DISSERTATIONES GEOGRAPHICAE UNIVERSITATIS TARTUENSIS
44

DISSERTATIONES GEOGRAPHICAE UNIVERSITATIS TARTUENSIS
44

TRIIN SAUE

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

TARTU UNIVERSITY PRESS

Department of Geography, Institute of Ecology and Earth Sciences, Faculty of Science and Technology, University of Tartu, Estonia

Dissertation was accepted for the commencement of the degree of *Doctor philosophiae* in Geography at the University of Tartu on March 7, 2011 by the Scientific Council of the Institute of Ecology and Earth Sciences, University of Tartu.

Supervisor: Jaak Jaagus, University of Tartu, Estonia
Jüri Kadaja, Estonian Research Institute of Agriculture, Estonia

Opponent: Pierluigi Canaca, Agroscope Reckenholz-Tänikon, Research Station ART, Dept. of Natural Resources and Agriculture, Air Pollution and Climate Group, Switzerland

Commencement: Scientific Council Room in University Main Building, Ülikooli 18, on 19 May, 2011, at 10:15

Publication of this thesis is granted by the Institute of Ecology and Earth Sciences, University of Tartu and by the Doctoral School of Earth Sciences and Ecology created under the auspices of European Social Fund.

European Union
European Social Fund

Investing in your future

ISSN 1406–1295
ISBN 978–9949–19–636–4 (trükis)
ISBN 978–9949–19–637–1 (PDF)

Tartu Ülikooli Kirjastus
www.tyk.ee
Tellimus nr 214

CONTENTS

ORIGINAL PUBLICATIONS 7

ABSTRACT 8

1. INTRODUCTION 10

2. THEORETICAL GROUNDS 14
   - 2.1. Agricultural data as regional climate indicators 14
   - 2.2. Crop modelling 15
     - 2.2.1. Estonian school of crop modelling 18
     - 2.2.2. Possible applications of crop models 19
     - 2.2.3. Model deduced effects of climate change on crop yields 20
   - 2.3. The model based on the principle of maximum plant productivity 23
     - 2.3.1. Principle of maximum plant productivity 23
     - 2.3.2. Concept of reference yields 25
     - 2.3.3. POMOD 27

3. DATA AND METHODS 33
   - 3.1. Data used 33
     - 3.1.1. Meteorological data, locations and time frame 33
     - 3.1.2. Measured potato yields 35
     - 3.1.3. POMOD input data for the present climate 35
     - 3.1.4. POMOD input data for the future climate 36
     - 3.1.5. Circulation data 37
   - 3.2. Methodology of the calculations 38
     - 3.2.1. Analyses of the observed yields 38
     - 3.2.2. Calculating the agroclimatic resources 38
     - 3.2.3. Calculating MPY correlations with other variables 39
     - 3.2.4. Development of methodics for soil moisture measurements 40

4. THE RELATIONSHIPS BETWEEN OBSERVED POTATO CROP VARIABILITY AND METEOROLOGICAL ELEMENTS 41

5. MODELLED TIME SERIES OF MPY FOR THE PRESENT CLIMATE 45
   - 5.1. MPY series and variability 45
   - 5.2. Correlations between MPY and accumulated meteoelements 48
   - 5.3. Correlations between MPY and atmospheric circulation 51
     - 5.3.1. Correlations between MPY and North Atlantic Oscillation (NAO) 51
     - 5.3.2. Correlations between MPY and circulation types 52
   - 5.4. A possible application: Accounting the precipitation redistribution in the MPY calculations 55

6. MPY OF THE FUTURE CLIMATE 56

7. TESTING OF SOIL MOISTURE EVALUATION TECHNIQUE 60
CONCLUSIONS 61
REFERENCES 64
SUMMARY IN ESTONIAN 83
ACKNOWLEDGEMENTS 86
PUBLICATIONS 87

ORIGINAL PUBLICATIONS

This dissertation is based on following papers I–VI, which are referred to in the text by their roman numerals:

I. **Saue, T**., Viil, P., & Kadaja, J. (2010). Do different tillage and fertilization methods influence weather risk on potato yield? *Agronomy Research*, 8, 427–432.
II. **Saue, T**., & Kadaja, J. (2009). Simulated crop yield – an indicator of climate variability. *Boreal Environment Research*, 14(1), 132–142.
III. **Saue, T., &** Kadaja, J. (2011). Possible effect of climate change on potato crops in Estonia. *Boreal Environment Research,* 16, xx–xx. (In press)
IV. Sepp, M., & **Saue, T.** Correlations between the Modelled Potato Crop Yield and the General Atmospheric Circulation. (submitted to International Journal of Biometeorology).
V. **Saue, T**., & Kadaja, J. (2009). Modelling crop yield response to precipitation redistribution on slopes. *Biologia*, 64(3), 502–506.
VI. Kadaja, J., Plakk, T., **Saue, T**., Nugis, E., Viil, P., & Särekanno, M. (2009) Measurement of soil water and nutrients by its electrical properties. *Acta Agriculturae Scandinavica: Section B, Soil and Plant Science*, 59, 447–455.

The contribution of the author in the listed publication is as follows:

Publication I:	The author participated in field experiments and is fully responsible for the data analysis and writing.
Publication II:	The author participated in field experiments and modelling and is fully responsible for the data analysis and writing.
Publication III:	The author is fully responsible for the climate change calculations of the manuscript and writing, and partly responsible for the rest of the data analyses.
Publication IV:	The author is partly responsible for data analyses and participated in the writing.
Publication V:	The author participated in the modelling and is responsible for the writing.
Publication VI:	The author is the initiator of the study, participated in the field experiments, data analysis and writing, however she is not fully familiar with the theoretical background.

ABSTRACT

During the past decades, climate variability and change has had a marked influence on agriculture. However, it is not easy to determine the direct effect of climate from that of the other influencers like changing management, new varieties or improved ferilization. Throughout the present thesis, the concept of the meteorologically possible yield (MPY) is used for that purpose, which expresses the highest yield under the existing meteorological conditions, not limited by soil quality (except its hydrological properties) or management. Such approach enables to distinguish the direct effect of meteorological conditions and their variability/change on crops. Additionally, the results can be interpreted backwards and the yield of agricultural crops can be considered as a complex variable for integrally describing summer weather/climate conditions.

The main objective of the study is to assess summer climate variability and possible change in Estonia through the resultant impact on potato crop. The main effort was to determine whether computed yields give additional information about climatic variability compared with the traditional use of the mean values of individual meteorological elements. For that purpose, the MPY series for an early and late variety of potato were computed with a potato-production model (POMOD) at three localities in Estonia (Tallinn, Tartu and Kuressaare) for present and future periods. Long-term MPY series were compared to accumulated meteorological data as well as to some parameters of atmospheric circulation. For comparison purposes, the observed potato yields series from a long-term field experiment were analysed from a point of view of their weather-sensitivity.

Overall, only weak and insignificant trends exist in the century-long MPY series. Significant polynomial relationships between the MPY and the cumulative meteorological elements appeared at all considered localities, whereas linear regression was significant only in the western coastal zone (Kuressaare). The significant changes in MPY variability, 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. The polynomial relationships, the continuously high variance around them, 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 in January only for a late variety of potato at an inland station.

Analysis applying the circulation types revealed that the types having negative influence on the potato crop yield are more clearly represented than those with positive influence. Circulation has the most effect on potato crop

yield in Kuressaare that represents the maritime climate and where frequent water deficit acts as a main limiting factor for plant growth. The effect of circulation types in Tartu that has a mainland climate and in Tallinn that has a combination of mainland and maritime climates is relatively weak. The potato crop yield in seaside locations was found to depend more on the types inducing summer drought, while in the inland-Estonia the potato crop yield is limited by excessive water supply and tenous warmth.

The relief-related soil water differences were considered by supplementation of a subroutine to account precipitation redistribution in the slope to POMOD and its influence in a sloping field on potato yield. In the frequently dry Kuressaare yield limiting by water deficiency is characterized by change in MPY through slope – the more additional inflow is available, the higher the yield. In the generally moister Tallinn, the worst growing conditions appear at the foothill due to excess water.

To assess the effect of climate change on agrometeorological resources for potato growth, some climate change scenarios were employed and the possible mean MPY was computed for the centre and end of the current century. For the early variety, all tested future climate scenarios predict yield losses in all three localities, mainly due to the accelerating development, smaller LAI and thus shortened growing period. Stronger scenarios cause higher losses. For the late potato varieties, moderate climate warming has a positive influence through prolonging the growing period, which is today limited by the general temperature level and night frosts. However, more radical changes lead to the decline of agroclimatic resources. The yield losses are mostly related to the increase in air temperature, while incresing precipitation has a small compensatory effect. A more positive (or less negative, in case of more extreme scenarios) effect of climate change is detected for Northern Estonia (Tallinn). By the end of the century, the uncertainty of computed yields, originating from the diffusion of GCM results, attains to the same magnitude with the interannual variability.

Presented results indicate that soil moisture conditions and their comprehensive relief-related variations play a crucial role in potato yield forming. To allow better representation of site-specific soil moisture differencies into the model, a new mobile equipment was tested and calibrated to simplify and speed the determination of soil moisture in different soil layers. Logarithmic relationship and additional corrections considering stoniness were established between dielectric constant and volumetric soil content.

1. INTRODUCTION

It was already in the early 1900s, when it was recognized that the year-to-year variations in yields are associated with variations in climate (Decker 1994). Despite technological advances, such as improved varieties, genetically modified organisms, and irrigation systems, weather is still a key factor in agricultural productivity. It has been found that 60–80% of the variability of agricultural production is due to the variability in weather conditions (Petr 1991, Fageria 1992, Gobin 2010). Temperature, solar radiation and water availability are the critical agrometeorological variables that determine agricultural production. The production potential (dry matter accumulation), determined by the incoming radiation, is greatly modified by temperature and rainfall. Temperature is the main weather variable that regulates the rate of vegetative and reproductive development (Hodges 1991, Haverkort et al. 2004, Craufurd and Wheeler 2009) and through these the growing period duration (Woodward 1988, Haverkort and Verhagen 2008), but also other processes linked with the accumulation of dry matter (leaf area expansion, photosynthesis, respiration, evapotranspiration etc.) are affected thoroughout the life cycle (Roberts and Summerfield 1985). Precipitation does not directly control any of the plant processes. It is considered to be a modifier, which indirectly affects many of the plant growth and developmental processes. For instance, rainfall and driven by it soil water availability may affect the photosynthetic efficiency, nutrients assimilation and duration of growth through leaf area duration. When there is less water available than needed for optimal growth, growth will be reduced.

These universal climatic constraints on agricultural production are modified by local climatic constraints. In Northern countries the length of growing season, late spring and early autumn frosts and solar radiation availability are typical climatic constraints, limiting the productivity of crops (Carter et al. 1996). For example, in Germany the growing season is one to three months longer than in Scandinavian countries (Mela 1996).

During the recent decades, global climate change has been at the centre of quite many scientific studies. The recent IPCC report (2007a) confirmed that global climate change is real, that it is occurring rapidly, and that roughly 1˚C of warming is expected globally by 2030 regardless of what happens to emissions of greenhouse gases. Despite such consensus on a global scale, changes on a regional or local scale are more variable and less easily attributable to an increased greenhouse effect. However, agricultural production is more directly impacted by the changes at regional scale. Among other things, regional climate change could considerably affect the growth and yield of most crops (e.g. Adams et al. 1990, Easterling et al. 1992a, b, Olesen and Bindi 2002, Lobell and Field 2007, Torriani et al. 2007, Semenov 2009).

During the past decades, climate variability and change have already had a marked influence on agriculture (e.g. Orlandini et al. 2008, Reidsma et al. 2009). Trends in individual climate variables or their combination into agroclimatic 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, for both natural communities (e.g. Fitter and Fitter 2002, Root and Hughes 2005, Visser and Both 2005, Ahas and Aasa 2006), and crop plants (Hu et al. 2005, Menzel et al. 2006, Tao et al. 2006, Estrella et al. 2007, Craufurd and Wheeler 2009). In temperate regions, there are also clear signals of reduced risk of frost (e.g. Meehl et al. 2000, Jylha et al. 2008, Kreyling 2010), longer growing season duration (e.g. Menzel and Fabian 1999, White et al. 1999, Schwartz and Reiter 2000, Chmielewski and Rötzer 2002, Walther et al. 2002, Linderholm 2006, Schwartz et al. 2006, Menzel et al. 2006, Peltonen-Sainio et al. 2009a), etc., that are in agreement with regional warming.

Since the plant productivity is directly driven by climate, it should also be logical and reasoned to reverse the relation and consider the observed series of crop yields as a parameter of change of the climate. Still, no detectable change in observed crop yields directly and definitely attributable to current climate change has been reported for Europe (IPCC 2007b, Peltonen-Sainio 2009b). 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 (e.g. Lamb et al. 1997, Machado et al. 2002, Kravchenko et al. 2005). Realized yield changes rather reflect differences in local environments as well as differences in management practices. For instance, as discussed by Craufurd and Wheeler (2009), many of the changes in crop phenology may be associated with changing farming activities, not just warmer winter/spring temperatures. In addition, changes in crop management may also counter direct the effects of temperature warming and the timing of farming operations. The worldwide trends in increasing crop yield 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). Also the augmented CO_2 levels may have contributed to the yield increase (e.g. Miglietta et al. 1998, Amthor 2001). Therefore, studies that robustly attribute the observed changes in phenology or production (crop yields) to changes in climate are not found for managed ecosystems.

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 (Rosenzweig and Hillel 1998, Hoogenboom 2000, Olesen and Bindi 2002, Miraglia et al. 2009 etc). These models are compiled from the 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 (e.g. Hansen et al. 2006, Reidsma et al. 2009, Garbrecht et al. 2010, Calanca et al. 2011 etc). Additionally, those results can be turned backward and model-calculated yields can be used as an indicator to describe climate resources (e.g. Donnelly et al 2004). As formulated by Sivakumar et al. (2000), "there is a lot to be gained from looking at climate not only as a hazard, but also as a resource". Resources must be known, assessed in quantitative terms and properly managed if they are to be used sustainably, and climate is no exception. In this thesis, the concept of meteorologically possible yield (MPY) – the maximum yields under given meteorological conditions – is applied to derive qualitatively new information about climate, its change and variability.

Throughout the thesis, the relation between the series of model-calculated potato yields and traditional weather elements is searched and interpreted. The main objective of the thesis is to analyse weather/climate variability and possible climate change as agricultural resources through the resultant impact on field crops, namely on potato crop. For that purpose, several steps were accomplished.

First, the variability of observed potato yields within a long-term field trial was analysed in relation to weather variability (PAPER I). The main hypothesis of this study was that the variability in meteorological conditions influences the long-term effect of different tillage and fertilization regime on potato yield. In the context of the thesis, the possible interaction between management practice and weather is of interest.

Further, the concept of using model-calculated MPY as an indicator of climate variability was applied. For this purpose, the dynamic potato production model POMOD was used as a tool. 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 (Sepp et al. 1989, Pensa et al. 2006) or whose growth is strongly influenced by climate, such as many arable crops (Hay and Porter 2006). MPY based on long observed meteorological series was calculated, variability within the series, possible tendencies of changes and the relevance of different meteofactors in those changes was analysed in PAPER II.

As cited by Hurrell et al. (2003), agricultural harvests, among other things, are directly affected by the large-scale atmospheric circulation. Earlier, significant correlations between atmospheric circulation and winter weather in Estonia have been established (e.g. Tomingas 2002, Jaagus 2006). Possible relationships between crop yields and circulation indices might help to explain the potential impact of atmospheric circulation on the integrated complex of summer weather conditions and identify the indirect correlations. Therefore, the correlations between MPY and some parameters of the atmospheric circulation were additionally examined. NAO indices (PAPER II) and circulation types frequencies (PAPER IV) were used.

To reckon with site-specific differences in ground relief and, resultantly, water supply, a calculation scheme was developed to consider precipitation redistribution on slope; resultant yield differences were calculated (PAPER V). Possible changes in MPY by middle and end of the current century were calculated and analysed using climate change scenarios from MAGICC/SCENGEN software and arising resultant changes in air temperature and precipitation (PAPER III).

Throughout the project, field measurements were participated for model development and parameter determination. A new complex equipment was tested and calibrated (PAPER VI) to simplify and speed the determination of soil moisture, which is one of the most important input parameters in the model.

2. THEORETICAL GROUNDS

2.1. Agricultural data as regional climate indicators

Burroughs (2001) has stated that, in terms of considering the implications of changes in the climate, it is the regional variations which provide the most interesting material, as long as they are properly set in the context of global change. 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. Since the early 1990s, different indicators have gained importance.

The OECD (1993) defines an indicator as "a parameter, or a value derived from parameters, which points to/provides information about/describes the state of a phenomenon/environment/area with a significance extending beyond that directly associated with a parameter value". Indicators therefore provide information about the phenomena that are regarded as typical for, and/or critical to, environmental quality and they are used to simplify a complex reality (Smeets and Weterings 1999). Environmental indicators have taken on such importance because they provide "a sign or signal that relays a complex message, potentially from numerous sources, in a simplified and useful manner" (Jackson et al. 2000). However, it is a major challenge to determine, which of the numerous measures of ecological systems characterize the entire system yet are simple enough to be effectively and efficiently monitored and modeled.

Agricultural crop plants, their growth and production is considered as one integral indicator of the regional climate change in this thesis. One of the basic axioms of agroclimatology postulated by a number of authors (e.g. Petr 1991, Fisher et al. 2000) is the notion that specific crops grow well in specific climate regions and that the success of a crop can be related to climatic factors (e.g., accumulated air temperature, total rainfall, length of growing season), physical factors (e.g., soil, slope) and economic factors (e.g., intensity of the crop production), as shown by Reidsma (2007), among others. The general response of biological organisms to variations in the weather and climate has been understood for a long time. An example of the effect of temperature on growth was reported already by Lehenbauer (1914). By the 1960s and early 1970s, extensive literature had documented the response of plant growth and development to environmental conditions, chiefly to weather conditions (e.g. Gardner 1960, Moss et al. 1961, Murata and Iyama 1963, Evans et al. 1964, Budyko and Gandin 1964, De Wit 1965, Budyko 1971, McCree 1974, etc). Interactions between the biosphere (plants growth, phenology, yield) and the atmosphere (single meteoelements, weather, climate) have since been studied by several disciplines (e.g. Budyko 1974, Dmitrenko 1976, Fritts 1976, Bolin 1977, Tooming 1977, 1984, Loomis et al. 1979, Chmielewski and Köhn, 2000, Scheifinger et al. 2002, Menzel 2003, Aasa et al. 2004, McPherson 2007 etc.). Several biology-related indicators have been used by several scientists to assess past and present climate, its changes and variability, such as growth season beginning and length (e.g. Menzel and Fabian 1999, Schwartz et al. 2006, Sparks and Tryjanowski 2007), or dates of phenological phases (e.g. Ahas et al. 2000, Fitter and Fitter 2002, Badeck et al. 2004, Ahas and Aasa 2006, Estrella et al. 2007 etc.).

