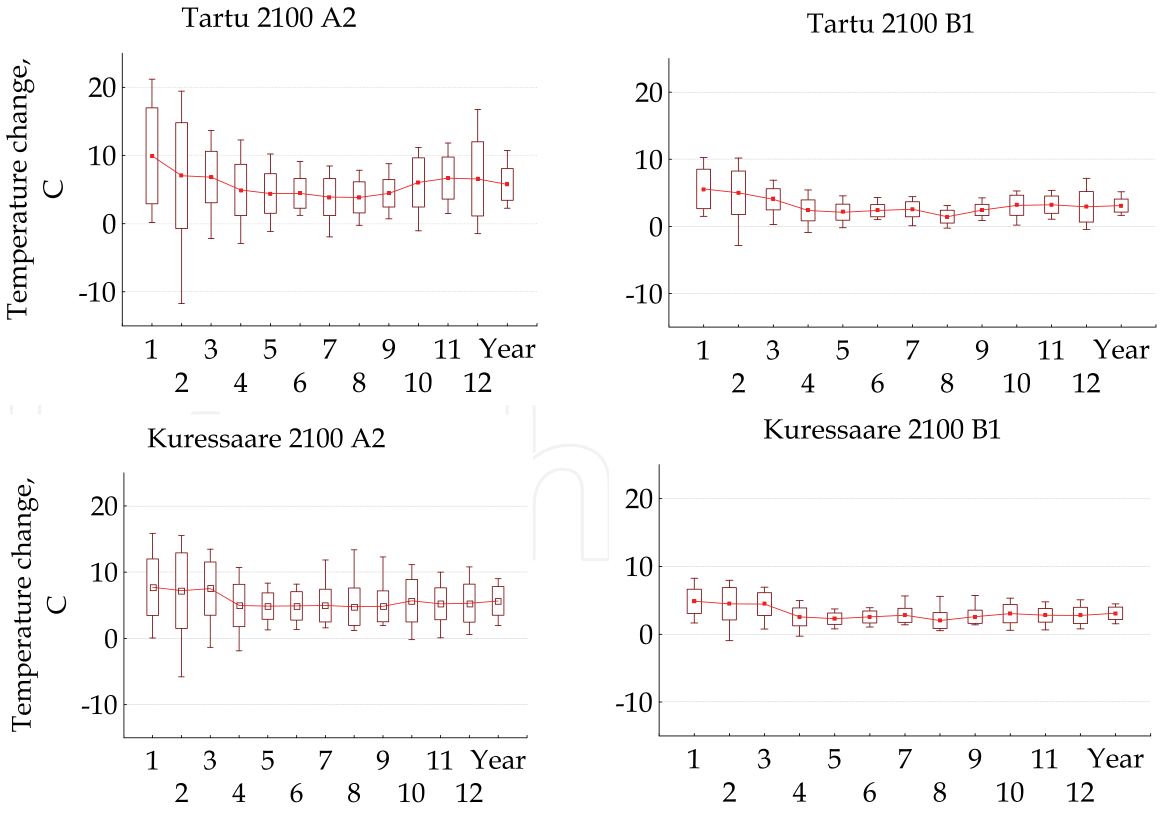

Fig. 6. Changes in monthly mean temperature (° C) predicted by 18 global climate models for the A2 and B1 emissions scenarios for year 2100 compared to the baseline period (1961–1990) at two Estonian sites. Lines connect the values of monthly mean change, boxes mark mean change ± standard deviation and whiskers mark the range of all models.

