# Simulated crop yield — an indicator of climate variability

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Biological production of plants is a complex variable, which integrates summer weather conditions. To assess summer climate variability over the last century, the concept of the meteorologically possible yield (MPY) can be used, which expresses the highest yield under existing meteorological conditions, not limited by soil quality (except its hydrological properties) or management. The MPY for early and late varieties of potato were computed with a potato-production model (POMOD) for three localities in Estonia for periods of 83–106 years. The computed yields were compared with cumulative meteorological factors and a set of the North Atlantic Oscillation indices. Significant polynomial relationships between the MPY and the cumulative meteorological elements appeared for all localities, whereas linear regression was significant only for the western coastal zone. The dual relationships, the continuously high variance around a polynomial relationship and the changes in the MPY series variability not expressible as single factors, indicate that MPY gives qualitatively new information about climatic variability in a synthesis of different factors. Correlations between the NAO index of some late autumn and winter months and MPY values were significant, albeit weak. The highest, negative correlations, expressing the effects of anticyclonic patterns, proceeded from the previous November. Positive correlations were identified for January only for a late variety of potato at an inland station.

## Introduction

When assessing climatic changes and variability, we often use several meteorological elements, their mean and cumulative values, and the limits of their variation. Because climate variability is the result of many different factors, integral indices are also sought in different fields. For instance, in agricultural meteorology, indices that reflect the balance between radiation or warmth and water resources are widely used. One of the complex variables, integrally describing summer weather conditions, is the biological production of plants. The primary requirement for the success of a plant in a particular area is that its phenology fits 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 and Porter 2006). Still, experimental studies of climate change through plant productivity are complicated, as it is hard to distinguish the impact of climate variability from the effects of soil, landscape, and management. Furthermore, although the yield of agricultural crops is a quite commonly measured value, there are no long, homogeneous time series of field crop yields in Estonia because fields are interchanged with crop rotation and varieties; agricultural techniques and management or other factors also change. Therefore, the use of 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.

This study is based on a computed yield series for potato (*Solanum tuberosum*), which is one of the typical agricultural crops of Estonia (Kotkas 2006). We calculated the potato yields using the production process model, POMOD (Sepp and Tooming 1991, Kadaja and Tooming 2004), based on the principle of maximum plant productivity and the method of reference yields. To assess whether separate meteorological elements can describe the variation in the simulated yields as a complex estimate, we performed a correlation analysis of the yields and the accumulated meteorological elements of the growing season (May–September). The main objective of the study was to determine whether the computed yields provide additional information compared with the traditional use of individual meteorological elements in the assessment of climate variability.

In climate studies, a large number of variables characterizing the large-scale atmospheric circulation are broadly used and are related to climatic variables, usually air temperature and precipitation. Since Yarnal (1993) extended the definition of synoptic climatology, the range of topics/elements compared has expanded significantly, and include among others the biotic environment. There are many ways to characterise atmospheric circulation. Over the middle and high latitudes of the northern hemisphere, the most prominent and recurrent pattern is the North Atlantic Oscillation (NAO) (Hurrell 1995, Hurrell and van Loon 1997, Dickson *et al.* 2000). The NAO index, calculated as the difference between the standardized sea-level pressure anomalies between the Azores high and the Iceland low, can be defined as a measure of the intensity of the westerlies in the Atlantic–European sector. High index values denote a large air-pressure gradient and a strong westerly airflow. Under such conditions, the weather is moister and winters are warmer than normal in northern Europe. Negative values indicate a small pressure gradient, thus weakening the westerlies. The irregular and largely unpredictable swings from one phase of NAO to another are responsible for much of the variability in the weather of Europe. However, the influence of the NAO on the local climate becomes more obvious during the cold seasons. A strong connection between the NAO and the Baltic Sea climate has been shown (Chen and Hellström 1999, Sepp and Jaagus 2002, Omstedt *et al.* 2004, etc.). Given the small territory of Estonia (ca. 45 000 km$^2$), the effects of global circulation cannot be spatially very different across the country, although the NAO effects are more distinct in the western coastal area and are less explicit inland. As demonstrated by Jaagus (2006), the increase in the intensity of the westerlies during the cold period has caused evident warming of the winter in Estonia. Changes in the winter circulation and conditions also significantly influence the warming in spring (Tooming and Kadaja 2006).