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, such as Palmer Drought Severity Index PDSI (Palmer 1965) or Seljaninov Hydrothermic coefficient SHC (Seljaninov 1966) are widely used (Makra et al. 2002, Szep et al. 2005, Mpelasoka et al. 2007); in climatology atmospheric circulation is often described by several phenomena like North Atlantic Oscillation (NAO) (Hurrell et al. 2003), El Nino/Southern Oscillation (ENSO) (Rasmussen and Carpenter 1982, Rasmusson and Wallace 1983) or circulation patterns, e.g. *Grosswetterlagen* (Baur et al. 1944). One of the complex variables, integrally describing summer weather conditions, is also the biological production of plants and yield of agricultural crops. For instance, potato crop yield has been used as a potential climate change indicator in North Ireland climate change assessments (Donnelly et al 2004); records of grape ripening (Chuine et al. 2004) and cherry blossoming (Tagami 1993, 1996) have been used to assess historic climate; Tarand and Kuiv (1994) and Nordli (2001) have used the recorded dates of the grain harvest to reconstruct historical spring-summer temperatures, etc. Since such long series of recorded data are quite rare, modelled potato crop yields are proposed in this thesis as an integrate index for summer climate assessment, applicable for both past and future.

2.2. Crop modelling

The progress of dynamic crop growth models, which started more than fifty years ago, has considerably improved the analytic solution of problems in crop sciences. Today, a lot of tasks in, e.g., plant physiology, agricultural meteorology/climatology etc., are solved by the use of computer technology, mostly computer modeling. Computer models, in general, are a mathematical representation of a real-world system (Mize and Cox 1968), while crop models, particularly, are mostly based on mathematical equations of balance. Due to the complexity of the system and the incomplete status of present knowledge, it becomes impossible to completely represent the system in mathematical terms and hence, agricultural models are only crude representations of the real systems. Or, as it has been already stated by Box (1979), “all models are wrong, but some are more useful than others”.

Crop modelling emerged out of several branches in biology, agriculture and agrometeorology. The pioneering papers on plant modelling were published as early as the 1950s (e.g., Monsi and Saeki 1953, De Wit 1959). The basic fundamental works on plant photosynthesis and crop productivity by Nichiporovich

(1956), Davidson and Philip (1958), Went (1958), Budagovskij (1964), de Wit et al. (1965), Ross (1966) initiated further developments. In these works attention was mostly paid to the general tasks of modelling. The common element is a perception of plant growth in physical terms, preferably laws that can be expressed in mathematical equations. Such use of law-like statements can already be traced from the works of Justus von Liebig (1803–1873). A particular law he formulated and that dominated in the perception of plant growth for a long time, was the law of the minimum, also referred to as a limiting-factor paradigm. Although the advance of field experimentation formulated new laws describing the plant-nutrients relation in a more appropriate way, von Liebig's law remained as a source for explanation. An important point for crop modelling here is the practice of using law-like statements that can be expressed in mathematical equations for describing the interaction between plant and nutrients.

A crucial factor in the evolution of plant modelling was the development of computers. In an overview article about the "Dutch school" of crop modelling (van Ittersum et al. 2003), the origin of the discipline is set to the moment in 1960's when "computers had evolved sufficiently to allow and even to stimulate attempts to synthesize detailed knowledge on plant physiological processes". Subsequent progress in computer technology also promoted progress in plant modelling.

The first tool to answer some of the needs for mathematical expressions to simulate production were accomplished through the early statistical analyses (Smith 1914, 1920, Hooker 1921). Fisher (1925) was the first person to evaluate the relationship between yields and rainfall using multiple correlation. Further, these same tools, using more refined statistical techniques and modern computer technologies, were developed into statistical-empirical crop models. Probably the best known of these first statistical models were published by Thompson (e.g. 1969, 1970). Statistical or empirical models are direct descriptions of the observed data and thus they do not require detailed information about the plant involved but rely mainly on statistical techniques, such as correlation or regression, relating to the appropriate plant, environmental variables and location.

On the other hand, a dynamic plant growth model is the one whose output varies with time and in which processes are characterized. In the 1960s and early 1970s, reports documenting the response of plant growth and development to the environmental conditions began to appear in the literature (e.g., Gardner 1960, Lemon 1963, De Wit 1965, Baker and Meyer 1966). These developments paved the way for work on mathematical models of plant response to environmental conditions (e.g., Duncan et al. 1967, Tooming 1967a, de Wit et al. 1970, Curry 1971, Passioura 1973, De Wit and Goudriaan 1974, Penning de Vries 1977), followed by the attempts to model the complex biological processes (Sirotenko 1981, Bondarenko 1982, Penning de Vries and van Laar 1982, Polevoy 1983, 1988, Ng and Loomis 1984, Weir et al. 1984, van Keulen and Wolf 1986, Penning de Vries et al. 1989, Poluektov 1991, Bouman et al.

1996). The result was in the development of mathematical models which were driven by the environmental variables defined by weather and soil conditions. Perhaps the best known and most widely used of these models is the GOSSYM model (Baker et al. 1983).

There is also a group of models which lie somewhere in between the statistical model and the physiological model. These models use empirical relationships between the biological processes and environmental condition to simulate the development and yields of economically important crops. Perhaps the best known of these models are the CERES group of models (Ritchie and Otters 1984, Jones and Kiniry 1986).

Several models/model groups have since been developed and many are presently available. Some of them have been listed by, e.g., Whisler et al. (1986), Ritchie (1991), Jame and Cutforth (1996), Wolf and van Ittersum (2009). These lists are not all inclusive because new crop models are being developed almost monthly. As stated by Orlandini et al. (2008), the three most important "schools of development" come from Australia, the Netherlands, and the United States; however, there are many teams around the whole world building and developing crop growth simulation models for crops of major importance, such as CERES, WOFOST (Vandiepen et al. 1989), CropSyst (Stöckle et al. 2003), Daisy (Hansen 1990, 1991, Abrahamsen and Hansen 2000), STICS (Brisson et al. 2003), APSIM models (Asseng et al. 2000) etc., just to name few. So far, WOFOST is the only model which is operationally integrated at the European level for crop yield prediction systems (Orlandini et al. 2008). Among others, one of the most extensive systems is the DSSAT (Decision Support System for Agrotechnology) software (Jones et al. 2001, 2003) that combines different crop, soil and weather databases into standard formats for access by crop models and application programs. The operational Crop Growth Monitoring System (CGMS) (Bouman et al. 1997) covering the EU is also used to monitor the influence of weather on crop growth and yields.

The development of crop modelling for potato has parallelled that of other crops: first, potential production was calculated under ideal conditions for growth (e.g. Sepp and Tooming 1982, MacKerron and Waister 1985a, b); this was followed by yield simulation under various yield-limiting factors and other applications (e.g. van Keulen and Stol 1995, Kooman 1995, Kooman and Haverkort 1995). Models for the potato productivity and yield were proposed by, e.g., Belmans et al. (1982, 1983), Polevoy (1983), Ng and Loomis (1984), Ingram and McCloud (1984), Fishman et al. (1985), Hodges et al. (1992), Kooman and Haverkort (1995), Ritchie et al. (1995), Van der Broek and Kabat (1995), Wolf (1999a,b, 2002), Wolf and van Oijen (2002, 2003), Streck et al. 2007, Pereira et al. 2008, and others. More recently, attention has been mainly focused on modelling the effects of potato diseases and pests (e.g. Kaukoranta 1996, Timmermans et al. 2009, Skelsey et al. 2010), while some, e.g., SUBSTOR, have been used for yield prediction (Šťastná et al. 2010) and climate change applications (e.g., De Temmerman et al. 2002, Hijman et al. 2003, Haverkort and Verhagen 2008, Gobin 2010).

2.2.1. Estonian school of crop modelling

It was the Russian plant physiologist Nichiporovich together with the geographer Budakovski, who had understood the need for a systematic approach in plant productivity studies. Having read the ideas by Tooming (1959, 1961) about the radiation regime in vegetation, they decided it was worth to develop the direction further. Thus the first working group in the former Soviet Union dealing with the modelling of the plant bioproduction was formed in Estonia, at the Tartu Actinometry Station of the Estonian Physics and Astronomics Institute, under the leadership of Juhan Ross. The research activity carried out there became known as 'the school of Juhan Ross'. The original idea of Nichiporovich was that it should be possible to find the optimum geometrical structure of plant canopies to gain a maximum yield and thus find a way to increase the productivity of the agricultural crops. Ross accepted the idea and the group launched a theoretical and experimental work in this field of research. The theoretical fundamentals for modeling the canopy radiation regime were proposed by Ross and Nilson (1963), Nilson (1968, 1971) and resumed by Ross (1975, 1981). Simplified semi-empirical formulas, describing radiation regime inside different crops, useful for practical calculations, were proposed (Tooming and Ross 1964, Tooming 1967b, 1968, 1977, Ross 1975). After the publication of the Russian version of the book *The Radiation Regime and Architecture of Plant Stands* (1975) and its translation into English (1981), Ross's works on the radiative transfer became known in the whole world.

On Ross's initiative, biologists and plant physiologists were invited to participate in the application of the obtained results in photosynthetic studies. However, the mind-set of the people with physical background was different from that of the biologists. Thus Ross decided to deal also with the biological/physiological part of the problem. This was an extremely fruitful idea that established the foundation to the photosynthetic studies carried out by the group lead by Agu Laisk. Ross himself formulated the problems of quantitative description of the photosynthetic productivity of vegetation, introduced the concept of growth functions of plants for the quantitative description of mass flows between plant organs (Ross 1966), etc. In fact, the original problem of creating new optimum plant structures as proposed by Nichiporovich, was never solved, but the by-products of the research appeared to be of fundamental importance to modelling of plant photosynthesis (Laisk 1970, 1977, 1982, Oja and Laisk 1995 etc.) and production (Tooming 1967a, 1970, 1977, 1988, Kallis and Tooming 1974, Bikhele et al. 1980, Sepp and Tooming 1982). Heino Tooming was one of the most productive scientists active in crop modelling area. Although the first models were not yet applicable in practical agriculture, they explained some regularities in plant production process, connected mostly with the radiation regime in crops and natural ecosystems (Tooming and Kallis, 1972; Kallis and Tooming 1974). Later on, Jüri Kadaja (Sepp) prosperously proceeded the modelling work and compiled practically applicable solutions. The succeeding generalising monographs had practical agricultural value

(Tooming 1984, Sepp and Tooming 1991). The principle of maximum plant productivity, described by Tooming (Tooming 1967a, 1970, 1977, 1984, 1988, 1993), Tooming and Kallis (1972) and resultant concept of reference yields (Tooming 1977, 1984, Zhukovskij et al. 1989, 1990, Sepp and Tooming 1991) is described later in this chapter; they form the theoretical basis for the potato production model POMOD (Sepp and Tooming 1982, 1991, Kadaja and Tooming 2004) applied in this thesis. The described methods and the model have become tools in the assessment of possible regional climate variability (PAPER II) and climate change impacts on agriculture (Kadaja and Tooming 1998, Karing et al. 1999, PAPER III).

The works of Juhan Ross and his school have had a strong influence on many areas of research in Estonia, which is continuing into today, primarily through the work of Agu Laisk, Heino Moldau, Tiit Nilson and Jüri Kadaja, and the research groups of their and Olevi Kull's students. The characteristic feature of this school is a strong theoretical foundation, the skill of mathematical modeling linked to well-designed experimental work.

2.2.2. Possible applications of crop models

Crop yields are strongly related to climate and its variability – globally (Lobell and Field 2007), regionally (Challinor et al. 2003) and locally (Ferris et al. 1998, Jacob et al. 2007). All crop model applications apply climate data in one way or another.

Simulation modelling can have several purposes. Crop simulation models have found their role at different levels of application, ranging from decision support for crop management at farm level to advancing understanding of different processes at research level. The neverending discussion of research applications of crop models can be found at, e.g., Loomis et al. (1979), Whisler et al (1986), Boote et al. (1996), Anbumozhi et al. (2003), Kumar and Chatu-revdi (2005). Generally said, one unfortunate feature that is shared by many simulation models, is that they may be very complex and detailed, being thus only suitable for scientific investigation and quite inappropriate for anything like a practical application. Hoogenboom (2000), Monteith (2000) and Mackerron (2008) have described a range of major areas in which the application of crop simulation models is well established.

A widely used application of the contemporary crop models is in climate change impact research on agriculture, both from general (e.g., Olesen et al. 2000, Alexandrov et al. 2002, Fischer et al. 2005, Cline 2007, Olesen et al. 2007, Orlandini et al. 2008, Butterworth et al. 2010, Lobell and Burke 2010, Szwed et al. 2010, etc.), or quite specific viewpoints (Mueller et al. 2010, Adam et al. 2011, etc.). The other group of widespread applications focus on crop yield forecasting in the grain, fruit, root, tuber or biomass yield, or any other harvestable product (e.g., Sepaskhah et al. 2006, Semenov and Doblas-Reyes 2007, Confalonieri et al. 2009, Mkhabela et al. 2011, etc.). Some specific applications of models related to policy issues can be found in, e.g., de Wit and van Keulen (1987), Rabbinge and van Latesteijn (1992), Gassman et al. (2010).

Following, some "most popular" applications are reckoned.

Strategic applications. Models can be used to compare alternative crop management scenarios, which can combined with different weather, biological and economic factors (e.g., Sivakumar 1992, Thornton and Wilkens 1998, Bachinger and Zander 2007). Strategic applications are, among others, seasonal analysis, when management decision is evaluated for a single season (e.g., Aubrey et al. 1998, Sarkar and Kar 2006), and the sequence or crop rotation analysis, when different cropping sequences are simulated across multiple years (e.g., Plentinger and Penning de Vries 1997, Castellazzi et al. 2010).

Tactical applications. Models are run prior to or during the growing season to integrate the growth of a crop with the current observed weather conditions, and to decide on a daily basis as to which management decisions should be made. Most of the tactical decisions during the growing season are related to irrigation management (e.g., Boggess 1988, Scheierling 1997, van der Velde et al. 2010) and nitrogen fertilizer management (e.g., Smith 1997, Gibbons et al. 2005, Meyer-Aurich et al. 2010, etc.). In the area of pest and disease management, the application of models has been shown to be very profitable (e.g., Kaukoranta 1996, Pusey 1997, Chander et al. 2007).

Forecasting applications. Very similar to the tactical applications, however the main interest is in the final yield and other variables predicted at the end of the season. Crop simulation models can play a critical role in crop yield forecasting applications if accurate weather information is available, both with respect to observed conditions as well as weather forecasts (e.g., Nichols 1991, Abawi et al. 1995, Hansen et al. 2006, Semenov and Doblas-Reyes 2007, Kadaja et al. 2009, Calanca et al. 2011).

Climate change and variability applications. Crop models can be used to study the potential impact of climate change and climate variability. Crop models are useful tools for translating climate forecasts and climate change scenarios into changes in yields and other outcomes. Additionally, those results can be turned backside and model-calculated yields can be used as an indicator to describe climate resources. Next section will concentrate more deeply in climate change applications.

2.2.3. Model deduced effects of climate change on crop yields

Schimel (2006) has written that, at least in some regions, agriculture may be one of the bright spots, "the silver lining in the climate change cloud". Such credit generally derives from crop models applications.

Physically based crop models have long been used to explore the impacts of climate change on agricultural productivity, potential food production and adaptation options at both global (e.g., Rosenzweig and Parry 1994, Parry et al. 1999, Fischer et al. 2002, Hijmans et al. 2003, Parry et al. 2004, 2005, Easterling and Apps 2005, Parry 2007, etc.) and national or regional scales (e.g., Adams et al. 1990, Mela 1996, Olesen et al. 2000, Alexandrov et al. 2002, Olesen and Bindi 2002, Reilly 2003, Cline 2007, Olesen et al. 2007, Kaukoranta and Hakala 2008, Butterworth et al. 2010, Gobin 2010, Moriondo et al. 2010, etc.). In most climate change applications, long-term historical weather data are used as input for the crop models; different climate change scenarios can then be applied to these data records. A regularly used approach is to use the outputs from the GCMs to modify the historical weather data and the modified historical weather data are used as input for the crop simulation models. The crop models can then be run, using various climate change scenarios.

The first model-based studies of effects on global food supply were published in the early 1990s, using low resolution climate models. The yield data calculated by crop models was used as input to a dynamic model of the world food system in order to assess the possible impacts on the future levels of food production, food prices and the number of people at risk from hunger (Rosenzweig et al. 1993). The general conclusions of that work still hold today: that climate change is likely to reduce global food potential and that risk of hunger will increase in the most marginalised economies (Rosenzweig and Iglesias 1994, Rosenzweig and Parry 1994). Some analyses also included the effects of enhanced ambient CO_2 levels on crop growth both through altered water-use efficiency and rates of photosynthesis. The results showed that climate change scenarios which exclude the direct physiological effects of CO_2 predict decreases in simulated yields in many cases, while the direct effects of increasing atmospheric CO_2 mitigate the negative effects primarily in mid and high latitudes.

After the mid-1990s the spatial resolution of GCMs has increased and their simulation of air-ocean interactions and other feedback mechanisms has improved. This has substantially enhanced the accuracy of their projections of climate change. Many were now capable of producing time-dependent scenarios, thus enabling the evaluation of climate change impacts on agriculture at several different time horizons throughout this century (e.g., Fischer et al. 2005, Lobell and Field 2007, Lobell and Burke 2008, 2010, Tao et al. 2009, Moriondo et al. 2010, Supit et al. 2010, etc.). Coupling crop models with climate models has also been done by several research groups (e.g. Schulze et al. 1993, Gervois et al. 2004, de Noblet-Ducoudre et al. 2004, Baigorria et al. 2007, Bondeau et al. 2007, Osborne et al. 2007, Oleson et al. 2008). A different approach from point-based crop-growth modelling is the study of how zones of crop suitability may shift location in response to changes of climate (e.g. Fischer et al. 2002, Peltonen-Sainio et al. 2009, Trnka et al. 2009). Another increasingly interesting applications are to investigate climate change effects on crop quality (e.g., Lin et al. 2005, DaMatta et al. 2010) or crop–disease–climate interactions (e.g., Sporleder et al. 2004, Butterworth et al. 2010).

Overall, as concisely concluded in the assessments by the Intergovernmental Panel on Climate Change (IPCC), global agricultural production will not be seriously affected by climate change, but the regional distribution of change is uncertain. An earlier comprehensive climate change impact study by Parry et al. (2004) also concluded that future global production appears stable, but regional differences in crop production are likely to grow stronger through time. As a recent result, IPCC (2007b) deduced with high confidence, that, for instance, in Southern Europe, climate change would reduce crop productivity, while in Northern Europe the initial effect (1 to 3 ºC warming) of climate change was projected to increase crop yields. Global agricultural output was estimated to decrease by 16 per cent assuming no carbon fertilisation, and by 3 per cent with full carbon fertilisation. However, some findings suggest that under field conditions the positive effects of high CO_2 concentrations observed in the lab will prove to be considerably lower than previously expected (e.g., Long et al. 2006, Ainsworth et al. 2008). The real magnitude of the CO_2 fertilisation effect remains quite uncertain (Sun et al. 2009).