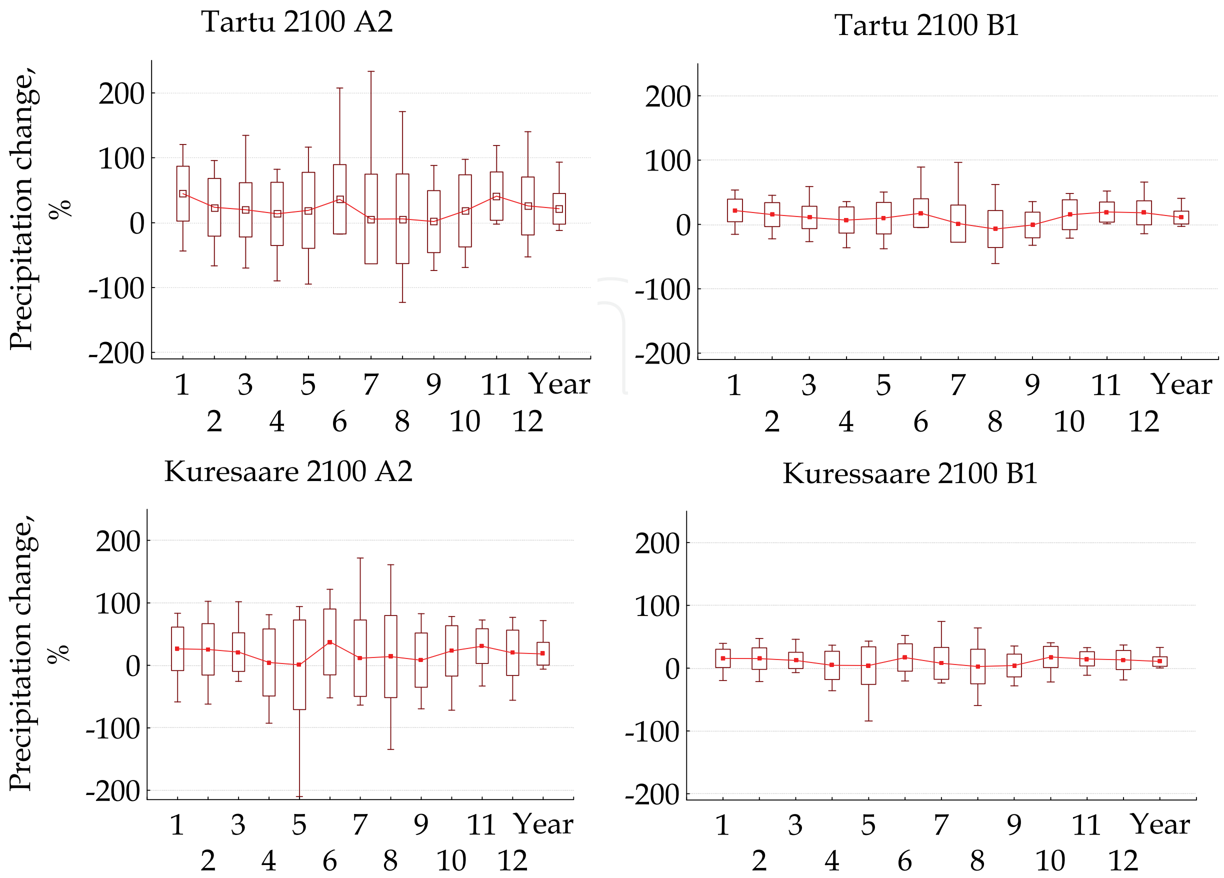

Fig. 7. Changes in monthly sum of precipitation (%) predicted by 18 global climate models for the A2 and B1 emissions scenarios for year 2100 compared to the baseline period (1961–1990) at two Estonian sites. Lines connect the values of monthly mean change, boxes mark mean change ± standard deviation and whiskers mark the range of all models.

3.4 MPY in the future

From now on, all changes in MPY are referred as compared to baseline period (1965-2006) and we will discuss the yields achieved with optimal planting time. The productivity and yield changes related to the rise of CO_2 in the atmosphere rise are not considered.

For the late variety 'Anti', the long-term mean MPY values, calculated by using historical climate data of 1965-2006 with computed optimal planting time, describing the optimal climatic resources for plant growth, are 58.9 t ha-1 in Tartu and 50.2 in Kuresaare (see Table 1). For the early variety 'Maret' the values are 44.0 and 39.3, respectively.

For early variety, all four considered scenarios predict losses in all given localities (Fig. 8). Stronger scenarios cause higher losses, up to 37% in Tartu and 32% in Kuressaare by 2100. In Kuressaare, the change in mean MPY is statistically significant for the year 2050 only by the strongest, A2 scenario (p=0.03); for the year 2100 all scenarios predict significant loss (p<0,001). In Tartu, for the year 2050 the change in MPY is significant by A2 (p=0.002), A1B (p=0.01) and B2 (p=0.03) scenarios; for the year 2100, the loss in MPY is significant by all scenarios (p<0.001).