As pointed by Hurrell *et al.* (2003), agricultural harvests, among other things, are directly affected by the NAO. Therefore, in the present study, computed yields were also correlated with the NAO index of different periods. Significant correlations have been established between large-scale circulation variables and meteorological factors in Estonia, principally for the winter half of the year (Tomingas 2002, Jaagus 2006). However, possible relationships between crop yields and circulation indices might also help to explain the potential impact of atmospheric circulation on the integrated complex of summer weather conditions and identify indirect correlations.

## The model and the category of meteorologically possible yield (MPY)

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 (Kadaja and Tooming 2004) was applied based on the principle of maximum plant productivity (Tooming 1967, 1970, 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.

This concept is applied in the dynamic model POMOD to model the potato production process and yield (Sepp and Tooming 1991, Kadaja and 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. As a result, MPY expresses agrometeorological resources. Its mean value over a long period characterizes 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 and 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 photosynthetic rate is expressed by equations derived from the principle of maximum plant productivity (Tooming 1967). 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 as a function 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.

The biological parameters of the potato varieties were determined on the basis of field experiments, when not limited by nutrient deficiency, when properly cultivated, when weed and pest free, and when regularly protected from late blight (Sepp and Tooming 1991, Kadaja 2004). The computed yields 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 and Tooming 1991). Further verification of the model has been made on the basis of 20-year yield series for 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 for three stations, whereas for the fourth, the correlation was not significant because of an increase in the level of plant diseases. The relative variability of MPY was less than that of the real yields, with coefficients of variation of 0.20 and 0.27, respectively, in the Variety Control Network, and averagely 0.12 and 0.20, respectively, if the territorial mean was simulated and the commercial yields were compared (Sepp and Tooming 1991).

## Locations and input data

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 three stations: Tartu (58°15´N, 26°27´E), Tallinn (59°23´N, 24°36´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 and Truu (2004), Tartu and Tallinn are located in the Mainland Estonia climatic region, characterized by a more continental climate, and Kuressaare is located in the Island Estonia region, with a much more maritime climate. Tallinn and Tartu fall into different climatic subregions. Tallinn is a typically semicontinental subregion, where the continental influence prevails, but it is also significantly influenced by the Baltic Sea. Tartu is located in the far hinterland in the continental subregion, with practically no climatic effect of the Baltic Sea. Spring is much warmer there and summer starts earlier. In addition to different temperature regimes, there are considerable differences in precipitation between the stations. In the plant-growing period (May–September), the precipitation average in 1961–1990 was 270 mm in Kuressaare, compared with 334–335 mm in Tartu and Tallinn. 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 as compared with that at the other two stations under discussion. 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.

The length and completeness (i.e., lack of gaps) of the data series were used as additional criteria. For Tartu, data were available for the period 1901–2006, for Tallinn in 1920–2006, and for Kuressaare in 1923–2000. Therefore, for 2001–2006, we had to calculate the meteorological data for Kuressaare 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).

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 and Tooming 2004).

The first group includes daily data on global radiation, air temperature, and precipitation from May to September. Direct measurements of global radiation have only been made since 1954 in Tartu and since 2004 in Tallinn. We computed the missing daily sums of global radiation from sunshine duration, using regression equations established separately for every month in Tartu.

Annual information includes 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. 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), at Saku (near Tallinn), 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 Tallinn and 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 (kg $CO_2$ $s^{-1}$ $W^{-1}$), the irradiation density of adaptation (W $m^{-2}$), and the photosynthesis and respiration rates at the saturated PAR density given per unit mass of leaves (kg $CO_2$ $kg^{-1}$ $s^{-1}$) were estimated initially from the literature and were specified for the model by a calibration method from experimental field data (Saue 2006). Growth functions were determined on the basis of field experiments made from 2001 to 2006 (Kadaja 2004, 2006a).