Responses of different species to climate change can be different. Potato (*Solanum tuberosum*), one of the typical agricultural crops and main food crop in Estonia (Kotkas 2006), is best adapted to temperate climates. Therefore, temperature rise is generally expected to decrease the overall yields (Haverkort 1989, Haverkort et al. 2004, Haverkort and Verhagen 2008). Due to its high water sensitivity, potato is also responsive to any changes in the precipitation regime. Similarly to other crops, there have been numerous, sometimes quite contradictory research studies about the possible climate change related changes in potato production. These studies have utilized a variety of climate change and agricultural models, including or not the effect of increasing CO_2. Such diversity, combined with the large variation in climatic conditions around the world, makes it quite difficult to generalize and apply this information directly to a particular region.

In a study about the possible climate change related changes in global potential potato growth (Hijmans et al. 2003), a decrease in global potato tuber yield was predicted. However, at high latitudes, global warming is supposed to lead to changes in the time of planting, the use of later-maturing cultivars, and a shift of the location of potato production. In many regions, Hijmans et al. (2003) predicted the future changes in potato yields to be relatively small, and sometimes positive. By other authors, higher temperatures are predicted to increase potato yields in England and Wales (Davies et al. 1996), Scotland (Peiris et al. 1996) and Finland (Carter et al. 1996), primarily because of a longer growing season. However, an overall yield decrease has been predicted for the USA (Rosenzweig et al. 1996), Ireland (Holden et al. 2003) and Belgium (Gobin 2010) owing to drought and heat stress. Wolf and van Oijen (2003) showed that irrigated tuber yields increased with temperature rise in the northern EU, and remained the same and decreased in central and southern EU, respectively.

Some authors point out the positive influence of increasing CO_2 concentration, compensating the negative impact of temperature rise and increasing potato yield, mainly for higher latitudes. There have however been mixed experimental responses to elevated CO_2 in potato. Gourdrain and de Ruiter

(1983) found a slight negative response, Wheeler and Tibbitts (1997) found no response in tuber growth (only in above ground biomass), while Schapedonk et al. (2000) and Finnan et al. (2002) reported a significant increase in fresh tuber weight. When CO_2 is combined with climate change, Wolf (1999a, 2002) has concluded small to considerable increases in a mean tuber yield in the Northern Europe, being caused by the higher CO_2 concentration and by the temperature rise. Rosenzweig and Hillel (1998), Wolf and van Oijen (2002, 2003), De Temmerman et al. (2002) have shown tuber yield of potato to increase across the EU, mainly due to the positive yield response to the increased CO_2. But, for southern regions and/or under hotter scenarios, the positive effect of CO_2 enrichment may be counteracted by the negative effect of a concomitant temperature rise (e.g., Rosenzweig et al. 1996, Wolf 1999b, 2002, Miglietta et al. 2000, Tubiello et al. 2002, Stöckle et al. 2010).

Although the variability of climate in the future may change (Rind et al. 1989, Mearns 2000), inducing possible decrease in mean crop yields (Semenov and Porter 1995, Semenov et al. 1996), some researchers (Barrow et al. 2000, Wolf 2002, Peltonen-Sainio et al. 2009b) 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 (ratio of the standard deviation to the mean). On the other hand, in a review by Olesen and Bindi (2002) it is concluded that although climate change scenario studies performed using crop models have not shown consistent changes in mean potato yield, an almost constant increase in yield variability is predicted for the whole Europe.

2.3. The model based on the principle of maximum plant productivity

2.3.1. Principle of maximum plant productivity

One of the most outstanding figures in mathematical modelling of plant productivity in the former Soviet Union, now in Russia, Sirotenko (1996, 2001) has written that in crop modelling, it is not often that mathematics serves as a creative starting point. Frequently, the models proposed are just an impoverished formalisation of ideas put forward by biologists a long time ago and well described in textbooks. Nevertheless, some examples can be given in which the initial hypothesis may be attributed to the ideas of mathematical origin. According to Sirotenko (2001), a most impressive example is the principle of maximum productivity of a photosynthesising system proposed by Tooming (1967a).

According to the principle of maximum plant productivity, adaptation and succession processes in a plant and plant community are directed towards providing the maximum productivity of net photosynthesis possible under the existing environmental conditions:

$$A_n = \int_{t_1}^{t_2} \int_{0}^{L_0} (A_g - r) dL dt = \max, \tag{2.1}$$

where A_n is the net photosynthesis of plant community per unit ground area, A_g the gross photosynthesis rate per unit leaf area, r the respiration rate per unit leaf area, L the leaf area index (LAI) indicating the leaf area above the given level in the canopy, L_0 the LAI of the whole plant community, t the time variable, t_1 and t_2 are the limits of the time interval observed (Tooming 1967a). According to this formula, the productivity is maximum when $A_g \to \infty$ and $r = 0$. In real life, these conditions will never apply since energy supply is limited and photosynthesis is not feasible without respiration. Thus, an assumption was made that there exists a linear dependence of respiration rate on gross photosynthesis rate at the saturating radiating density A_{max}, $r = cA_{max}$.

When the adaptation to radiation is expressed by variations of the maximum rate of gross photosynthesis, the following formulas have been obtained for the light curves of gross photosynthesis (Tooming 1967a, 1970, Tooming and Nilson 1967):

$$A_g = \frac{aR(L,t)}{1 + \frac{\sqrt{c}}{1-\sqrt{c}} \frac{R(L,t)}{R_a}} \tag{2.2}$$

and respiration rate:

$$r = a\sqrt{c}(1-\sqrt{c})R_a, \tag{2.3}$$

where $R(L, t)$ is the flux density of photosynthetically active radiation (PAR) absorbed by the canopy at the given level L at the time t, a the initial slope of photosynthesis irradiance curve, i.e., the PAR use efficiency (the efficiency of PAR energy conversion) in gross photosynthesis as the PAR tends to be zero, R_a the irradiation density of adaptation (IDA), i.e., the PAR density at which the PAR use efficiency in net photosynthesis has its maximum, $c = \sigma_2/\sigma_1$ the loss factor of respiration or the ratio of respiration σ_2 to photosynthesis rate σ_1 at the saturated PAR density (σ_1 and σ_2 are given per unit dry mass of leaves).

The meaning of parameters of gross and net photosynthesis irradiance curves are illustrated in Fig. 2.1 (Tooming 1984). 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.

Proceeding from the principle of maximum plant productivity, gross photosynthesis at saturating PAR density is expressed as follows:

$$A_{\max} = \frac{aR_a(1-\sqrt{c})}{\sqrt{c}} \tag{2.4}$$

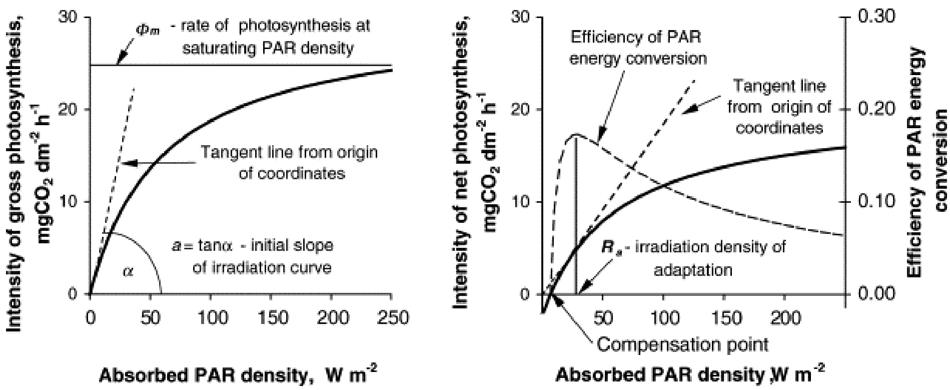

Figure 2.1. Gross and net photosynthesis irradiance curves and their characteristics (Tooming 1984a, b).

Also the specific leaf weight (SLW) μ, i.e., the dry mass of unit leaf area as a factor between A_{max} and σ_1 can be written using the same parameters (Kallis and Tooming 1974, Tooming 1977):

$$\mu = \frac{a}{\sigma_1}\frac{1-\sqrt{c}}{\sqrt{c}}R_a \tag{2.5}$$

2.3.2. Concept of reference yields

Plant productivity and thus the yields of field crops depend on many different closely interrelated factors. It is complicated to introduce all of them into the model simultaneously. Thus, on the basis of the principle of maximum plant productivity (Tooming 1967a, 1970, 1977, 1984, 1988, 1993, Tooming & Kallis 1972), the concept for separation of factors has been elaborated, referred to as a concept of reference fields (Tooming 1967a, 1970, 1975, 1977, 1984, 1988, 1993, 1998, Zhukovsky et al. 1989, Sepp and Tooming 1991, Kadaja 1994, Kadaja and Tooming 2004).

Proceeding from the principle of maximum plant productivity, the maximum production and yields are observed under different limiting factors divided into agroecological groups: in general into biological, meteorological, soil and agrotechnical groups. According to the concept of reference or model yields, these groups are included in the model separately, step by step, starting from optimal conditions for the plant community. Because the conditions specified as optimal involve no limitations, no input information regarding their optimal and limiting ranges is necessary. The main categories of reference yields are, in descending order, potential yield, meteorologically possible yield, practically possible yield and commercial yield (Fig. 2.2) (Zhukovsky et al. 1989). This set of yield categories provides an ecologically based reference system for comparison and analysis of different yield values obtained from field trials as well as from model experiments. Additionally, each of these categories represents ecological resources for plant growth expressed in yield units.

In Kadaja and Tooming (2004), the potential yield (PY) of potato is defined as the maximum yield possible under the existing conditions of solar radiation, with all the other environmental factors considered to be optimal. Therefore, the PY is determined by the biological properties of the species/variety and available radiation resources, and it practically expresses the solar radiation resources for cultivating a given species/variety in yield units.

The meteorologically possible yield (MPY) is the maximum yield conceivable under the existing irradiance and meteorological conditions with optimal soil fertility and agrotechnology. As a result, MPY expresses agrometeorological resources, i.e., a complex of meteorological conditions influencing agricultural crop during a growing cycle in their chronological order, while its mean value and variability distribution over a long period characterizes the agroclimatic resources, i.e., climatic conditions in a given location for crop growth, 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.

Practically possible yield (PPY) is the maximum yield achievable under the existing meteorological and soil conditions with optimal agrotechnology. The PPY is the yield category expressing resources of soil fertility under actual meteorological conditions.

Commercial yield (CY) reckons all the factors limiting the production process and the crop yield. In addition to biological properties, meteorological environment and soil fertility, this yield category depends on inadequate soil tilling, plant diseases, pests and weeds. CY is the yield attainable under existing farm conditions (Kadaja and Tooming 2004).

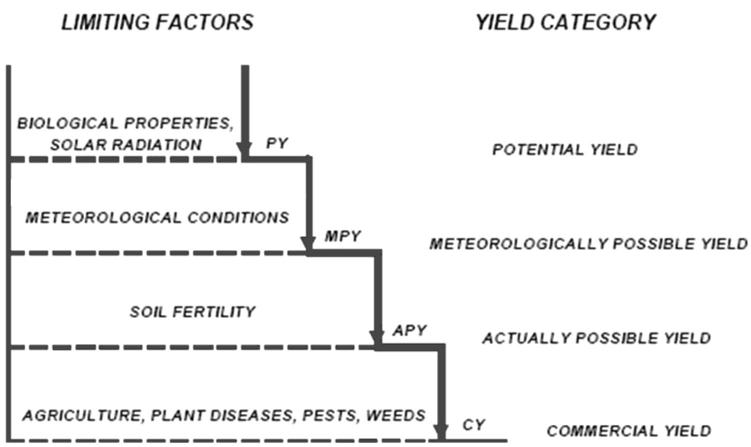

Figure 2.2. Reference yields and limiting factors taken into account in each (Zhukovsky et al. 1989).

The method of reference yields allows studying the production process step by step, starting from higher yield levels, considering first the limiting factors not dependent or only slightly dependent on other factors and human activities. Such factors are above all the biological properties of the variety, which determine the yield if all environmental conditions are optimal. Likewise, incoming solar radiation is independent of other limiting factors. After that other meteorological factors, basically temperature and water supply, are included. In turn, limitations induced by soil fertility and the level of agriculture are introduced.

Using the concept of meteorologically possible yield and mathematical models of crop productivity, agrometeorological and agroclimatic resources can be transformed into their yield equivalents and easily compare different complexes of conditions. The technique of reference yields enables to study theoretically the supposed response of varieties to the past weather conditions and estimate a yield time series long before the variety itself came to existence (Sepp and Tooming 1991, Tooming 1993). Also, plant response to possible climate change estimations in the future can be assessed.

2.3.3. POMOD

The principle of maximum plant productivity and the concept of the reference yields have been applied in the dynamic model POMOD to model the potato production process and yield (Sepp and Tooming 1982, 1991, Kadaja and Tooming 2004). The model POMOD (POtato MODel) was first compiled at the Estonian Agrometeorological Laboratory with an orientation for agrometeorological research and prognosis. Today it is under development at the Estonian Research Institute of Agriculture.

In its present state, POMOD allows the computation of the potential and meteorologically possible yields. In this thesis, the results of computing meteorologically possible yield (Fig. 2.3) are analysed and discussed. The complete description of model structure and governing equations can be found at (Kadaja and Tooming 2004). Hereafter a brief description about its main features and input parameters will be given.

The underlying parameters of POMOD are the total biomass of the crop M and the masses of plant organs m_i (leaves, stems, roots, and tubers) accounted per unit ground area by mass balance equations (Sepp and Tooming 1991, 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:

$$\Delta M_j = \int_0^{t_0} \int_0^{L_0} \varepsilon (A_g - r_g) dL dt - r_m \, , \qquad (2.6)$$

where j is the number of time step, ΔM_j the growth increment of total biomass in time step j, A_g is the gross photosynthesis rate per unit leaf area, r_g the growth respiration rate per unit leaf area, r_m the maintenance respiration per unit ground area, ε the transition coefficient from the net photosynthesis to dry matter, t_0 the length of the time step, t the time variable within the diurnal cycle, L the leaf area index inside the canopy, being zero above the canopy and equal to the LAI of the whole canopy L_0 below it.

The original input information for the model can be generally divided into four groups: daily meteorological data, annual information, parameters of location, and biological parameters of the potato variety (Fig. 2.4)

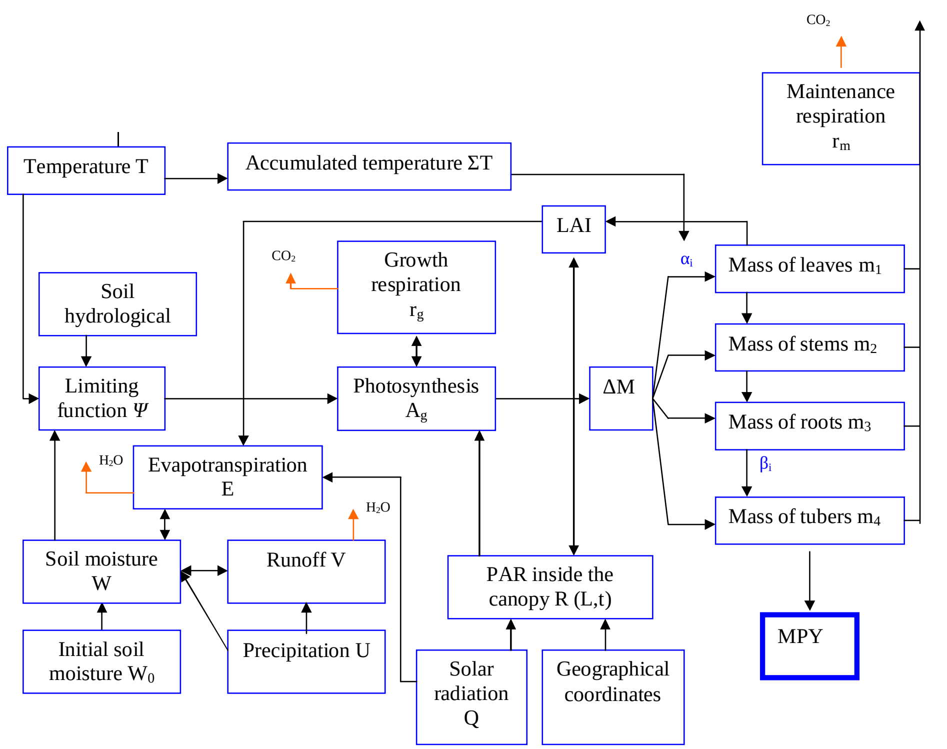

Figure 2.3. Functional scheme of the model POMOD for calculating meteorologically possible yield (MPY).

Of daily meteorological data, air temperature, precipitation and solar radiation are applied.

Annual information includes the year, 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 moment, when the temperature rises permanently above 8°C is considered as the planting time for the calculations. If the soil is too wet, the planting delays to the arrival of the field capacity. In the case of late night-frosts in early summer, planting time is postponed to an even later date to avoid frost damage to the tops of plants. The computation of biomass dynamics begins at the moment when the growth rate of roots, stems and leaves exceeds the rate of decrease of dry mass from the seed tuber. The calculations are ended, when the first night-frosts of below −2 °C occur in autumn or when the mean diurnal temperature remains permanently below 7°C.

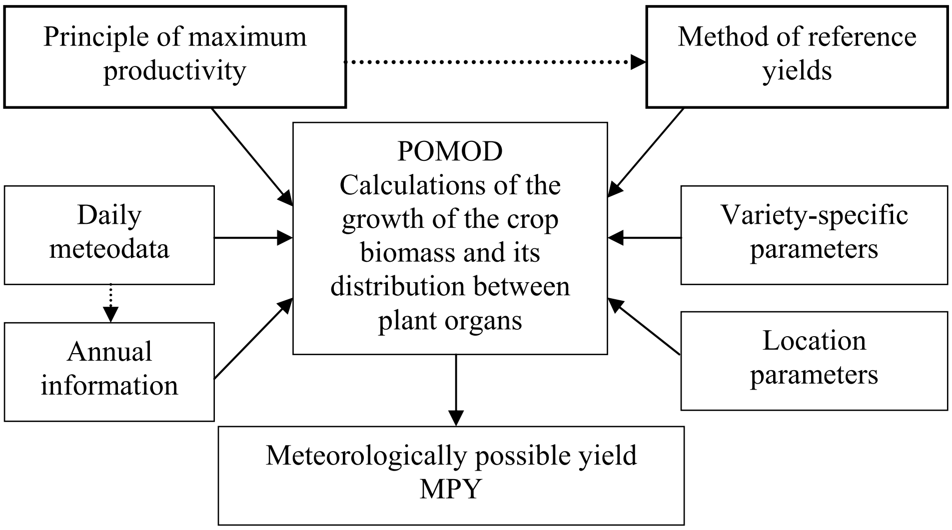

Figure 2.4. Illustrative scheme of POMOD for calculations of MPY with current climate data.

Locations are characterized by their geographical coordinates and soil hydrological parameters such as the wilting point, field capacity, and maximum water capacity. Also, dated initial soil moisture value in the spring or the date of soil moisture drop below the field capacity are needed as input.