For late variety, remote rise in yields is predicted for year 2050. Lower temperature rise through milder scenarios is more favourable for potatoes – B1 scenario predicts 5.5% yield rise in Tartu and 5% in Kuressaare, while for A2 scenario the rise is 2.5 and 2%. For year 2100, all scenarios predict yield losses, stronger scenarios up to 15% in Tartu, up to 19% in Kuressaare for 2100 as compared to present climate. The changes in 'Anti' MPY are however not statistically significant for any location, year or scenario.

Compared to yield variability in baseline climate, the predicted yield variability of 'Anti' turned to be significantly ($p<0.05$) lower in Kuressaare in case of the strongest climate change (A2 scenario for the year 2100) (standard deviation 11.6 compared to 15.8 t ha^{-1}). The 'Maret' MPY variability is also lower in Kuressaare in 2100 by scenarios A1B ($p<0.001$), A2 ($p<0.001$) and B2 ($p=0.02$), standard deviation declining from 10.1 to 6.3, 5.7 and 7.7 t ha^{-1}, respectively. In Tartu, the change in variability was only significant ($p=0.009$) for A2 in 2100 (standard deviation 7.8 to 5.4 t ha^{-1}).

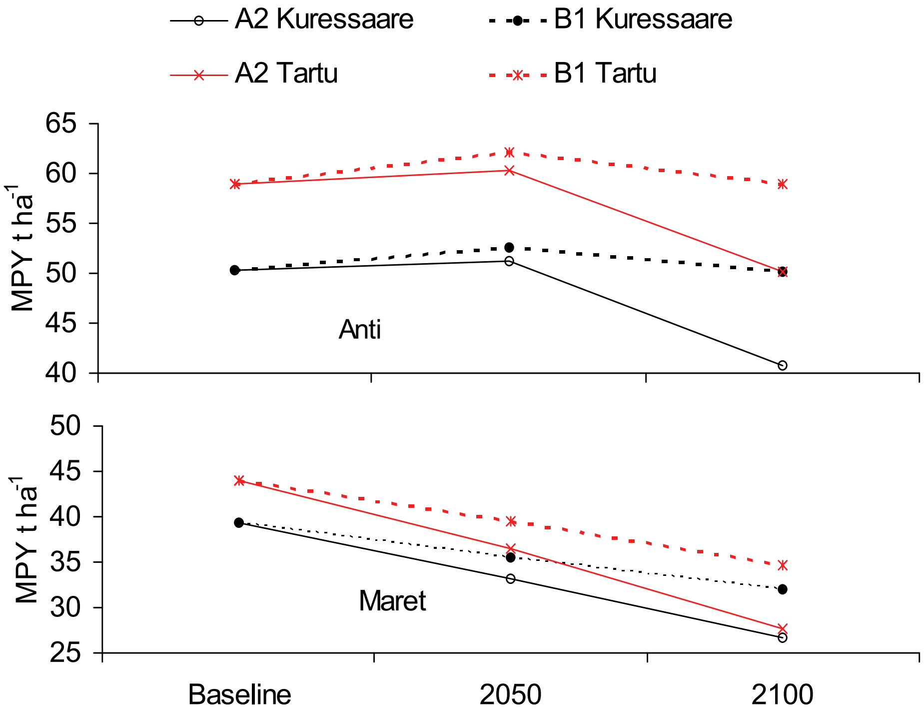

Fig. 8. Mean values of the meteorologically possible yield (MPY) of late potato variety 'Anti' and early potato variety 'Maret' for baseline period (1965-2006), years 2050 and 2100 by the two scenarios predicting the strongest (A2) and weakest (B1) warming.

3.5 Cumulative distribution of MPY

An applicable method for comparing the extent of MPY variability among different varieties and locations is based on their cumulative distributions, which expresses the probabilistic climatic yield forecast (Zhukovsky et al., 1990). For the baseline climate, the late variety 'Anti' produced higher yields across the entire range of probabilities and the distribution of the yield is not a symmetric one. Low yields, corresponding to extreme meteorological conditions and forming deep deviations in time series (Fig. 5), stretch the cumulative distribution out in the left part (Fig. 9 & 10). For the current climate, the decline in the cumulative distribution is quite steep after the mean value of MPY. High MPY values correspond to the years in which the different meteorological resources are well balanced throughout the summer period. As a rule, these are climatically similar to the climatic norms for all the factors in Estonia. The MPY distribution for ‘Anti’ is lower in Kuressaare, predominantly in the range of lower and central MPY values, resulting in a smoother decline in the range of the highest yields. Even larger inequalities in mean values as well as in their distributions appear between two locations for the early variety ‘Maret’. We can conclude that the differences in climatic conditions during the first half of summer have a greater effect on early varieties. The shape of the distribution curve is more symmetric for the early variety.