We also compared MPY with the NAO index of different periods. We used an index set calculated on the basis of the pressure data for Ponta Delgada (Azores) and Stykkisholmur/Reykjavik (Hurrell and van Loon 1997). An updated version of the dataset is available at http://www.cgd.ucar.edu/cas/jhurrell/indices/html.

## Time series of meteorological resources

The late variety produced higher yields at all locations. For 'Anti', the long-term mean MPY values, which describe the climatic resources for plant growth, were 55.5 t $ha^{-1}$ in Tartu and Tallinn, and 50.3 t $ha^{-1}$ in Kuressaare. The mean MPY values of the early variety 'Maret' were 45.0, 48.6, and 37.8 t $ha^{-1}$, respectively.

Generally, 'Anti' demonstrated a greater variation in yield. The variation coefficients in Kuressaare are 0.21 for 'Maret' and 0.27 for 'Anti'. Concurrently, in Tartu and Tallinn, the variation coefficients were smaller: around 0.17 for 'Maret' and 0.19 for 'Anti'. Comparison of the MPY variability in different periods showed a significant increase in variance in Tartu since the early 1980s. For 'Maret', the standard deviations of MPY were 6.4 t $ha^{-1}$ in 1901–1980 and 9.5 t $ha^{-1}$ in 1981–2006 ($F$-test: $P < 0.01$); for 'Anti', the corresponding values changed from 10.0 to 13.4 t $ha^{-1}$ ($P < 0.05$). 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. Therefore, the separate meteorological elements did not reflect the influence of their combined effect on the variability of biological production. In Tallinn and Kuressaare, variability does not seem to have been higher in the last 25 years than in other periods. 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 ($P < 0.05$).

Overall, the MPY series show only weak and insignificant trends (Fig. 1), although reliable trends are apparent for some shorter periods. The longest period with a significant ($P <$ 0.05) increasing trend was observed in Tallinn from 1927 to 1990, and a decreasing trend was observed in Kuressaare from 1977 to 2006. In general, it is supposed that climate change should have some positive effects at high latitudes, as in Estonia (for example, the lengthening of the growing season should favour agricultural production). Indeed, the calculations based on different climate change scenarios for Estonia, which predict an increase in both temperature and precipitation (Keevallik 1998), have predicted a rise in MPY for both low and medium climate change scenarios, of up to 2%–16%, with a shift in the optimum range for potato production to the Estonian latitudes (Kadaja and Tooming 1998, Kadaja 2006b). The gain is supposed to be the highest in northern Estonia (including the Tallinn region), mainly attributed to an increase in temperature and in the duration of the growing period, and on the islands Hiiumaa and Saaremaa, primarily attributed to increased precipitation. This discrepancy with the results computed on the basis of a series of actual meteorological data arises because these climate change scenarios do not reflect day-to-day or month-to-month variability, but calculate changes in mean values.