Photosynthesis variables – the initial slope of the photosynthesis irradiance curve a, the irradiation density of adaptation R_a, and the photosynthesis and respiration rates at the saturated PAR density given per unit mass of leaves, σ_1 and σ_2 respectively – are considered as variety-specific input parameters for the model calculations.

The distribution of total increase of biomass between different plant organs is determined by the growth equation based on growth functions (Ross 1966):

$$\frac{\Delta m_i}{\Delta t} = \alpha_i \frac{\Delta M}{\Delta t} + \beta_i m_i \,. \qquad (2.7)$$

The vegetative growth functions α_i characterise the distribution of total growth between plant organs; the reproductive growth functions β_i characterise the part of biomass converted into tubers from other plant organs after their vegetative growth has stopped The values of the growth functions α_i and β_i are also considered variety-specific parameters and these are accessible from field biometric measurements. The growth functions are calculated per degree-day. For the potato crop, the best coincidence of experimental growth functions data has been achieved using accumulated daily mean temperatures above zero (Sepp 1988).

To calculate the meteorologically possible yield, POMOD takes into account the impact of temperature on photosynthesis and respiration and the effect of soil moisture on photosynthesis. The effect on photosynthesis is considered approximately by multiplying its potential value at every time step with the normalised limiting function Ψ. The latter expresses the total effect of meteorological factors (temperature and soil moisture) on photosynthesis. These functions are expressed for both factors as normalised curves with the maximum value in the optimum range of the factor.

The limiting function for temperature is presented in an exponential form (Dmitrenko 1976). Its parameters are evaluated on the basis of data obtained from the literature (Winkler 1971).

$$\Psi_T=\exp[-a_T(T-T_{opt})^2], \qquad (2.8)$$

where T is the air temperature, T_{opt} = 18.6°C, the optimal temperature for potato photosynthesis and a_T = 0.0038 (°C^{-2}) is an empirical parameter.

The limiting function of soil moisture is presented as an exponential curve with a wide range of maximum values:

$$\Psi_w = \exp\left[-b_1\left(\frac{W_{opt,1}-W}{W_{opt,1}}\right)^2\right], \qquad \text{if } W<W_{opt,1},$$

$$\Psi_w = 1, \qquad \text{if } W_{opt,1}<W<W_{opt,2}, \qquad (2.9)$$

$$\Psi_w = \exp\left[-b_2\left(\frac{W-W_{opt,2}}{W_{max}-W_{opt,2}}\right)^2\right], \qquad \text{if } W> W_{opt,2},$$

where W is the available water content (mm or kg m^{-2}), $W_{opt,1}$ and $W_{opt,2}$ are the limits of optimal available water content, which depend on soil type and correspond in the model to 60 and 100% of field water capacity (the maximum amount of water that a particular soil can hold), b_1=1.4 and b_2=0.7 are the empirical parameters for the 0.5 m soil layer, evaluated by the calibration method, using the data on soil water content and crop production measured by the agrometeorological observation network (Kadaja and Tooming 2004).

To calculate the total simultaneous limitation of Ψ_T and Ψ_W, the Liebig minimum law is used, modified to some extent to consider these interactions.

Available water storage W in the soil is calculated by the soil water balance equation (2.10) considering initial available water storage in the soil W_0, precipitation U, evapotranspiration E and the sum of runoff and percolation to ground water, V:

$$W = W_0 + U - E - V \tag{2.10}$$

Measured data are traditionally required for initial water supply and precipitation, while evapotranspiration is calculated by a simple empirical equation, based on measurements of evaporation from bare soil and evapotranspiration from soil with plants:

$$E = R_s(0.0872 + 0.0406\sqrt{L_0})\min(1, \frac{W}{W_{opt,1}}), \tag{2.11}$$

where R_s is the global radiation (MJ m^{-2}), L_0 the total leaf area index of the canopy (m^2 m^{-2}). To get the resulting evapotranspiration in mm (or kg m^{-2}), the numerical coefficients of the formula are given in units of kg MJ^{-1}. The soil water storage W affects evaporation only if it drops below the optimum limit, i.e., $W < W_{opt,1}$. The daily precipitation over 20 mm is considered as runoff; additionally cumulative rainfall over 60 mm in ten successive days is treated as runoff. Those runoff rates have been achieved by comparing the observed soil moisture values with computed values. In PAPER V, an additional scheme to consider topography-related runoffs, is described.

POMOD was originally developed with a orientation for agrometeorological research and prognosis – for the assessment of agroclimatical resources, for yield forecasting, planning and application in agricultural practice. It has been used in several applications, however not yet by practical agricultural manufacturers.

An assessment of potato cultivation efficiency was carried out in the Baltic states (Sepp and Tooming 1983, 1991, Kadaja 1994). Similar estimation of resources was carried out for the Komi territory situated near the Polar Circle adjacent to the Ural Mountains (Sepp et al. 1989). Using the longest available series of meteorological data for Estonia and the neighbouring Russian areas, the PY and MPY series were calculated from the end of the 19th and beginning of the 20th century (Sepp and Tooming 1991).

The probabilistic yield forecast method for a current year has been elaborated, using meteorological information from previous years (Sepp 1988b, Zhukovskij et al. 1989, Kadaja et al. 2009a, b).

The model has also been used for the optimal allocation of potato crops considering microclimatical conditions, particularly on slopes. Influence of fertilisation on potato growth functions was conducted (Kadaja 2004).

Overview of the possibilities of agriculture according to the principle of maximum plant productivity and mathematical modelling of crop productivity in the former Soviet Union was published in Russian by Tooming (1984b, 1991).

Assessment of possible regional climate change impacts on agriculture has been realized (Tooming 1993, 1998, Kadaja and Tooming 1998, Karing et al. 1999, Kadaja 2006).

POMOD, written initially in FORTRAN and transferred later into Visual Basic of Excel, has open code and its output is not restricted.

3. DATA AND METHODS

3.1. Data used

3.1.1. Meteorological data, locations and time frame

PAPER I is based on long-term field experiment data from Kuusiku Experimental Station (58°59'N, 24°42'E) (Fig. 3.1); corresponding meteorological series are used from Kuusiku Meteorological Station (58°58'N, 24°44'E). Time-series of average and accumulated temperatures and sums of precipitation were applied. Data of single and differently grouped months, and periods between phenological phases of potato (planting, emergence, flowering and harvest) were used in analysis.

In the model-related part of the thesis (PAPERS II–V), the meteorological and agrometeorological data from three meteorological stations are applied: Tartu (58°15´N, 26°27´E), Tallinn (59°23´N, 24°36´E), and Kuressaare (58°15´N, 22°29´E). Daily meteorological data – solar radiation, air temperature and precipitation – for those three stations originate from the archives of the Estonian Meteorological and Hydrological Institute. Since direct measurements of global radiation have only been made since 1954 in Tartu and since 2004 in Tallinn, the missing daily sums of global radiation were computed from sunshine duration, using regression equations established separately for every month on the basis of the data in Tartu-Tõravere.

PAPER II uses long data series from May to September up to 2006. For Tartu, such series were available from 1901, for Tallinn from 1920 and for Kuressaare for 1923–2000. Therefore, for 2001–2006, meteorological data for Kuressaare were calculated on the basis of an adjacent station (Virtsu, Sõrve, Vilsandi, or Ristna, depending on which had the highest correlation for a particular factor and period). The dates of night frosts and temperature transitions (to above 8°C in the spring and to below 7°C in the autumn) were also obtained from the meteorological datasets of the stations. The data for the soil water status in spring were 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.

In other papers, meteorological data are derived similarly to PAPER II. PAPER III uses all three station's data from 1965–2009 to derive possible distribution of weather in 2050 and 2100 using climate change scenarios. Since PAPER IV uses circulation types generated on the basis of the data from ERA 40 (Uppala et al. 2005) air pressure database, the observed period is 1958–2001; all three stations are involved. In PAPER V, empirical distribution of precipitation is compiled using precipitation data from the automatic precipitation gauge on field for 2005–2007; subsequent model experiments employ meteorological data of Tallinn and Kuressaare for the same periods as in PAPER II. In the experimental work (PAPER VI), soil measurements carried through both in Kuusiku and on the experimental fields of the Plant Biotechnological Research Center EVIKA at Saku (59°17'N, 24°40'E) are described. Two years (2005 and 2006) meteorological data from Kuusiku Meteorological station and on-site field meteostation at Saku were also used.

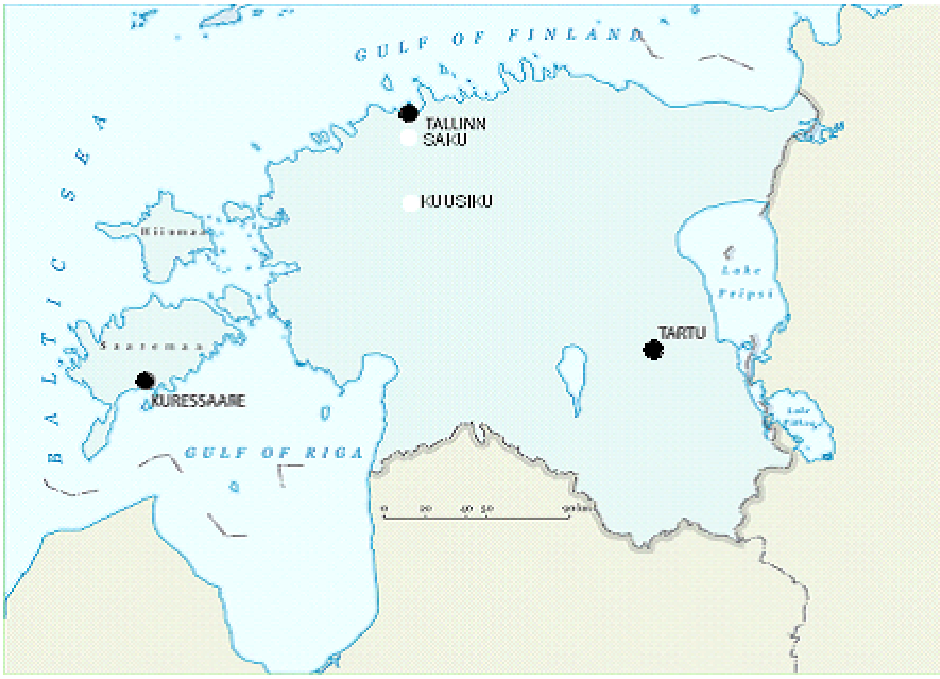

Figure 3.1. Location of the used meteorological stations (black circles) and experimental fields (white circles).

Tallinn, Tartu and Kuressaare are located in regions with different local climates, while Kuusiku and Saku are considered to belong to the same region as Tallinn. 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 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 and solar radiation between the stations (Table 3.1).

Table 3.1. Mean values of average temperature and monthly sums of global radiation and precipitation at the three locations of the summer half-year in the period 1965–2009.

Month	Average temperature, ºC			Global radiation, MJ m^{-2}			Precipitation, mm		
	Tallinn	Kures-saare	Tartu	Tallinn	Kures-saare	Tartu	Tallinn	Kures-saare	Tartu
April	3.8	3.9	4.9	394	399	380	35.6	32.7	33.4
May	9.7	10.0	11.0	587	591	555	41.3	29.7	54.9
June	14.3	14.6	15.1	626	626	595	59.7	43.9	71.8
July	16.7	17.1	17.1	601	608	580	83.0	57.9	70.7
August	15.7	16.7	15.9	467	484	452	78.9	61.6	79.8
September	11.1	12.4	10.9	270	284	265	76.1	65.7	60.0

3.1.2. Measured potato yields

The results presented in PAPER I and Chapter 4 are based on the data of an ERIA's long-term trial of soil management and fertilization methods with a six-year crop rotation (winter rye – potato – barley – barley/clover – grassland – grassland) at the Kuusiku experimental station conducted by Peeter Viil (Viil and Nugis 2002, Viil and Võsa 2006), on sandy loam, Calcic Luvisol (WRB 2006). Each range of a particular crop was divided between three parallel tillage techniques (minimum, conventional and deep tillage), each containing four fertilization treatments in four replications. In the current study, 19 year series of potato yields were examined. During the run of the experiment, 3 late potato varieties bred for local conditions were grown: 1989–1992 'Eba'; 1993–2002 'Ando'; 2003–2007'Anti'.

Since the effect of replication proved insignificant, the yields were averaged over replications. Significant yield differences between varieties were eliminated from further analysis by normalizing yields over varieties – individual yield values were divided by mean yield values for the particular variety.

3.1.3. POMOD input data for the present climate

PAPERS II, IV and V are based on the calculations of long-term series of meteorologically possible yield (MPY) by POMOD, using existing meteorological and agrometeorological data as described in the subchapter 3.1.1.

The locations are characterized in the POMOD by their geographical latitudes and the hydrological parameters of the soil, such as the wilting point, field capacity, and maximum water capacity. The parameters of the field soils (Kitse 1978) prevalent at the locality were used (by WRB for Tartu Albeluvisol; for Tallinn and Kuressaare the Skeletic Regosol are prevaviling). All the soils are sandy silt loam, with quite similar hydrological parameters.

Early variety 'Maret' and the late variety 'Anti', both bred for Estonian conditions, were used throughout the study. The variety-specific biological parameters of the two varieties were determined on the basis of field experiments, as described by Kadaja (2004). Growth functions (Fig. 3.2) were determined on the basis of field experiments made for 'Anti' at Saku in 2001–2004 (Kadaja 2004) and at Kuusiku in 2005–2007 and for 'Maret' at Saku in 2005–2006 (Kadaja 2006). The scope for the values of the variety-specific photosynthesis parameters *a* (the initial slope of photosynthesis irradiance curve), R_a (the irradiation density of adaptation), σ_1 and σ_2 (the photosynthesis and respiration rates at the saturated PAR density), had been estimated initially from the literature (Tooming 1977) and the most suitable values for those parameters were specified for the model by the calibration method using experimental field data (Saue 2006). Data of leaf area index and the biomass of all organs at all measurement dates were used in that comparision. Resultant most suitable values for the parameters are listed in the Methodology paragraph of PAPER III.

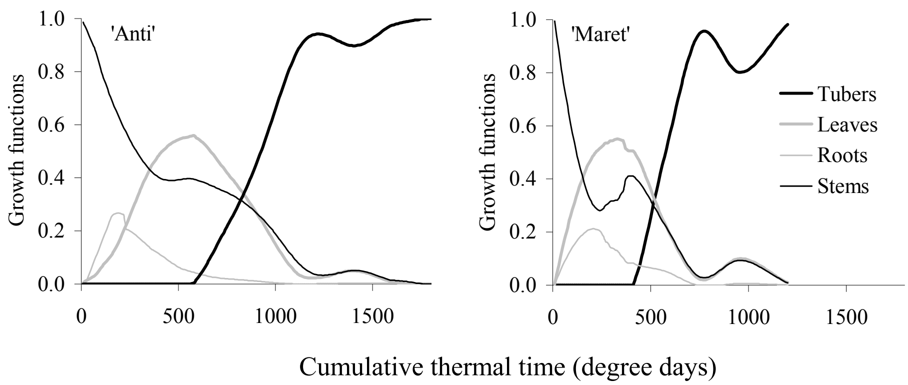

Figure 3.2. Experimentally determined growth functions of late potato variety 'Anti' and early variety 'Maret'.

3.1.4. POMOD input data for the future climate

For the calculations with the future climate scenarios data (PAPER III, Chapter 6), a new calculation scheme was enclosed into the model, requiring also a different set of input data.

To achieve temperature and precipitation data for the middle and end of the current century (hereafter marked briefly as projection for the target years 2050 and 2100, i.e., the central years for a climate averaging interval of 30 years), climate change scenarios were generated for Estonia using the 5.3 version of the MAGICC/SCENGEN software – a simple coupled gas-cycle/climate model that drives a spatial climate-change scenario generator. Information on the basic properties of MAGICC has been published in Wigley and Raper (1992), Raper et al. (1996) and Hulme et al. (2000). Four alternative illustrative emission scenarios were used in this study to generate climate change scenarios for Estonia: A1B, A2, B1, B2, (Nakićenović & Swart 2000). The highest climate warming is projected by A2; the lowest by B1. For each scenario we exploited predicted changes in mean monthly air temperature and precipitation from 18 IPCC AR4 GCM experiments (IPCC 2007a).

The data are displayed in MAGICC/SCENGEN in a grid resolution of 2.5º latitude/longitude, thus the Estonian territory is covered by three grid boxes, with medium coordinates 58.8ºN/21.3ºE, 58.8ºN/23.8ºE and 58.8ºN/26.3ºE. Tallinn, Kuressaare and Tartu all fall into different boxes. To calculate the future values of MPY, historical (observed) daily weather data in those stations during the baseline period 1965–2006 was used. 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. Hereinafter, the term "weather years" (as in Jame and Cutforth 1996) is used to refer to that new dataset. This way, not just the one average future value for temperature and precipitation, but the possible weather distributions (4 scenarios × 18 GCM × 45 weather years = 3240 alternatives) are suggested for both target years.

Thus converted future daily weather data series are employed to calculate the necessary annual information. The calculation logics is thoroughly described in PAPER III.

3.1.5. Circulation data

There are several ways to describe the general atmospheric circulation. For the middle and high latitudes of the northern hemisphere, the NAO index (Hurrell 1995, Hurrell and van Loon 1997, Dickson et al. 2000, Wanner et al. 2001, Hurrell et al. 2003), calculated as the difference between the standardized sea-level pressure anomalies between the Azores high and the Iceland low, is often used. 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 North Europe. Negative values indicate a small pressure gradient, thus weakening the westerlies. To discover the connections between MPY and the general atmospheric circulation, the correlations with NAO indices of different periods were analysed in PAPER II. An index set calculated on the basis of the pressure data for Ponta Delgada (Azores) and Stykkisholmur/

Reykjavik (Hurrell and van Loon 1997) was used (an updated version of the dataset is available at http://www.cgd.ucar.edu/cas/jhurrell/ indices/ html).

Another method mostly employed by the synoptic climatology, is to classify the general atmospheric circulation into a relatively small number of circulation types according to the position of the low and high pressure areas, the location of fronts, etc. Huth et al. (2008) defines the classification of atmospheric circulation as "a task of grouping entities, so that they share common features within each group while being dissimilar between groups". In PAPER IV, 73 circulation types from the COST 733 database are used in the comparison with the MPY. The compared circulation data variables included the circulation type frequencies for spring (March, April, May), summer (June, July, August) and the whole year. More information about the used classification can be found from the Data and Methodology chapter of PAPER IV as well as from Huth et al. (2008), Huth (2010) and Philipp et al. (2010).

3.2. Methodology of the calculations

3.2.1. Analyses of the observed yields

In PAPER I, the effects of tillage, fertilization and experimental year (weather) on potato yields were examined using one- and three-way factorial ANOVA. In the case of a significant ANOVA result, the Tukey HSD *post hoc* test was used to evaluate the differences among means. Also a variance components test with the experimental year as a random factor was conducted for generalisation.
Before the factorial ANOVA, the division of experimental years into larger groups was conducted by the joining tool of cluster analyses (tree clustering), using potato yields from 12 different tillage/fertilization combinations in those years as the measure of similarity.