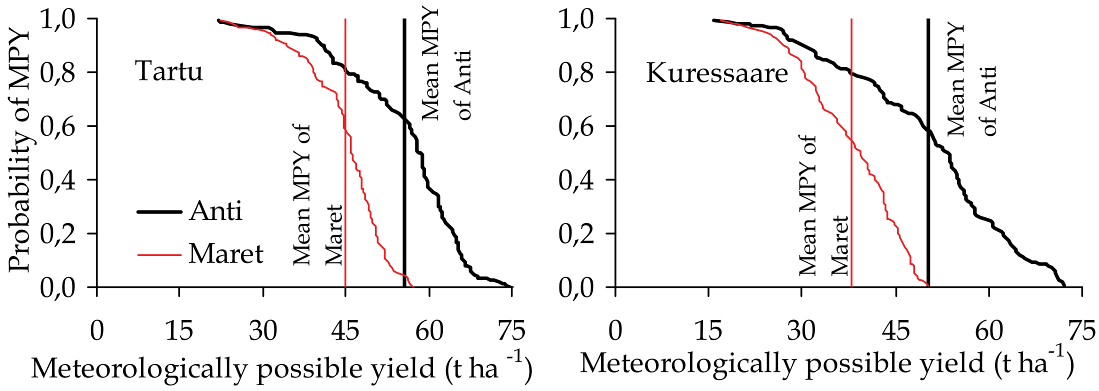

Fig. 9. Cumulative distribution of the MPY for the current climate, achieved by real planting dates.