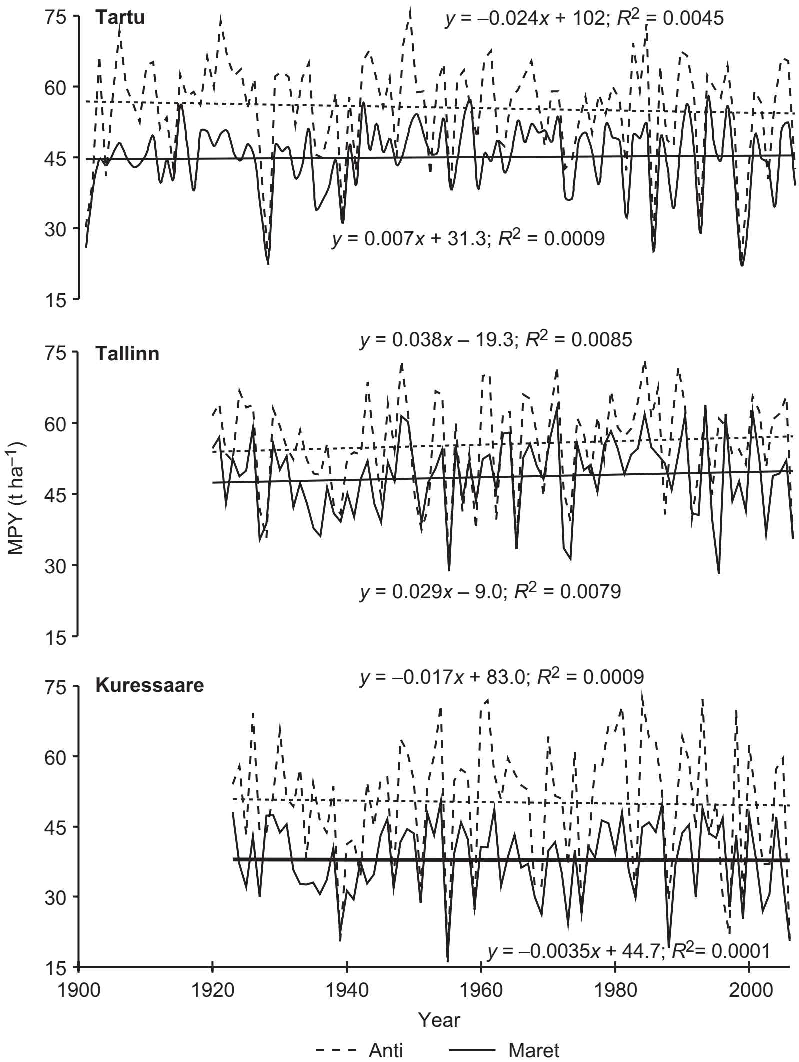


**Fig. 1**. Series of meteorologically possible yields (MPY) of the early potato variety 'Maret' and the late variety 'Anti' at three meteorological stations.

Therefore, in Kuressaare, the decreasing trend in the MPY associated with climatic changes that have already occurred is probably caused by the increased variability in precipitation, the limiting factor during the growing season. This leads to more frequent drought periods and more intense flooding rainfalls, which are not always expressed in the cumulative values for precipitation. In Tartu and especially in the south-eastern part of Estonia, the predicted advantages of climate warming are small, and a strong negative impact will follow the strong climate change scenarios (Kadaja and Tooming 1998).

An applicable method of comparing the extent of MPY variability among different varieties and locations is based on their cumulative distributions, which express the probabilistic climatic yield forecast (Zhukovsky *et al*. 1990). The late variety 'Anti' produced higher yields across the entire range of probabilities and the distribution of the yields is not symmetric (Fig. 2). Low yields, corresponding to extreme meteorological conditions and forming deep deviations in time series (Fig. 1), stretch the cumulative distribution out in the left part (Fig. 2). 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