The relationships between the weather conditions and yields were analysed with linear regression analysis.

3.2.2. Calculating the agroclimatic resources

The concept of using calculated weather-reliant yields as a measure of agro-climatic resources of different locations and agrometeorological resources of different years is realised in the thesis. For that purpose, long-time series, mean values and cumulative distributions of MPY were compiled for the specified varieties and locations. MPY series were calculated by the model POMOD, described in subchapter 2.3.3., with the existing meteorological data series, thus describing the existing climatic resources for plant growth during the used period.

Changes and additions to the original modelling scheme of POMOD have been described in more details in the corresponding papers.

For PAPER II, the calculating scheme was modified to enable calculating long-term series of MPY. The same scheme was used to derive data for PAPER IV. A similar approach has been earlier used by several papers published in Russian (e.g., Sepp and Tooming 1983, Sepp et al.); however, a new modelling scheme had to be compiled due to the changing of modelling language.

In PAPER III, calculating scheme was modified to enable future calculations. This approach can be fully browsed at the Methodology paragraph of the article.

In PAPER V, an additional set of calculations has been included into the soil moisture calculations scheme to enable precipitation runoff by a slope and is profoundly described in the article. Romanova (1966, 1977) has defined summer precipitation redistribution by coefficients considering slope incline, soil moisture and rainfall intensity. In PAPER V, an additional transition scheme from rainfall intensities into daily precipitation sums was compiled, using Romanova's runoff coefficients, POMOD-computed soil moisture values and summer precipitation data from automatic meteorological station. As a result, total amount of runoff water for any daily precipitation value can be defined. Precipitation redistribution and corresponding MPY values were determined for three different parts of a notional slope.

3.2.3. Calculating MPY correlations with other variables

In PAPER II and subchapter 5.2, the correlations between simulated potato yields and a direct meteorological series of precipitation, temperature, and solar radiation, using accumulated values for these meteorological elements over different periods were calculated, in order to explain the extent to which the individual factors allow us to describe the whole complex. A correlation analysis with linear and second-order polynomial curves was performed.

To discover the connections between MPY and the general atmospheric circulation, linear correlations with NAO indices of different periods were analysed in PAPER II. In PAPER IV the correlation between the modelled potato crop yield and the circulation type frequencies was also assessed by linear correlation. To determine the classification best related to potato growth, the number of circulation types in each classification giving a significant correlation with different time-series in different seasons was summed. It must be noticed, that these circulation types often overlapped – for example, the same type gave a strong correlation in the summer for Kuressaare with both varieties, but in the total sum it counts as two types. To unify the weight of strongly correlating circulation types in order to rank the types, the total sum was divided by the sum of the actual number of annual, spring and summer types of the classification and the result was multiplied by 100 to convert the result into the percentage.

3.2.4. Development of methodics for soil moisture measurements

In PAPER VI and paragraph 6, development of methodics for model parameter determination is described. More precisely, indirect determination of soil water content is dealt with.

The only technique measuring soil water content *per se* is the gravimetric technique (see e.g. Robock et al. 2000 and Robinson et al. 2008 for overview). Thereby, soil samples are extracted from the field and weighted before and after drying. From the changes in mass, the original soil moisture content (absolute, relative, volumetric) can be derived. While this method represents the actual "ground truth" (for single samples), there are several issues with its implementation. The most important is that the measurement method is destructive, and can thus not be reproduced. Moreover, significant manpower is required for the retrieval of the samples and the lab measurements. Nonetheless, gravimetric measurements still represent the reference measurements for calibrating other soil moisture measurement methods, since all other approaches are indirect.

There exist several indirect methods for *in-situ* measurements of soil moisture. Two of the most common ones, time domain reflectometry (TDR; see, e.g., Topp and Reynolds 1998, Robinson et al. 2003, Topp 2003, Robinson et al. 2008) and soil capacitance measurements (e.g., Plakk 1990, Topp 2003, Bogena et al. 2007, Robinson et al. 2008) both make use of the dependency of the dielectric permittivity of the soil on soil moisture content, i.e., the great difference between the dielectric constant of soil components and water. Similarly, within the present research, measurements of soil dielectric constant ε_r were carried out on soils under potato crop to investigate contents of soil volumetric water θ for eventual use in a model. Electrical properties and temperature of soils were measured with a commercial device of Adek Ltd dubbed a 'percometer' (PERmittivity and COnductivity METER) – a frequency domain instrument for the successive and nondestructive *in situ* measurement of the dielectric constant and specific conductivity of soil and other materials. The device was above all selected because of its convenient design as a single-tube sensor (Figure 3.3), enabling quick and easy mobile measurements in soil layers of selected depth, even in gravelly soils. The information about the methodics of soil measurements as well as percometer's principle of working is available from PAPER VI and from the patent description presented on the basis of these measurements (Nugis et al. 2008).

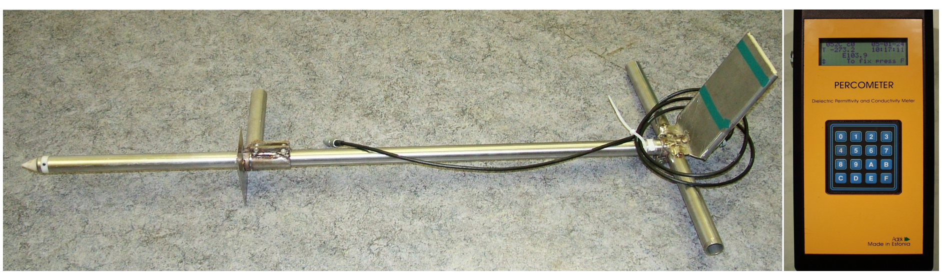

Figure 3.3. Percometer and its display panel.

4. THE RELATIONSHIPS BETWEEN OBSERVED POTATO CROP VARIABILITY AND METEOROLOGICAL ELEMENTS

The main question of the study presented in PAPER I was whether the variability in meteorological conditions influences the long-term effect of different soil tillage and fertilization regime on potato yields. Another objective of the study was to analyse the relationships between yields in the long-term experiment and the common weather parameters. In the context of the thesis as a whole, PAPER I is mainly included for comparision („reality touch“) purposes, since even the best crop growth model simulations could explain only to a limited extent the inter-annual yield variation from the inter-annual variation in weather conditions (Olesen et al. 2000, Šťastná et al 2010). In addition to modelled results, it is thus valuable to examine the relations between real potato yields and weather elements.

By the means of cluster analyses, experimental years were divided into three larger groups with high, medium and low yields, referred further as A, B and C, respectively, and representing years with favourable, sufficient and unfavourable weather conditions for potato growth (Fig. 4.1). Those groups are used in further analyzis as a measure to outline the weather differences.

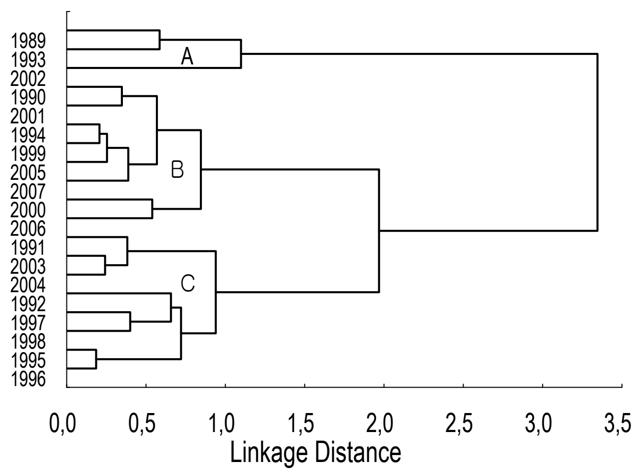

Figure 4.1. Classification of years into year clusters with high (A), medium (B) and low (C) potato yields.

The strong one-way effect of the experimental year on normalized potato yield was proved ($F_{18,\ 209}$=80.6; p<0.0001), while there was no significant one-way effect of fertilization or tillage. This proves the strong dependence of yields on weather, since we assume the differences between years to be mostly attributed to different weather conditions. Temporal variation in normalized yields was quite high (Fig. 4.2).

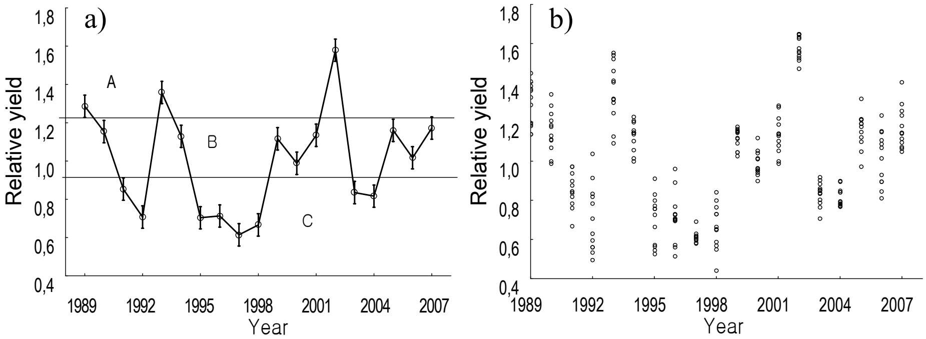

Figure 4.2. Normalized yields of the years, averaged over fertilization and tillage (a) and the overall range of normalized yields of all variants (b). A, B and C mark classification of years into high, medium and low yielding categories.

The integrated effect of tillage, fertilization and year clusters on relative potato yield in the experimental period is presented in Table 4.1. The effect of tillage tested insignificant, declaring that crop-rotational yield is only slightly or not at all affected by tillage intensity. Fertilization and year cluster both proved significant, while no significant interactions between variables were detected. By Tukey *post hoc* test, all three year clusters proved significantly different from each other, while for fertilization the significant difference was detected only between S0 (no fertilization) and S3 (the highest fertilization). However, when three year clusters are considered separately, the difference between S0 and S3 definitely comes from the high yielding years (cluster A), confirming the effect of high fertilization for convenient weather conditions. Also in the lowest yielding years (cluster C) the positive effect of the highest fertilization treatment is detectable. The negative effect of no fertilization appears for the years with high and medium yields.

Table 4.1. The effect of tillage, fertilization and year cluster on potato yields presented by three-way factorial ANOVA. Year cluster is used as a fixed variable.

Impact	*df*	*MS*	*F*	*p*
Tillage	2	0.0085	0.53	0.6
Fertilization	3	0.11	4.5	0.0004
Year cluster	2	6.85	216	<0.0001
Tillage×fertilization	6	0.0015	0.05	0.99
Tillage×year cluster	4	0.013	0.36	0.54
Fertilization×year cluster	6	0.028	1.3	0.13
Error	192	0.017		

df – degree of freedom; *MS* – mean square; *F* – the ratio of the *S*-squares; *p* – level of significance.

When results are generalized to the whole population, i.e., outside the observed years (Table 4.2), the effect of experimental year still remains very important (describing over 80% of the yield variance) and tillage still does not matter; the effect of the fertilization decreases slightly and significant interactions with experimental year appear both for fertilization and tillage, verifying that the effect of both tillage and fertilization is dependent on year-to-year weather differences. We can say that "in the real world" (or in longer perspective) both fertilization and tillage are expected to affect the influence of weather on yields, although this was not detected within given sample.

Table 4.2. The effect of tillage, fertilization and year on potato yields presented by three-way factorial ANOVA. Year is used as a random variable.

Impact	*df* effect	*MS* effect	*df* error	*MS* error	*F*	*p*
Tillage	2	0.009	36	0.02	449	00.64
Fertilization	3	0.98	54	0.017	5.65	0.002
Year	18	0.85	74.3	0.035	3.94	<0.0001
Tillage×fertilization	6	0.0017	108	0.002	0.83	00.55
Tillage×year	36	0.02	108	0.002	9.94	<0.0001
Fertilization ×year	54	0.017	108	0.002	8.5	<0.0001

df – degree of freedom; *MS* – mean square; *F* – the ratio of the *S*-squares; *p* – level of significance.

The influence of fertilization and tillage on the effect of weather on yields was studied by examining linear correlations between individual years' weather data and yields (Table 4.3).

Table 4.3. Linear correlations between average yields of 7 different variants (M1, M2, M3 averaged over fertilization variants; S0, S1, S2, S3 averaged over tillage range) and meteorological elements of different periods. Bold indicates significance $p < 0.05$.

Period	Element	Variant						
		M1	M2	M3	S0	S1	S2	S3
January	Average temperature	0.38	0.33	**0.46**	0.35	0.37	0.36	**0.47**
April – May	Average temperature	**0.71**	**0.71**	**0.76**	**0.71**	**0.69**	**0.71**	**0.77**
	Sum of precipitation	**–0.44**	**–0.48**	**–0.46**	**–0.54**	**–0.42**	**–0.44**	**–0.44**
April–August	Accumulated temperature	**0.58**	**0.57**	**0.61**	**0.62**	**0.64**	**0.60**	**0.47**
Planting – flowering	Accumulated temperature	**–0.49**	**–0.57**	**–0.53**	**–0.65**	**–0.48**	**–0.49**	**–0.50**
Flowering – harvesting	Sum of precipitation	**0.57**	**0.57**	**0.63**	**0.60**	**0.55**	**0.59**	**0.62**

The yields of all examined variants were found to be significantly correlated to spring weather – positively to temperatures and negatively to precipitation. Positive effect of higher temperatures before and around the time of planting and early growth of potatoes is evidently mediated by soil, but as the soil temperature of the top layer is closely related to air temperature, the latter serves as a good indicator. Positive correlations between yields and average temperatures in January probably derive from the influence of January temperature to spring conditions through its interactions with snow and ice cover (Tooming and Kadaja 2006). Positive significant correlation between yields and temperatures accumulated over longer periods, the longest being the whole summer half-year (April-August) was also detected, being stronger for more tilled and less fertilized variants. Negative correlation between yields and accumulated temperatures from planting to flowering proceeds probably from low temperatures prolonging period between the two phases and rising the risk of damage the sprouts by damping-off.

The correlations between yields and precipitation are weaker than the ones with temperatures. The reliably negative ($p<0.05$) effect of precipitation in spring and during early growth is probably connected with lower temperatures during rainy periods (Feddes 1987) and slower warming of the soil, which is supported by a negative correlation between rainfall and temperature. It results that warm and dry springs are more favourable for potato growth than wet and cold springs. Positive correlation exists between yields and precipitation summed from flowering to harvest, indicationg that potatoes are more susceptible to water stress during tuber formation period in July and August.

5. MODELLED TIME SERIES OF MPY FOR THE PRESENT CLIMATE

In addition to the apparent influence of weather on yields, as analysed in Chapter 4, this relation can be looked "upside down" and use biological and agricultural data in climate assessments. 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 modelled potato yield as an indicator of summer climate variability is discussed. Computed series of weather-reliant potato yields based on real existing meteorological series are described. Trends and variability changes within the series are assessed and compared to variability in the series of meteorological data and atmospheric circulation data. An application of using simulated time-series for topography-related yield differences is described.

5.1. MPY series and variability

Long-time series and mean values of MPY were compiled for early and late maturing potato varieties in three Estonian localities, Tallinn, Tartu and Kuressaare (Table 5.1). MPY series were calculated with existing meteorological data series, thus describing the existing climatic resources for plant growth during the given period.

Table 5.1. Mean MPY in Tallinn, Tartu and Kuressaare for two potato varieties.

Variety/Location	Tallinn	Tartu	Kuressaare
Early variety 'Maret'	48.6	44.1	37.8
Late variety 'Anti'	55.5	55.5	50.1

As expected, the late variety 'Anti' produced higher yields at all locations. An opposite situation is realised in some years with extremely wet conditions. As excessive soil moisture accumulates in Estonia mostly in the second half of the growing season, it has stronger effect on the late variety.

In Tartu, the lowest MPY in the series are related to the excessively wet years, 1928, 1985 and 1998 (Fig 5.1), whereas the MPY values between 30 and 40 t ha^{-1} are mostly caused by dry conditions. The generally lower yields in Kuressaare are mostly due to frequent insufficiency of water, the lowest achieved in the driest summers – 1939, 1955, 1997, 2006. There appears no such definite prominence in Tallinn.

Overall, the MPY series showed only weak and insignificant trends (Fig 5.1), although significant 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.

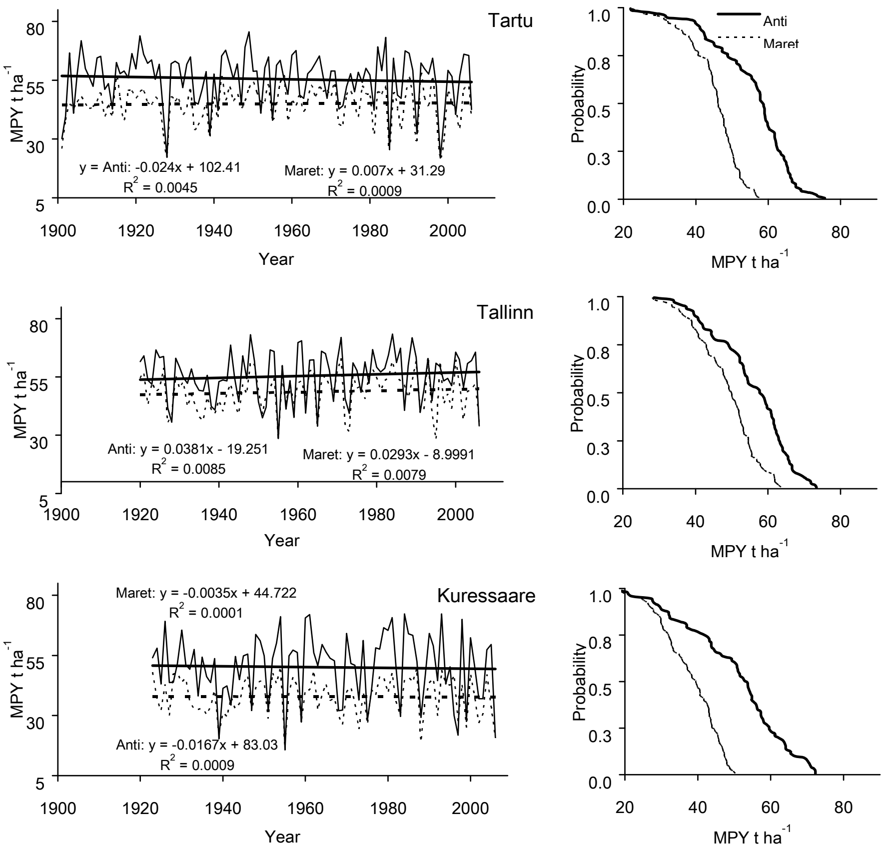

Figure 5.1. Series of meteorologically possible yields (MPY) (left) and their cumulative distribution expressing climatic MPY forecast (right) of the late potato variety 'Anti' (solid lines) and early potato variety 'Maret' (dotted lines) at Tartu, Tallinn and Kuresaare.

Generally, 'Anti' demonstrated higher variance in yields. For both varieties, the variability reached higher in Kuressaare.