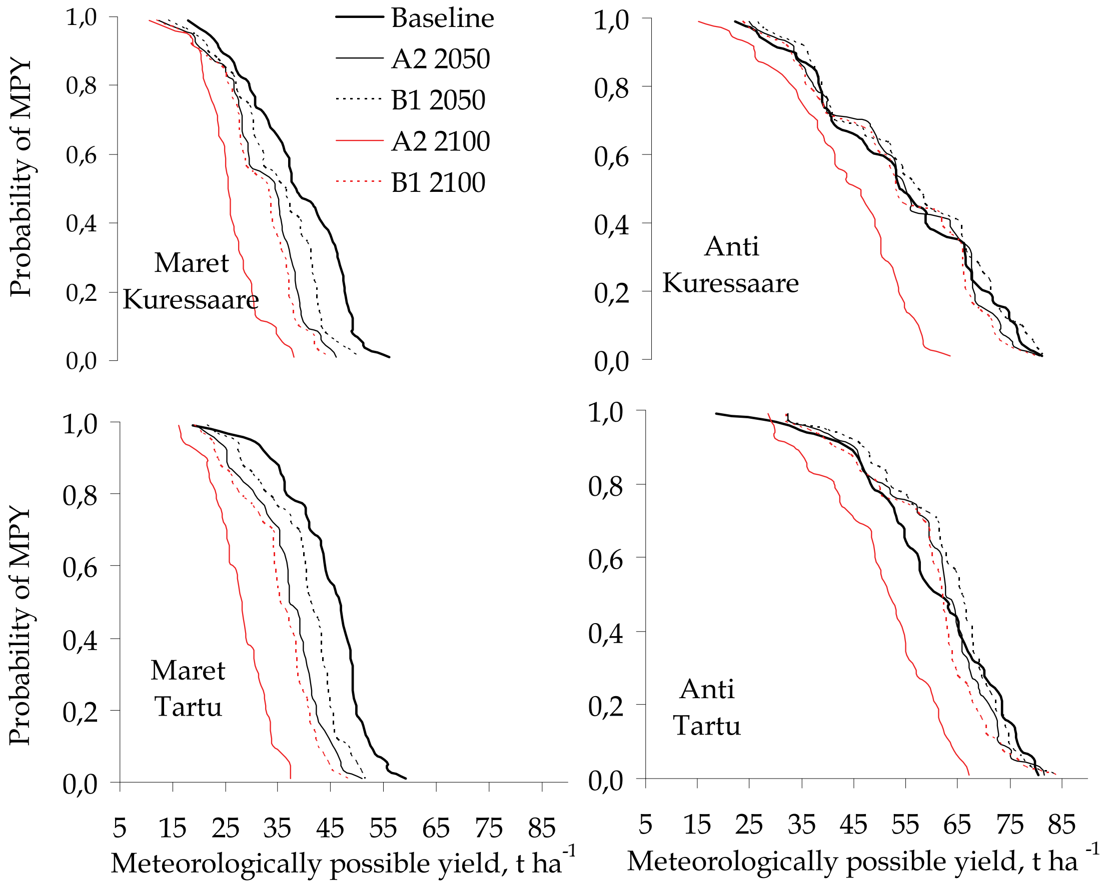

Fig. 10. Cumulative distribution of the MPY for baseline climate (1965-2006) and two climate change scenarios for the target years 2050 and 2100, achieved by computed planting dates.

Cumulative distribution of the future MPY values (Fig. 10) shows greater differences between scenarios and target years for 'Maret', witnessing the higher weather sensitivity of early variety. For all cases, A2 scenario certifies definite disadvantage of strong warming modelled for the year 2100. For 'Anti', the cumulative yield differences between scenarios and target years are not very stark, enabling to conclude the advantage of longer maturing varieties for future climate warming.

4. Conclusions and discussion

The main objective of this chapter was to show that computed yields give additional information about climatic variability compared with the traditional use of individual meteorological elements. Our results indicate that none of the observed separate meteorological factors sufficiently reflects the variations in the computed MPY series. We found significant linear correlations for only the western Estonian coastal zone, represented by the station at Kuressaare, because of the dominant limiting factor, the water deficit during the first half of summer in most years. Although the polynomial correlations were higher, indicating a dual influence of the factors, there was still high variance. The significant changes in MPY variability, as observed in Tartu in the second half of the period, were only weakly expressed in the precipitation series and were absent from the temperature and radiation data. Evidently, the combined effects of weather conditions on plant production processes have a more complex character than can be measured with long-term statistics for individual meteorological elements. Consequently, the use of MPY to express the agrometeorological resources available for plant production in yield units introduces additional information about the impact of climatic variability. The changes in MPY and their statistical distribution are better indicators of the impact of climate change on plant production than are changes in the time series of any individual meteorological elements. This holds particularly true if simulations for species adapted to local climatic conditions are used. If species are located at the borders of their distribution areas, some meteorological factors will predominantly limit their growth and will describe the climatic resources without being combined with other factors. The MPY series collected through 83-106 years revealed no significant trends. However, significant trends do exist in terms of shorter periods. The variability of MPY has been increasing in the island regions of Estonia since the 1940s and in the continental areas since the 1980s.

The above-described results have been further expanded into the future and future values of meteorologically possible potato crop yield have been generated. This allows to estimate the influence of climate change on agrometeorological resources for potato growth in Estonia. All of the four climate change scenarios projected the increase in annual mean temperature for Estonia, the highest warming during the cold part of the year. Average annual precipitation was also predicted to increase, however, changes in the annual range of monthly precipitation vary highly between models and scenarios and are less certain than changes in temperature. All the projected climatic tendencies have already been noted in observations during the last century (Jaagus, 2006), indicating evident climate warming in Estonia.

Changes in MPY were calculated using historical weather variability and projected changes in mean monthly values. For early potato variety, all scenarios predict losses in potato yields, while the scenarios of more notable warming cause higher losses. For late variety, a slight rise in yields is predicted for 2050, which turns to loss by 2100. However, the changes are not statistically significant for the late variety. This result is a development from previous results with the same model (Kadaja & Tooming, 1998; Karing et al., 1999; Kadaja, 2006), which predicted yield rise with moderate scenarios for late variety and loss only occurs with strong warming scenarios.