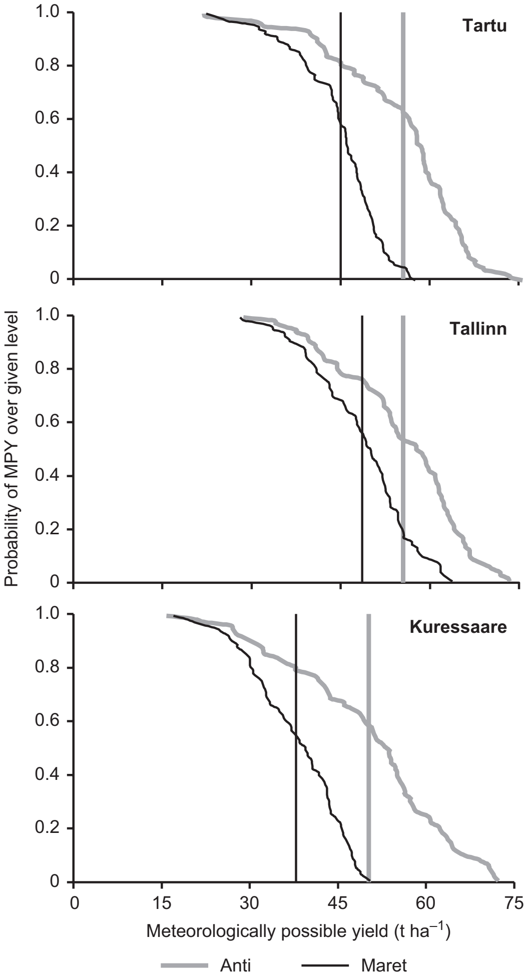


**Fig. 2**. Cumulative distribution of the meteorologically possible yield (MPY) of potatoes for the early variety 'Maret' and the late variety 'Anti' at three meteorological stations. Vertical lines indicate the mean values for MPY.

rule, these years are climatically similar to the climatic norms for all the factors in Estonia. The MPY distribution for 'Anti' is quite similar at the Tartu and Tallinn stations, whereas it 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.

Major inequalities in mean values, as well as in their distributions, appear in different localities 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. Like the late variety 'Anti', the lowest mean yield for 'Maret' occurs in Kuressaare, but there are also differences between Tartu and Tallinn, mostly in the range of higher yields. The shape of the distribution curve is more symmetric for the early variety.

## Relationships between MPY and other indicators

We compared simulated yields and a direct meteorological series that included precipitation, temperature, and solar radiation, using accumulated values for these 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, and another comparison was made with the NAO index.

In Tartu and Tallinn, linear correlations between MPY and the accumulated meteorological factors were weak, although they were significant in some cases since the series were long (Table 1). 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 the other two stations 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 (Fig. 3) is applied, better correlation will be apparent between MPY and the accumulated meteorological elements. This means that for all factors, 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 for 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, where intense rainy periods result in soil moisture near its maximum content in June and July, causing the loss of soil aeration and a very significant reduction in yield, as can be seen in the rightmost points in Fig. 3.

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)

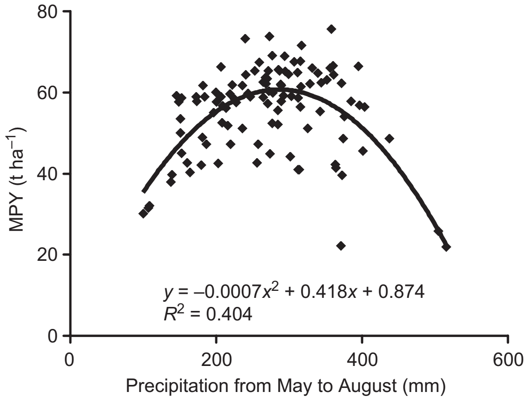


**Fig. 3**. Relationship between accumulated precipitation from May to August and the meteorologically possible yield (MPY) in Tartu and the corresponding second-order polynomial curve.

**Table 1**. 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 three meteorological stations. Statistically significant correlations ($P < 0.01$) are set in boldface.