In all three stations, the variability expressed by moving standard deviation is quite different in the different intervals of the periods (Fig. 5.2). In Tartu the instability of MPY was higher in the 1920s and 1930s and increased again from the early 1980s, causing significant trends in running course of standard deviation. Standard deviation of MPY was significantly lower for 'Maret' in 1901–1980 compared to 1981–2006 (p = 0.0055, according to F test); for 'Anti', the change was smaller yet significant (p = 0.046). It can be concluded that in the inland part of Estonia the climatic conditions during the growing period have grown more unstable than these were earlier. Extreme years as well as years with well-balanced meteorological conditions have increased in frequency. Of the meteorological elements series, only precipitation revealed similar difference in variability between 1901–1980 and 1981–2006. Although over the whole period (1901–2006) the variability of precipitation has reliably increased, the difference in precipitation variability between 1901–1980 compared to 1981–2006 was lower than for MPY (e.g., p = 0.013 for the precipitation accumulated from June to August). Therefore, we can say that the long-term means of the separate meteorological elements do not reflect the influence of their combined effect on the variability of biological production. The variability in the late variety series in Tartu is equally associated to variability in the accumulated temperature and precipitation series (r=0.61 for temperature and r=0.58 for precipitation), while variability in the early variety series is more strongly related to variability in cumulated precipitation series (r=0.82 for precipitation, r=0.61 for temperature).

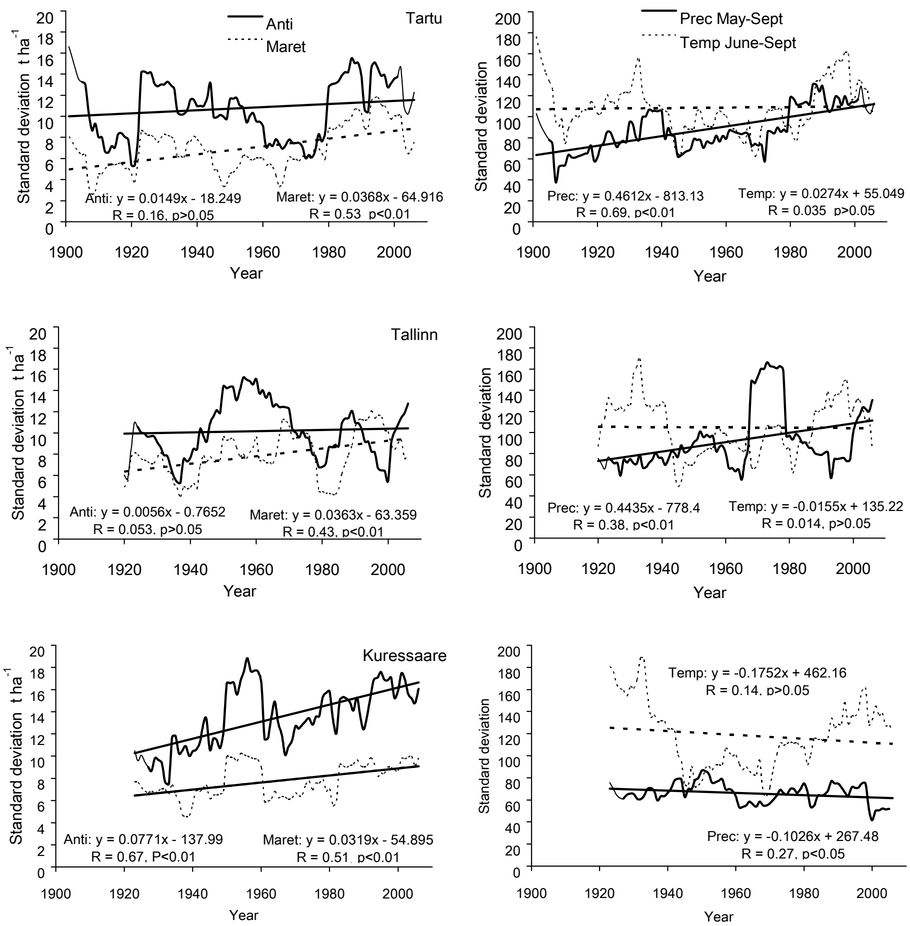

Figure 5.2. Courses of moving standard deviations calculated over 11-year intervals for two varieties in three locations (left) and for corresponding accumulated precipitation and temperature (right).

In the coastal stations, Tallinn and Kuressaare, a peak in the yield variability can be found in the 1950s. In Kuressaare, a rise in yield variability, not identified in the meteorological series, appears for 'Anti', the standard deviation being approximately two times lower before 1939 than in later periods (p = 0.017). In those two stations there exist no strong statistical relations between variability in MPY series and meteorological series.

5.2. Correlations between MPY and accumulated meteoelements

Simulated yields and a direct meteorological series of precipitation, temperature, and solar radiation, using accumulated values for these meteorological elements over different periods, were compared (Table 5.2), in order to explain the extent to which the individual factors allow us to describe the whole complex.

In Tartu and Tallinn, the linear correlations between MPY and the accumulated meteorological factors were generally weak, although they were significant in some cases due to the long time-series. The correlations with temperature were 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: positive for precipitation and negative for solar radiation and temperature.

The curve with a maximum describable by a second-order polynomial gives better correlation between MPY and the accumulated meteorological elements. This means that for all factors, the limitation derives from both deficit and excess (Fig 5.3 & 5.4). Again, the highest correlations occurred in Kuressaare: for 'Maret' with temperature from June to September ($r = -0.71$) and for 'Anti' with precipitation (June-August: $r = -0.77$, May–August: $r = -0.76$).

The results for Kuressaare are different from those for the other two stations because its mild marine climate and dry summers. Low precipitation at the beginning of summer causes water deficit as the main limiting factor there. For the early variety the correlations are almost equal on the linear and polynomial curves, so the limiting factor for the early variety in most years is definitely a deficit of precipitation. For the late variety, the decrease in yield is occasionally also caused by an excess of water. However, the latter is much more common in inland regions, where intense rainy periods produce soil moisture near its maximum content, causing the loss of soil aeration and a very significant reduction in yield.

The relationships between MPY and solar radiation and temperatures are largely indirect, as these factors correlate negatively with precipitation.

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).

Table 5.2. Correlations between cumulative meteorological elements and MPY. POL-polynomic correlation, LIN-linear correlation, R-solar radiation, P-precipitation, T-temperature. Bold indicates statistically significant correlations at *p<0.05*.

Station	Meteo-element	Relation-ship	Early variety 'Maret'			'Late variety Anti'		
			Mai–Aug.	June–Aug.	June–Sept.	Mai–Aug	June–Aug	June–Sept.
Tartu	R	LIN	0.03	0.02	0.01	0.01	–0.03	–0.02
		POL	**–0.36**	**–0.41**	**–0.34**	**–0.47**	**–0.52**	**–0.45**
	P	LIN	–0.07	–0.02	–0.01	–0.06	–0.12	0.08
		POL	**–0.53**	**–0.40**	**–0.35**	**–0.64**	**–0.56**	**–0.53**
	T	LIN	**–0.26**	**–0.37**	**–0.33**	–0.04	–0.20	–0.16
		POL	**–0.35**	**–0.50**	**–0.39**	**–0.41**	**–0.55**	**–0.41**
Tallinn	R	LIN	–0.03	–0.12	–0.09	–0.01	–0.10	–0.05
		POL	–0.25	**–0.32**	**–0.35**	**–0.34**	**–0.35**	**–0.37**
	P	LIN	0.19	**0.27**	0.11	**0.26**	**0.34**	0.17
		POL	**–0.31**	**–0.33**	**–0.29**	**–0.42**	**–0.46**	**–0.45**
	T	LIN	–0.17	**–0.41**	**–0.42**	0.14	–0.09	–0.11
		POL	**–0.41**	**–0.52**	**–0.46**	**–0.46**	**–0.44**	**–0.36**
Kuressaare	R	LIN	**–0.50**	**–0.55**	**–0.55**	**–0.46**	**–0.56**	**–0.54**
		POL	**–0.50**	**–0.55**	**–0.55**	**–0.47**	**–0.57**	**–0.55**
	P	LIN	**0.65**	**0.61**	**0.60**	**0.65**	**0.72**	**0.66**
		POL	**–0.68**	**–0.66**	**–0.63**	**–0.76**	**–0.77**	**–0.69**
	T	LIN	**–0.56**	**–0.68**	**–0.71**	**–0.30**	**–0.44**	**–0.47**
		POL	**–0.58**	**–0.69**	**–0.70**	**–0.48**	**–0.57**	**–0.60**

The limiting from two sides and high variances between MPY and the cumulative meteorological elements allow 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.

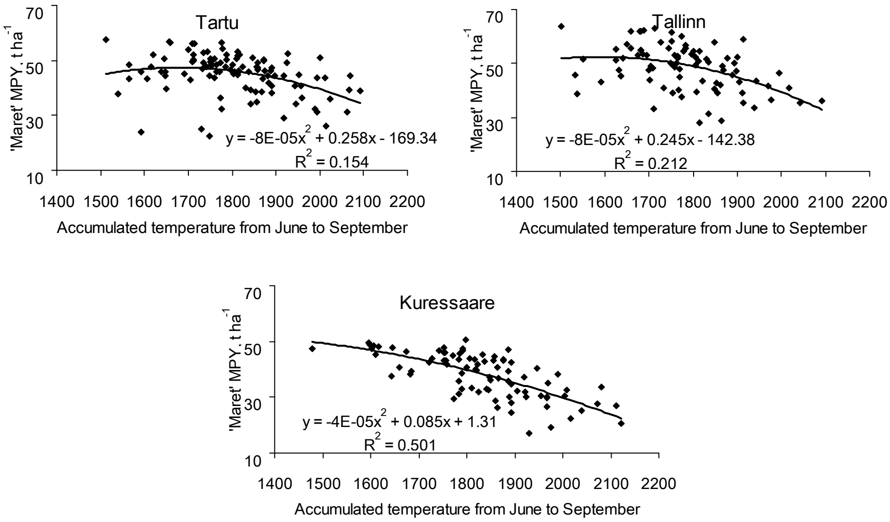

Figure 5.3. Correlation between cumulative temperature from June to September and MPY of the early variety 'Maret' in three stations.

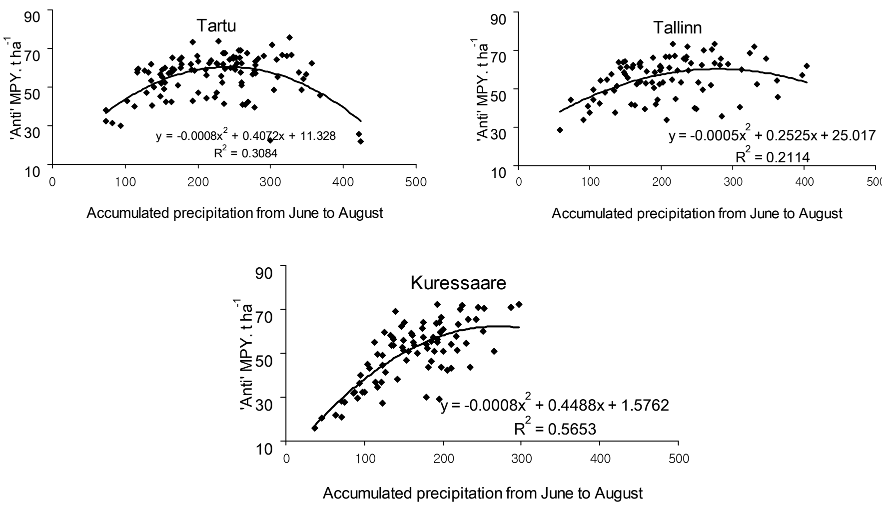

Figure 5.4. Correlation between cumulative precipitation from June to August and MPY of the late variety 'Anti' in three stations.

5.3. Correlations between MPY and atmospheric circulation

5.3.1. Correlations between MPY and north atlantic oscillation (NAO)

Significant correlations have earlier been established between large-scale circulation variables and meteorological factors in Estonia, principally for the winter half of the year (e.g., Tomingas 2002, Sepp 2005, 2009, Jaagus 2006). The possible relationships between crop yields and NAO were sought in PAPER II to help to explain the potential impact of atmospheric circulation on the integrated complex of summer weather conditions and to identify the indirect correlations.

There were 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 5.3). 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 (Tallinn and Kuressaare). 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. Those correlations reflect the positive influence of a mild winter (positive NAO index) on the following summer growing conditions, probably through earlier spring season and soil drying (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. Significant 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.

Table 5.3. Linear correlation coefficients between MPY and values of the NAO index calculated on the basis of Ponta Delgada-Stykkisholmur/Reykjavik. Statistically significant correlations at the $p < 0.05$ significance level are marked in bold.

Station	Variety	Period					
		November	November–December	November–February	January	January–May	September
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
Kures-saare	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

5.3.2. Correlations between MPY and circulation types

As shown in previous chapters, 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. Thus the interest to use combined weather variables arises. In this subchapter and PAPER IV, circulation type occurrence is applied as such combined variable and correlations between circulation types occurrence from different classifications and MPY are analysed. The motivation was to find out if there would exist a calculable connection between potato yields and any feature of the atmospheric circulation. Circulation types can be regarded as the integral indicators of different meteorological parameters – the position of low and high pressure areas and the concurrent airflow determines whether there is a sunny, warm and dry, or a cool and rainy weather in the observed location. The second objective of the research was to asses if any of the classifications or classification methods associates better with the potato crop yield. The main hypothesis behind that approach is that the best classification for characterizing potato growth conditions is the one with the highest number of statistically significant correlations with potato yields.

425 circulation types exist, which annual, spring or summer frequency time-series produced statistically significant correlations with potato crop yield. These circulation types give 786 statistically significant correlation rates in different combinations of seasons, locations and varieties (Table 5.4). Although statistically significant correlation coefficients constitute only 3.4% of all the calculated coefficients, there is at least one circulation type in each of the analyzed classifications with at least one statistically significant correlation with potato crop yield whether in Kuressaare, Tallinn or Tartu. The maximum number of correlations to one circulation type was six. No classifications with circulation types describing the atmospheric processes having effect on the crop yield in all of the three chosen observation stations at the same time were revealed.

As a rule, there are more negatively correlated circulation types; i.e., circulation types inducing a decrease in the potato crop yield are more clearly represented (Table 5.4). Clear differences exist between the observed geographical locations as well as between the seasons – especially the summer season and Kuressaare stand out. Of potato varieties, late 'Anti' seems to be more influenced by circulation, especially in Kuressaare. The results of the whole year are quite similar to the results of summer.

Relatively few types give strong correlations in the spring – seemingly the calculated MPY is not much affected by the spring circulation conditions. The missing connection probably derives from the fact that the given crop yield calculations are made beginning from the planting date when the temperature rises permanently over 8ºC; often the date is even further postponed to avoid damages by night frosts. Therefore, thus calculated potato yield is affected by the weather conditions in March and April only through the initial water supply in the soil and not through direct weather conditions expressed by circulation types.

The large correlation between the yearly sums of circulation type frequencies and calculated potato yields is also fairly surprising. One may assume that the correlation lies in the fact that those circulation types that bring about harder winter conditions are also responsible for the drought in the summer.

Table 5.4. The number of circulation types having statistically significant correlation with MPY and dominating pressure areas on the mean sea level pressure (MSLP) type map. N-negative correlation, P-positive correlation; L-low and H-high pressure area, C-center, other letters mark the general direction of air masses (e.g. N – north etc.) that flow into Estonia depending on the position of pressure areas, ? – situations, where the dominating pressure area or direction of air masses cannot be clearly determined.

Period	Relation-ship	Early variety 'Maret'			Late variety 'Anti'		
		Tartu	Tallinn	Kures-saare	Tartu	Tallinn	Kures-saare
Year	N	11/LC	9/LC	18/HW	27/LC-LE	11/HN	94/HW
	P	1/L	3/LW	28/H-L	1/L	8/LW	58/LC
Spring	N	17/LC	17/LE-LC	11/LC	15/LC	2/L	–
	P	5/H	1/HC	2/L	–	1/L	2/L
Summer	N	11/LNW	16/HC-HW	83/HC	10/LNW	2/?	127/HC-HW
	P	3/HW	11/L	70/LC	2/?N	2/?	107/L

In the circulation types related to low pressure areas, statistically significant correlation with potato yields is typical for the types, in which the low pressure area covers either the whole domain with its conditional centre located in the centre of the domain (Fig. 5.9a), or the low pressure area covers the northern part of the domain and its centre is located in the north-west (Fig. 5.9b) or in the north-east from Estonia (Fig. 5.9c). A common characteristic of all these types is the dominant west flow above Estonia, causing rainy and relatively cool weather for a summer. The circulation types with this kind of precipitation generally have a positive effect on the potato crop yield in Kuressaare and a negative effect in Tartu (Table 5.4). This is a clear indication that the limiting factor of potato growth is the lack of water in Kuressaare, while in Tartu there probably exists a dual limiting by the influence of the excess water and low temperature, delaying the plant development. There is no such clearly visible distinction in Tallinn; rather, there is a combination of correlations distinctive to the mainland Tartu and the marine Kuressaare. Such result reflect the fact that crop yield is a complex variable, integrating the effect of several meteorological elements.

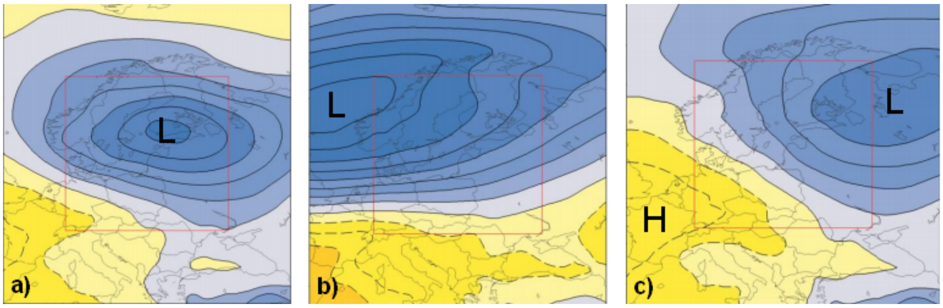

Figure 5.9. Examples of circulation types with dominant low pressure areas. a) – classification TPCAC09 type 3; b) – HBGWL type 2; c) – CKMEANSC09 type 4.

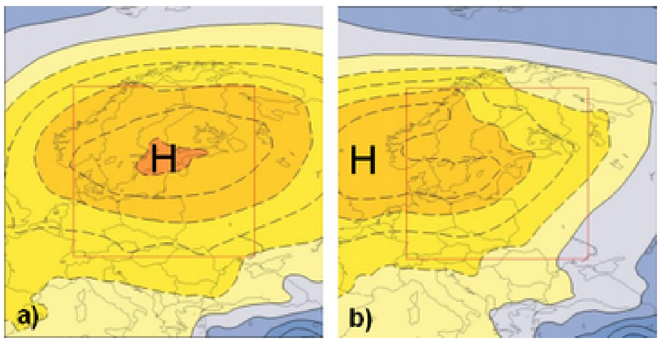

Figure 5.10. Examples of circulation types with dominant high pressure areas. a) – classification EZ850C30 type 3; b) – TPCAC18 type 12

When the high pressure area is dominant in the domain, there are also 2–3 contrasting circulation patterns that give strong correlations with the potato yields. One typical pattern describes a situation in which the high pressure area covers the whole domain and its centre lies above the Baltic Sea (Fig. 5.10a). In the other situations, the anti-cyclone covers the northern part of the domain (Fig. 5.10b) and, depending on the position of the centre of the pressure area, the eastern or north-eastern winds are dominant in Estonia. In summer, such types bring about sunny and warm above the average weather, which may cause a lack of water that is needed for potato growth in the habitats that often suffer from drought, such as Kuressaare. The high pressure areas clearly influence the Estonian potato crop yield mainly through water supply. The secondary influences – possible night frosts caused by the radiative cooling or by the advection of cold air masses that are common for anti-cyclones – appear insignificant. In Kuressaare, the anti-cyclonic weather conditions have a negative effect on the potato crop yield (Table 5.4), whereas the warm and dry weather has a positive effect on the potato crop yield in Tartu.