There have been several researches in different regions about possible climate-change-related variation in potato growth. Peiris et al. (1996) calculated increases in tuber yield by temperature rise for potato in Scotland due to faster crop emergence and canopy expansion and thus a longer growth period. Wolf (1999 a, 2002) has reported small to considerable increases in a mean tuber yield with climate change in the Northern Europe, being caused by the higher CO_2 concentration and by the temperature rise. Wolf and van Oijen (2002) showed yield increase for the year 2050 in all regions of the EU, mainly due to the positive yield response to increased CO_2. Such disagreement with our results likely derives from the fact that in our study no effect of CO_2 rise on potato growth has been considered. There is clear evidence since 1950s (Keeling et al., 1995) that atmospheric CO_2 is increasing, and plant physiologists have repeatedly demonstrated that such increases likely have already caused substantial increases in leaf photosynthesis of C_3 species (Sage, 1994). The presence of large sinks for assimilates in tubers makes potato crop a good candidate for large growth and yield responses to rising CO_2; this effect tends to be smaller for late cultivars (Miglietta et al., 2000). However, since the optimal temperature range for tuber growth (between 16 and 22 ^oC) is small (Kooman, 1995), and since with climate change the prevailing temperature during tuber growth will likely be different, the positive effect of CO_2 may be counteracted by the effect of a concominant temperature rise. Wolf (1999a; 2002) has shown such effect for central and southern Europe, where the negative effect of temperature rise was expected sometimes to exceed the positive effect of CO_2 enrichment. Under hotter and wetter scenarios for Great Britain, Wolf (1999b) demonstrated tuber yields to become lower, caused by the temperature rise, which speeded the phenological development of the crop and reduced the time for growth and biomass production. At the same time, under the smaller temperature rise the yield had mainly increased at the same locations. Rosenzweig et al. (1996) have also calculated decreases in tuber yield for most sites in the USA due to the negative effect of temperature rise on yield that was stronger than the positive effect of CO_2 enrichment. Miglietta et al (2000) have described a model experiment for Dutch weather conditions, where the elevated temperature reduced the positive effect of elevated CO_2. For predicted future temperature rise (without an increase in atmospheric CO_2) over England and Wales, Davies et al. (1997) calculated variable and little changes in tuber yield of potato.

Based on this knowledge and our current research result, we can thus say that the climatic resources for potato growth are predicted to become worse under climatic change because of increased temperature and variable rainfall; however in higher latitudes this effect may be altered and turned positive by the change in plants photosynthetic activity and production.

The variability of potato yields is predicted to decrease slightly due to climate change. This is however not a plausible result, since the change in meteorological variability has not been counted in. Further investigation need rises in this area. Also Wolf (1999a) has shown the variability of non-irrigated tuber yield to essentially zero to moderately decrease in Northern Europe.

Acknowledgements

Financial support from the Estonian Science Foundation grants No 6092 and 7526 is appreciated.

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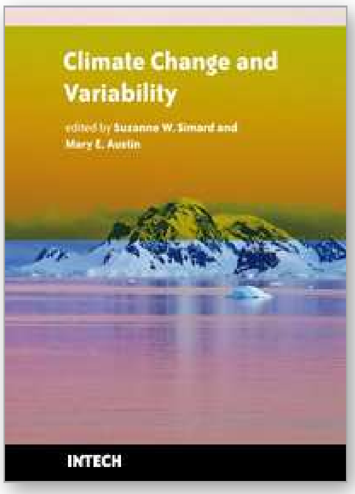

Climate Change and Variability

Edited by Suzanne Simard

ISBN 978-953-307-144-2
Hard cover, 486 pages
Publisher Sciyo

Published online 17, August, 2010

Published in print edition August, 2010

Climate change is emerging as one of the most important issues of our time, with the potential to cause profound cascading effects on ecosystems and society. However, these effects are poorly understood and our projections for climate change trends and effects have thus far proven to be inaccurate. In this collection of 24 chapters, we present a cross-section of some of the most challenging issues related to oceans, lakes, forests, and agricultural systems under a changing climate. The authors present evidence for changes and variability in climatic and atmospheric conditions, investigate some the impacts that climate change is having on the Earth's ecological and social systems, and provide novel ideas, advances and applications for mitigation and adaptation of our socio-ecological systems to climate change. Difficult questions are asked. What have been some of the impacts of climate change on our natural and managed ecosystems? How do we manage for resilient socio-ecological systems? How do we predict the future? What are relevant climatic change and management scenarios? How can we shape management regimes to increase our adaptive capacity to climate change? These themes are visited across broad spatial and temporal scales, touch on important and relevant ecological patterns and processes, and represent broad geographic regions, from the tropics, to temperate and boreal regions, to the Arctic.

How to reference
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Triin Saue and Jüri Kadaja (2010). Simulated Potato Crop Yield - an Indicator of Climate Variability in Estonia, Climate Change and Variability, Suzanne Simard (Ed.), ISBN: 978-953-307-144-2, InTech, Available from: http://www.intechopen.com/books/climate-change-and-variability/simulated-potato-crop-yield-an-indicator-of-climate-variability-in-estonia

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