| Station | Meteoelement | Relationship | Early variety 'Maret' | | 'Late variety Anti' | |
|---|---|---|---|---|---|---|
| | | | May–Aug. | June–Aug. | May–Aug | June–Aug |
| Tartu | R | LIN | 0.03 | 0.02 | 0.01 | –0.03 |
| | | POL | **–0.36** | **–0.41** | **–0.47** | **–0.52** |
| | P | LIN | –0.07 | –0.02 | –0.06 | –0.12 |
| | | POL | **–0.53** | **–0.40** | **–0.64** | **–0.56** |
| | T | LIN | **–0.26** | **–0.37** | –0.04 | –0.20 |
| | | POL | **–0.35** | **–0.50** | **–0.41** | **–0.55** |
| Tallinn | R | LIN | –0.03 | –0.12 | –0.01 | –0.10 |
| | | POL | –0.25 | **–0.32** | **–0.34** | **–0.35** |
| | P | LIN | 0.19 | **0.27** | **0.26** | **0.34** |
| | | POL | **–0.31** | **–0.33** | **–0.42** | **–0.46** |
| | T | LIN | –0.17 | **–0.41** | 0.14 | –0.09 |
| | | POL | **–0.41** | **–0.52** | **–0.46** | **–0.44** |
| Kuressaare | R | LIN | **–0.50** | **–0.55** | **–0.46** | **–0.56** |
| | | POL | **–0.50** | **–0.55** | **–0.47** | **–0.57** |
| | P | LIN | **0.65** | **0.61** | **0.65** | **0.72** |
| | | POL | **–0.68** | **–0.66** | **–0.76** | **–0.77** |
| | T | LIN | **–0.56** | **–0.68** | **–0.30** | **–0.44** |
| | | POL | **–0.58** | **–0.69** | **–0.48** | **–0.57** |

or in arid regions, where the dominant factor is water deficit. For the stations analyzed in our study, Kuressaare is the most likely to be affected by a single dominant limiting factor, but the variance is still quite high there.

We found no direct correlation between MPY and the NAO index over the growing period. Significant, although weak, correlations exist with the NAO indices of a few autumn and winter periods (Table 2). Reliable negative correlations with the previous November's NAO index were observed for all stations and for both varieties. So, if the NAO index is negative (corresponding to anticyclonic situations) in the late autumn and early winter, there is a tendency for better conditions in the following summer. These negative correlations tended to be slightly higher at the coastal stations. If the NAO index is averaged over the periods from November to some following months, negative correlations appeared only in Tallinn. In Tartu, positive correlations between MPY and NAO occurred in January, lasting in the case of 'Anti' until May, and reflect the positive influence of a mild winter (positive NAO index) on the following summer growing conditions. This impact of a milder winter on the spring temperature can be expected because of the lesser thickness and duration of the snow and ice cover (Tooming and Kadaja 1999, 2006), allowing an earlier spring season and soil drying. This situation seems to have a positive effect in the continental region, but not in coastal areas, where it can lead to early drought. Reliable positive correlations appear again in Tartu in September, mostly for the late variety. Here, negative NAO indices probably imply early frosts, which prohibit the full potato yield.

## Conclusions

The main objective of our study was to determine whether 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 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, compared with the traditional climatic approach. 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

**Table 2**. Linear correlation coefficients between meteorologically possible yield (MPY) and values of the NAO index calculated on the basis of Ponta Delgada–Stykkisholmur/Reykjavik. Statistically significant correlations ($P < 0.05$) are set in boldface.

| Station | Variety | Nov. | Nov.–Dec. | Nov.–Feb. | Jan. | Jan.–May | Sep. |
|---|---|---|---|---|---|---|---|
| Tartu | Maret | **–0.21** | –0.1 | –0.003 | 0.15 | 0.07 | 0.14 |
| | Anti | **–0.28** | –0.16 | 0.03 | **0.19** | **0.18** | **0.22** |
| Tallinn | Maret | **–0.33** | **–0.27** | **–0.19** | –0.02 | 0.09 | –0.001 |
| | Anti | **–0.31** | **–0.20** | –0.10 | 0.02 | 0.16 | 0.06 |
| Kuressaare | Maret | **–0.23** | –0.11 | 0.02 | **0.19** | 0.08 | –0.09 |
| | Anti | **–0.29** | –0.13 | –0.04 | 0.10 | 0.09 | –0.03 |

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.

Like the individual meteorological factors, MPY does not correlate with the values of the NAO index of the growing period. Some weak indirect signals from the NAO of the previous winter were observed. Low NAO index in November affected MPY positively, mainly in the coastal region, and high values in January correlated with higher yields in inland areas. 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.

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