5.4. A Possible application: Accounting the precipitation redistribution in the MPY calculations

Historically, many of the biggest shortfalls in crop production have resulted from droughts caused by anomalously low precipitation (Kumar et al. 2004, Sivakumar et al. 2005). Soil moisture is often one of the most important stress factors for vegetation and crop yield (e.g. Ridolfi et al. 2000, Seneviratne et al. 2010). Among other factors, the agro-hydrological regime is strongly influenced by soil topography. Redistribution of precipitation on inclined surfaces increases the drought frequency on the slopes and causes excessively wet conditions in the foothills. Thus, in calculations of site-specific differences in the field, the relief-related soil water differences should be considered. PAPER V describes supplementation of a subroutine to account precipitation redistribution in the slope to POMOD and its influence in a sloping field on potato yield in two locations.

MPY for a plain area and three different parts of a notional slope (upper, lower and foothill) were compared in the study. Some significant MPY differences at the foothill area were revealed, corresponding to climatic specialty of given locations. For upper and lower part of a small (<3º) incline, no significant influence of runoff on long-term mean MPY values was detected; however, the situation can be quite different in individual years. Generally the upper part of the slope is believed to suffer from water runoff and produce lower yields compared to plain surface. This holds exclusively true in Kuressaare, where yield limiting by water deficiency is well characterized by change in MPY through the slope – the more additional inflow is available, the higher the MPY. In Tallinn, conversely, the advantage of the upper part of the slope arises from the runoff of excess water in several moist years. For the lower part of the slope, the positive influence of inflow water prevails in both localities, since excess water is enabled to run off. The greatest differences in yield compared to smooth surfaces occur for foothill, those are invariably positive in Kuressaare and mostly negative in Tallinn (Fig. 5.11).

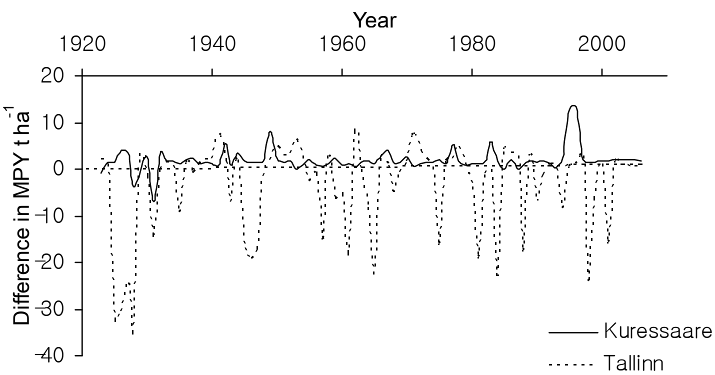

Figure 5.11. Differences in MPY at the foothill compared to plain area.

6. MPY OF THE FUTURE CLIMATE

Assessment of the present-day and expected climate change effects on global agriculture is considered as an important scientific and applied problem of agrometeorology. Most climate change scenarios project that greenhouse gas concentrations will increase through 2100 with a continued increase in average global temperatures (IPCC 2007a). In PAPER III, the results of the four illustrative emission scenarios, each containing 18 General Circulation Models (GCM) experiments were applied for three 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. 6.1a). During the plant-growth period (April to September), the increase of air temperature is predicted to be lower.

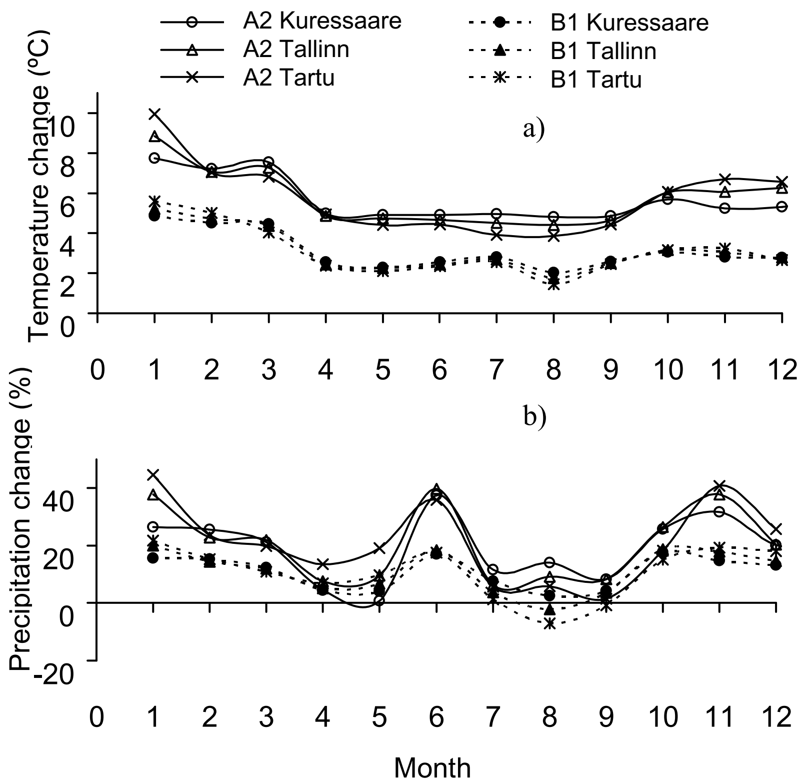

Figure 6.1. Changes in monthly mean temperature (º C) (a) and sum of precipitation (%) (b), as an average of 18 global climate models for the severe A2 and the modest B1 emission scenarios for year 2100 compared to the baseline period (1961–1990) at three Estonian sites.

The average annual precipitation is also predicted to increase (Fig. 6.1b); however, the changes in the annual range of monthly precipitation vary highly between models and scenarios and are less certain than changes in temperature (see Table 2 in PAPER IV). 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.

For the early variety, yield losses are predicted for both target years in all given localities under all climate change scenarios by almost all single GCM outputs (Table 6.1), indicating the debasement of agroclimatic conditions for early potato cultivation. The highest losses – up to 38% in Tartu and 34% in Kuressaare and Tallinn – are predicted under the scenario A2 by the year 2100. In all three stations, changes compared to current climate proved significant for all scenarios in both outcome years.

Table 6.1. Changes in the mean MPY (%) for different climate change scenarios and locations by the projections for 2050 and 2100 as compared to the baseline period 1965–2009. Bold indicates the statistical significance at $p<0.05$ of those changes by Tukey *HSD* test.

Variety	*Scenario*	*Year(s)*	*Location*		
			Kures-saare	Tallinn	Tartu
'Maret'	*Reference*	1965–2009	39,6 (t ha^{-1})	47,2 (t ha^{-1})	44,4 (t ha^{-1})
	A1B	Change by 2050	**–15,6**	**–13,0**	**–16,4**
	A2		**–16,8**	**–14,4**	**–18,1**
	B1		**–11,1**	**–8,5**	**–11,3**
	B2		**–14,0**	**–11,9**	**–15,4**
	A1B	Change by 2100	**–27,2**	**–27,7**	**–32,3**
	A2		**–33,9**	**–34,4**	**–38,8**
	B1		**–19,0**	**–17,9**	**–22,0**
	B2		**–24,9**	**–24,3**	**–28,7**
'Anti'	*Reference*	1965–2009	57,9 (t ha^{-1})	51,4 (t ha^{-1})	60,4 (t ha^{-1})
	A1B	Change by 2050	–1,3	9,1	0,1
	A2		–2,0	8,5	–0,5
	B1		1,8	**10,9**	2,5
	B2		0,6	**10,5**	1,0
	A1B	Change by 2100	–13,0	–3,3	**–13,9**
	A2		**–22,1**	**–13,0**	**–23,4**
	B1		–3,5	7,0	–3,4
	B2		–10,4	–0,2	**–10,0**

For a late variety, 9–11% rise in yields is predicted for 2050 in Tallinn by all scenarios, however the difference between present and future yields is statistically significant only for two weaker scenarios. In other stations, the change is marginal. Tallinn seems to be the most scoring location also for 2100, when the negative effect of change on yields only appears for two stronger scenarios and is significant only in case of A2, while B1 causes 7% rise in the yield (however, not statistically significant). In Tartu and Kuressaare, all scenarios predict yield losses for 2100, the most radical scenario A2 over 20% as compared to present climate.

There are quite extensive differences between the contributions of the single GCMs (Fig. 6.2). The highest MPY is predicted by the calculations based on GISS-EH climate model, prognosing large increase in precipitation and low rise in temperature for the summer period. In general, high MPY values for the late variety are induced by the models with moderate increase in summer temperature and precipitation, while early variety is favoured by low temperature increase and/or significant increase of precipitation in July. From the other hand, HadCM3 mostly leads to the lowest MPY values for Tallinn and Kuressaare, due to the highest increase in temperature and considerable decrease in precipitation in July and August. For Tartu, the highest summer temperatures were predicted by CM2.0 and IPSL, bringing about the lowest MPY values. The order of mean yields on Fig. 6.2 also suggests that for 2050 differences in yields are mostly determined by location, while for 2100 the influence of the "outermost" scenarios has started to overcome the influence of location.

Predicted losses in yields are mostly attributable to high temperature, which speeds the phenological development of the crop and reduces the time for leaf area development. As a result, the future values of LAI stay smaller than those calculated for the reference period. Although a numerically smaller decrease occurs for the early variety, its originally smaller LAI value makes the impact of the decrease quite critical. Additionally, the acceleration of development reduces the growing period of the early variety, which is not limited in present conditions. On the contrary, growing season of late variety, which is today limited by the general temperature level and night frosts, will elongate in the conditions of global warming. The highest increase is expected for Tallinn.

There is a strong negative correlation between MPY and rise in summer temperatures by the set of separate GCM. The correlation is stronger for the early variety and inland locations – Tartu and Tallinn -, but there are correlation coefficients over 0.9 for all locations and scenarios for some months or month combinations. The periods with strongest correlations between mean temperature rise and MPY are June-July for 'Maret' and June-August for 'Anti'.

Positive correlation exists between MPY and rise in precipitation, the highest at Kuressaare for 'Anti' and 2050. However, the compensatory effect of precipitation among negative influence of temperature rise is quite small even at Kuressaare and even smaller in inland stations. Of course, when the results by different weather years and GCM outputs are considered, the picture becomes quite variable.

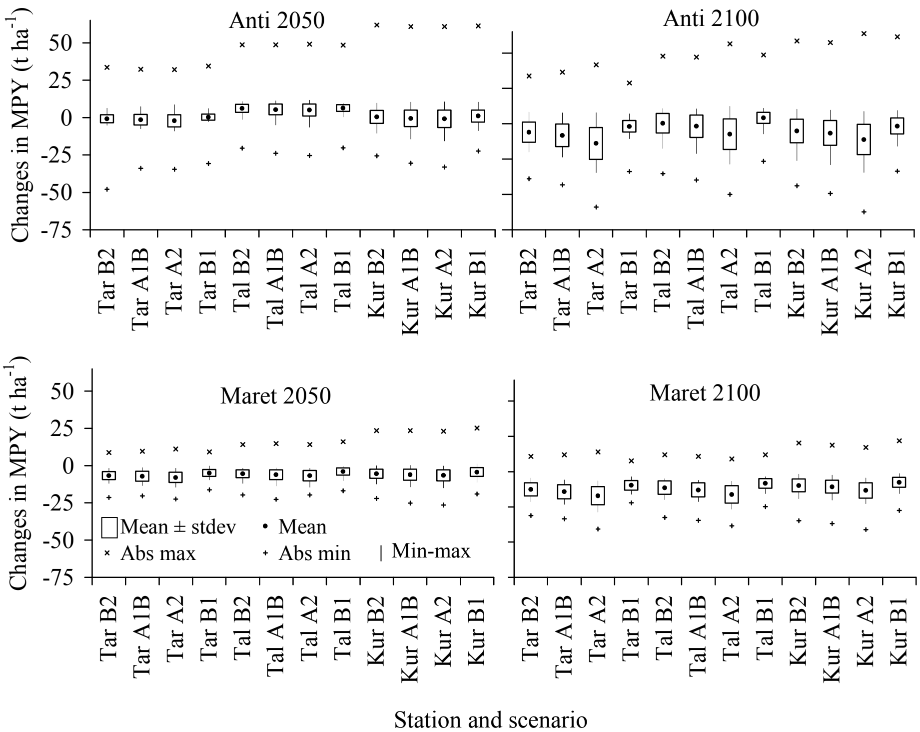

Figure 6.2. Changes in MPY, compared to the period 1965–2009, across 18 GCMs for late potato variety ‘Anti’ and early variety ‘Maret’ under four climate change scenarios for the three Estonian localities (Tal- Tallinn, Tar – Tartu, Kur – Kuressaare). Stdev and Min-max mark standard deviation and variation range over means by models; Abs max and Abs min mark the absolute range of change in all models and weather years.

7. TESTING OF SOIL MOISTURE EVALUATION TECHNIQUE

Soil moisture is an important measure in determining the crop yield potential. In the present state, POMOD uses water balance equation (2.10) to calculate soil moisture at every time-step. Measured soil moisture values are only needed to determine the initial soil moisture values at the beginning of the growing season. As the soil moisture depends greatly in relief (Romanova 1966, Vinnikov et al. 1996, PAPER V) and its values vary in time and space, the lack of site-specific soil moisture information produses inaccuracy in the calculations of meteorologically possible yield. Thus, PAPER VI was aimed to apply an indirect soil moisture measurement technique through dielectric constant, to determine soil water content for eventual use in a crop model. A commercial high-frequency FD instrument, measuring soil dielectric constant, electrical conductivity, and soil temperature, was evaluated.

For soil moisture evaluation, two different electric soil moisture devices (ThetaProbe and percometer) were tested in field experiments. Both devices performed credible soil moisture results, still percometer's construction proved to be more suitable for field work. Also both devices require a calibration curve. For percometer, a logarithmic connection was used to convert data from dielectric constant to volumetric moisture content. ThetaProbe data created an incline which should be corrected with linear relation. The best results are achieved if the calibration curve is composed individually for each observation site. It's also important to use appropriate soil layers if calibrating, especially for stony areas, where pits may influence the measurements of soil electric properties.

CONCLUSIONS

The main objective of the thesis was to inquire whether the model-computed yields can be used as an integral index providing information about climatic variability.

For background information, the variability of the observed potato yields within a long-term field trial was analysed in relation to weather variability. Variance of the potato yields under different tillage and fertilization treatments was found to be determined mainly by weather conditions; fertilization also has an effect, while observed tillage methods induce no significant yield differences. The fertilization-induced yield differences manifested most noticeably in the years with favourable growing conditions. However, in longer perspective, both fertilization and tillage affect the influence of weather on yields. Of meteorological conditions, potato proved the most susceptible to spring temperatures, yielding higher in years with a warm spring; negative relation between yields and precipitation during the same period concurred. The positive influence of precipitation was expressed after flowering. Since potatoes are not planted until May, the relationship between April-May weather and potato yields probably derives from the effect of weather on soil temperature/moisture, allowing early warm and dry springs to be more favourable for potato growth.

Further, the concept of meteorologically possible yields (MPY) was applied. Long series of model-computed yields were compiled and compared to accumulated meteorological elements and some parameters of atmospheric circulation. Overall, the MPY series through 83–106 years revealed no statistically significant trends. However, significant trends do exist in terms of shorter periods. The variability of MPY has been significantly increasing in the island regions of Estonia since the 1940s and in the continental areas since the 1980s. The changes in MPY variability were only weakly expressed in the variability of Tartu precipitation series and were absent from the temperature and radiation data.

None of the observed separate meteorological factors (temperature, precipitation, solar radiation) is sufficiently reflecting the variations in the computed MPY series. Significant linear correlations between yields and cumulated meteoelements only exist for 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 correlations of the polynomial relationships were higher, indicating a dual influence of the factors, there was still a high variance. 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 can thus be reckoned as suitable indicators of the impact of climate change on plant production.

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 is positively related to MPY, mainly in the coastal region, and high NAO values in January are correlated with higher yields in inland areas.The analyses between yields and different classifications of atmospheric circulation showed that circulation types inducing a decrease in the potato crop yield are more clearly represented. Clear differences between the observed geographical locations as well as between the seasons occurred: deriving from the number of significant circulation types, summer and Kuressaare stand out. Of potato varieties, late 'Anti' is more influenced by circulation. Analyse of MSLP maps of circulation types revealed that the seaside stations (Tallinn, Kuressaare) suffer from negative effects of anti-cyclonic conditions (drought), while Tartu suffers from the cyclonic activity (excessive water, low temperatures).

Including the redistribution of precipitation on a slope and resultant differences in soil moisture into the model scheme allowed relief-related computation of comparative long-term series of MPY in two localities, the generally moister Tallinn and the frequently dry Kuressaare regions. In both locations there was a significant influence of slope on potato yield, however the influence was unequal. In Kuressaare, yield was limited by water deficiency, as was characterized by the change in MPY through slope. However, the moister Tallinn had the worst growing conditions at the foothill due to excess water. Tallinn had the greatest topography-related differences in yield, events of extreme rainfall drive the losses.

To assess the effect of possible climate change on agrometeorological resources for potato growth, four different climate change scenarios were employed for Tartu, Tallinn and Kuressaare regions and the possible mean MPY was computed for the mid and end of the current century, marked briefly as 2050 and 2100. For early variety, all tested future climate scenarios predict yield losses in all three localities, while stronger scenarios cause higher losses. The losses are mostly due to the accelerating development, decreasing leaf area and shorter growing period. For late variety, slight rise in yields is predicted for 2050, while lower temperature rise through milder scenarios is more favourable for potatoes. The positive effect is mostly attributed to prolonging of the growing period, which is today limited by the general temperature level and night frosts. However, more radical changes lead o the decline of agroclimatic resources for potato. By the end of the century, Kuressaare and Tartu suffer losses for all scenarios; for Tallinn the situation tends to be more favourable – only the highest warming scenario causes significant yield losses compared to present climate. The yield losses are mostly related to the increase in air temperature, while increasing precipitation has a small compensatory effect.

As can be derived from previous results, soil moisture plays a crucial role in yield forming. To simplify the addition of those differences into the model in the future, an instrument for measurement of soil dielectric constant, electrical conductivity and soil temperature was tested on soils under potato crop to investigate the contents of soil volumetric water. To approximate the dependence of water content on dielectric constant, a logarithmic equation was chosen. Satisfactory results were obtained on stone-free areas, with the mean relative variance between soil moisture determined by dielectric constant and converted from a gravimetric method remaining within the limits of measuring error. Since variances were higher for stony soils, an additional formula was composed to reconcile data from stony and stone-free soils.

REFERENCES

Aasa A., Jaagus J., Ahas R. and Sepp M. (2004). The influence of atmospheric circulation on plant phenological phases in central and eastern Europe. *Int. J. Clim.,* 24, 1551–1564.

Abawi G.Y., Smith R.J. and Brady D.K. (1995). Assessment of the value of long range weather forecasts in wheat harvest management. *J. Agric. Eng. Res.* 62, 39–48.

Abrahamsen P. and Hansen S. (2000). Daisy: an open soil-crop-atmosphere system model. *Environmental modelling & software*, 15, 313–330.

Adam M., Van Bussel L. G. J.), Leffelaar P. A., Van Keulen H. and Ewert F. (2011). Effects of modelling detail on simulated potential crop yields under a wide range of climatic conditions. *Ecological modelling*, 222, 131–143.

Adams R. M., Rosenzweig C., Peart R.M., Ritchie J.T., McCarl B.A., Glyer J.D., Curry R.B., Jones J.W., Boote K.J. and Allen L.H. (1990). Global climate change and US agriculture. *Nature*, 345, 219–223.

Ahas R., Jaagus J. and Aasa A. (2000). The phenological calendar of Estonia and its correlation with mean air temperature. *Int. J. Biometeorol.*, 44, 159–166.

Ahas R. and Aasa A. (2006). The effects of climate change on the phenology of selected Estonian plant, bird and fish populations. *Int. J. Biometeorol.*, 51, 17–26.

Ainsworth E.A., Leakey A.D.B., Ort D.R. and Long S.P. (2008). FACE-ing the facts: inconsistencies and interdependence among field, chamber and modeling studies of elevated CO_2 impacts on crop yield and food supply. *New Phytologist,* 179, 5–9.

Alexandrov V., Eitzinger J., Cajic V. and Oberforster M. (2002). Potential impact of climate change on selected agricultural crops in north-eastern Austria. *Global Change Biol.,* 8, 372–389.

Amthor J.S. (2001). Effects of atmospheric CO_2 concentration on wheat yield: review of results from experiments using various approaches to control CO_2 concentration. *Field Crops Res.,* 73**,** 1–34.

Anbumozhi V., Reddy V.R., Lu Y.C.and Yamaji E. (2003). The role of crop simulation models in agricultural research and development: a review. *Agric. Eng. J.*, 12, 1–18.

Asseng, S., van Keulen H. and Stol. W. (2000). Performance and application of the APSIM Nwheat model in the Netherlands. *Eur. J. Agronomy,* 12**,** 37–54.

Bachinger J. and Zander P. (2007). ROTOR, a tool for generating and evaluating crop rotations for organic farming systems. *Eur. J. Agronomy,* 26, 130–143.

Badeck F.-W., Bondeau A., Böttcher K., Doktor D., Lucht W., Schaber J. and Sitch, S. (2004). Responses of spring phenology to climate change. *New Phytologist*, 162, 295–309.

Baier W. (1979). Note on the terminology of crop–weather models. *Agric. Meteorol.,* 20, 137–145.

Baigorria G.A., Jones J.W., Shin D.-W., Mishra A. and O'Brien J.J. (2007). Assessing uncertainties in crop model simulations using daily bias-correlated Regional Circulation Model outputs. *Clim. Res*., 34, 211–222.

Baker D.N. and Meyer R.E. (1966). Influence of stand geometry on light interception and net photosynthesis in cotton. *Crop Sci*., 6, 15–19.

Baker D.N., Lambert J. R. and McKinion J.M. (1983). GOSSYM: A simulator of cotton crop growth and yield. *South Carolina Agr. Expt. Sta. Tech. Bull*., 1089.

Barrow E. M., Hulme M., Semenov M. A. and Brooks R. J. (2000). Climate change scenarios. In: Downing T. E., Harrison P. A., Butterfield R. E. and Londsdale K. G.(Eds.). *Climate Change, Climatic Variability and Agriculture in Europe: an* *integrated assessment*. Environmental Change Institute, University of Oxford, UK, 11–27.

Baur F., Hess P. and Nagel H. (1944). *Kalender der Grosswetterlagen Europas 1881–1939.* DWD, Bad Homburg.

Belmans C., Dekker L.W. and Bouma J. (1982). Obtaining soil physical field data for simulating soil moisture regimes and associated potato growth. *Agric. Water Manag*., 5, 319–333.

Belmans C., Wesseling G.J. and Feddes R.A. (1983). Simulation model of the water balance of a cropped soil: SWATRE. *J. Hydrol*., 63, 271–286.

Bikhele Z.N., Moldau H. and Ross J. (1980). *About the mathematical modelling of plant transpiration and photosynthesis under unsufficient soil moisture conditions.* Gidrometeoizdat, Leningrad (in Russian, with English summary).

Bogena H.R., Huisman J.A., Oberdörster C. and Vereecken H. (2007). Evaluation of a low-cost soil water content sensor for wireless network applications. *J. Hydrol.*, 344**,** 32–42.

Boggess W.G. and Ritchie J.T. (1988). Economic and risk analysis of irrigation decisions in humid regions. *J. Prod. Agric.,* 1, 116–122.

Bolin B. (1977). Changes of Land Biota and Their Importance for the Carbon Cycle. *Science,* 196, 613–615.

Bondarenko N.F., Zhukovskij E.E., Mushkin I.G. and Nerpin S.V. (1982). *Modeling productivity of agroecosystem.* Gidrometeoizdat, Leningrad (in Russian, with English abstract).

Bondeau A., Smith P.C., Zaehle S., Schaphoff S., Lucht W., Cramer W., Gerten D., Lotze-Campen H., Müller C., Reichstein M. and Smith B. (2007). Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Glob. Change Biol*., 13, 679–706.

Boote K.J., Jones J.W. and Pickering N.B. (1996). Potential uses and limitations of crops models. *Agron. J.,* 88, 704–716.

Bouman B.A.M., Van Keulen H., Van Laar H.H. and Rabbinge R. (1996). The 'School of de Wit' crop growth simulation models: a pedigree and historical overview. *Agric. Systems*, 56, 171–198.

Bouman B.A.M., Van Diepen C,A., Vossen P. and Van Der Wal T. (1997). Simulation and systems analysis tools for crop yield forecasting. In: Teng P.S., Kropff M.J., ten Berge H.F.M., Dent J.B., Lansigan F.P. and van Laar H.H. (Eds.), *Applications of systems approaches at the farm and regional levels – proceedings of the second international symposium on systems approaches for agricultural development*, 1. Book series: Systems approaches for sustainable agricultural, 5, 325–340.

Box G. E. P. (1979). Robustness in the strategy of scientific model building. In: Launer R. L. And Wilkindon G. N. (Eds). *Robustness in statistics.* Academic, New York.

Brisson N., Gary C., Justes E., Roche D., Zimmer D., Sierra J., Bertuzzi P., Burger P., Bussière F., Cabidoche Y.M., Cellier P., Debaeke P., Gaudillère J.P., Hénault C., Maraux F., Seguin B. and Sinoquet H. (2003). An overview of the crop model STICS. *Eur. J. Agron*., 18, 309–332.

Budagovskij A.I., Nichiporovich A.A. and Ross J.K. (1964). About the quantitative theory of photosynthesis and using it for research and applied tasks in geography. *Izvestiya AN SSSR, Serija Geograficheskaja,* 6, 13–27 (in Russian).

Budyko M.I. (1971). *Climate and life*. Gidrometeoizdat, Leningrad (in Russian, with English abstract).

Budyko M.I. (1974). *Evolution of biosphere.* Gidrometeoizdat, Leningrad (in Russian, with English abstract).

Budyko M.I and Gandin L.S. (1964). Accounting the patterns of atmospheric physics in agronomic studies. *Meteorology and Hydrology,* 11, 3–11 (in Russian).

Burroughs W.J. (2001). *Climate Change. A Multidisciplinary Aproach*. Cambridge University Press.

Butterworth M.H, Semenov M.A., Barnes A., Moran D., West J.S. and Fitt B.D.L. (2010). North–South divide: contrasting impacts of climate change on crop yields in Scotland and England. *J. R. Soc. Interface,* 7, 123–130.

Calanca P., Bolius D., Weigel A.P., Liniger M.A. (2011). Application of long-range weather forecasts to agricultural decision problems in Europe. *J. Agric. Sci.,* 149, 15–22.

Carter T. R. (1996). Global climate change and agriculture in the North. *Agric. Food Sci. Finland*, 5, 222–385.

Carter T.R., Saarikko R.A. and Niemi K.J. (1996). Assessing the risks and uncertainties of regional crop potential under a changing climate in Finland. *Agric. Food Sci. Finland,* 5, 329–350.

Castellazzi M. S., Matthews J., Angevin F., Sausse C., Wood G. A., Burgess P. J., Brown I., Conrad K. F. and Perry J. N. (2010). Simulation scenarios of spatio-temporal arrangement of crops at the landscape scale. *Environmental modelling & software,* 25, 1881–1889.

Challinor A.J., Slingo J.M., Wheeler T.R., Craufurd P.Q. and Grimes D.I.F. (2003). Towards a combined seasonal weather and crop productivity forecasting system: determination of the working spatial scale. *Journal of Applied Meteorology*, 42, 175–192.

Chander S., Kalra N. and Aggarwal P.K. (2007). Development and application of crop growth simulation modelling in pest management. *Outlook on agriculture,* 36, 63–70.

Chmielewski F.-M. and Köhn W. (2000). Impact of weather on yield and yield components of winter rye. *Agric. Forest Meteorol.*, 102, 253–261.

Chmielewski F.-M. and Rötzer T. (2002). Annual and spatial variability of the beginning of growing season in Europe in relation to air temperature changes. *Clim. Res.,* 19, 257–264.

Chmielewski F.-M., Müller A. and Bruns E. (2004). Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961–2000. *Agric. Forest Meteorol.,* 121, 69–78.

Chuine I., Yiou P., Viovy N, Seguin B., Daux V. and Ladurie E.L.R. (2004). Historical phenology: Grape ripening as a past climate indicator. *Nature*, 432, 289–290.

Cline W.R. (2007). *Global Warming and Agriculture: Impact estimates by country.* Washington DC: Center for Global Development.

Confalonieri R., Rosenmund A.S. and Baruth B. (2009). An improved model to simulate rice yield. *Agron. Sustain. Dev.*, 29, 463–474.

Craufurd P.Q. and Wheeler T.R. (2009). Climate change and the flowering time of annual crops**.** *J. Exp. Bot.,* 60, 2529–2539.

Curry R.B. (1971). Dynamic simulation of plant growth. I. Development of model, *Trans. ASAE,* 14, 946–949.

DaMatta F.M., Grandis A., Arenque B.C. and Buckeridge M.S. (2010). Impacts of climate changes on crop physiology and food quality. *Food Res. Int.,* 43, 1814–1823.

Davidson J. L. and Philip J. R. (1958). Light and pasture growth. In: *Climatology and microclimatology*, *Proc. Canberra Symp*. 1956, Unesco, Paris. pp. 181–187.

Davies A, Jenkins T, Pike A, Shaq J, Carson I, Pollock CJ, and Parry MI. (1996). Modelling the predicted geographic and economic response of UK cropping systems to climate change scenarios: the case of potatoes. *Aspects Appl. Biol.,* 45, 63–69.

Decker W. L. (1994). Developments in agricultural meteorology as a guide to its potential for the twenty-first century. *Agric. Forest Meteorol.,* 69, 9–25.

De Noblet-Ducoudre N., Gervois S., Ciais P., Biovy N., Brissson N., Seguin B. and Perrier A. (2004). Coupling the Soil-Vegetation Atmosphere Transfer Scheme ORCHIDEE to the agronomy model STICS to study the influence of croplands on the European carbon and water budgets. *Agronomie*, 24, 397–407.

De Temmerman L., Hacour A. And Guns M. (2002). Changing climate and potential impacts on potato yield and quality 'CHIP': introduction, aims and methodology. *Eur. J. Agron*., 17, 233–242.

De Wit C.T. (1959). Potential photosynthesis of crop surfaces. *Neth. J. Agric. Sci.,* 7, 141–149.

De Wit C.T. (1965). Photosynthesis of leaf canopies. *Agricultural Research Report*, 663, Pudoc, Wageningen.

De Wit C.T., Brouwer R. and Penning de Vries F.W.T. (1970). The simulation of photosynthetic systems. In: Setlik I. (Ed). *Prediction and measurement of photosynthetic productivity*. Wageningen, The Netherlands: Centre for Agricultural Publishing and Documentation, 47–70.

De Wit C.T. and Goudriaan J. (1974). *Simulation of Ecological Processes*. Wageningen, Pudoc.

De Wit C.T. and van Keulen H. (1987). Modelling production of field crops and its requirements. *Geoderma*, 40, 253–265.

Dickson R.R., Osborn T.J., Hurrell J.W., Meincke J., Blindheim J., Adlandsvik B., Vinje T., Alekseev G. and Maslowski W. (2000). The Arctic Ocean Response to the North Atlantic Oscillation. *J. Clim.,* 15, 2671–2696.

Dmitrenko V. P (1976). *An assessment of the dependence of main cereals yield formation on air temperature and precipitation*. Leningrad, Gidrometeoizdat (in Russian).

Donnelly A., Jones M.B., Sweeney J. (2004). A review of indicators of climate change for use in Ireland. *Int. J. Biometeorol.*, 49, 1–12.

Duncan W.G., Loomis R.S., Williams W.A. and Hanau R. (1967). A model for simulating photosynthesis in plant communities. *Hilgardia,* 38, 181–205.

Easterling W.E., McKenney M.S., Rosenberg N.J. and Lemon K.M. (1992a). Simulations of crop response to climate change: effects with present technology and no adjustments (the 'dumb farmer' scenario). *Agric. Forest Meteorol.*, 59, 53–73.

Easterling W.E., Rosenberg N.J., Lemon K.M. and McKenney M.S. (1992b). Simulations of crop responses to climate change: effects with present technology and currently available adjustment (the 'smart farmer' scenario). *Agric. Forest Meteorol.*, 59, 75–102.

Easterling W. and Apps M. (2005). Assessing the consequences of climate change for food and forest resources: A view from the IPCC. *Clim. Change,* 70, 165–189.

Estrella N., Sparks T.H. and Menzel A. (2007). Trends and temperature response in the phenology of crops in Germany. *Global Change Biology,* 13, 1737–1747.

Evans L. T., Wardlaw I. F. and Williams C. N. (1964). Environmental control of growth,. In: Barnard C. (Ed.). *Grasses and grasslands*. Macmillan, London, 102–125.

Fageria N.K. (1992). *Maximizing Crop Yields*. Marcel Dekker, New York, USA.

Ferris R., Ellis R.H., Wheeler T.R. and Hadley P. (1998). Effect of high temperature stress at anthesis on grain yield and biomass of field-grown crops of wheat. *Ann. Bot.,* 82, 631–639.

Finnan J.M., Burke J.I. and Jones M.B. (2002). The effect of elevated concentrations of carbon dioxide and ozone on potato (*Solanum tuberosum* L.) yield. *Agric. Ecosys. Environ.,* 88, 11–22.

Fischer G., Shah M. and Velthuizen H. (2002). *Climate Change and Agricultural Vulnerability.* International Institute for Applied Systems Analysis, Vienna.

Fischer G., Shah M., Tubiello F.N. and van Velhuizen H. (2005). Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990–2080. *Phil. Trans. R. Soc. B*., 360, 2067–2083.

Fisher R.A. (1925). The influence of rainfall on the yield of wheat at Rothamsted. *Phil. Trans. R. Soc. B.*, 213, 89–142.

Fishman S., Talpaz H., Winograd R., Dinar M., Arazi Y., Roseman Y. and Varshavski S. (1985). A model for simulation of potato growth on the plant community level. *Agric. Syst.,* 18, 115–128.

Fitter A.H. and Fitter R.S.R. (2002). Rapid changes in flowering time in British plants. *Science,* 296, 1689–1691.

Fritts H.C. (1976). *Tree Rings and Climate*. Academic Press, London.

Garbrecht J. D., Zhang X.C., Schneider J.M. and Steiner J.L. (2010). Utility of seasonal climate forecasts in management of winter-wheat grazing. *Applied engineering in agriculture*, 26, 855–866.

Gardner W.R. (1960). Dynamic aspect of water availability to plants. *Soil Sci.*, 89, 63–73.

Gassman P.W., Williams J.R., Wang X., Saleh A, Osei E., Hauck L. M., Izaurralde R.C. and Flowers J. D. (2010). The agricultural policy/environmental extender (APEX) model: an emerging tool for landscape and watershed environmental analyses. *Trans. ASABE,* 53, 711–740.

Gervois S., de Noblet-Ducoudr´e N., Viovy N. and Ciais P. (2004). Including croplands in a global biosphere model: methodology and evaluation of specific sites. *Earth Interact*., 8, 1–25.

Gibbons, J. M., Sparkes D. L., Wilson P. and Ramsden S. J. (2005). Modelling optimal strategies for decreasing nitrate loss with variation in weather – a farm-level approach. *Agric. Syst.*, 83, 113–134.

Gobin A. (2010). Modelling climate impacts on crop yields in Belgium. *Clim. Res.,* 44, 55–68.

Gourdrain J. and de Ruiter H.E. (1983). Plant growth in response to CO_2 enrichment at two levels of nitrogen and phosphorus supply. 1. Dry matter, leaf area and development. *Neth. J. Agric. Sci.,* 31, 157–169.

Hafner S. (2003). Trends in maize, rice, and wheat yields for 188 nations over the past 40 years: a prevalence of linear growth. *Agriculture, Ecosystems & Environment,* 97,

Hansen J.W., Challinor A., Ines A.V.M., Wheeler T. and Moron V. (2006). Translating climate forecasts into agricultural terms: advances and challenges. *Clim. Res*., 33, 27–41.

Hansen S., Jensen H.E., Nielsen N.E. and Svendsen H. (1990). *Daisy – Soil Plant Atmosphere System Model*. Npo Forskning fra Miljostyrelsen, Vol A10. Miljostyrelsen, Copenhagen.

Hansen S., Jensen H.E., Nielsen N.E. and Svendsen H. (1991). Simulation of nitrogen dynamics and biomass production in winter wheat using the Danish simulation model DAISY. *Fert. Res*., 27, 245–259.

Haverkort A.J. (1989). Ecology of potato cropping systems in relation to latitude and altitude. *Agric. Syst.,* 32, 251–272.

Haverkort A.J., Verhagen A., Grasshoff A.C. and Uithol P. W. J. (2004). Potato-zoning: a decision support system on expanding the potato industry through agro-ecological zoning using the LINTUL simulation approach. In: MacKerron D.K.L. and Haverkort A.J. (Eds). *Decision support systems in potato production: bringing models to practice*. Wageningen Academic, Wageningen, 29–44.

Haverkort A.J. and Verhagen A. (2008). Climate change and its repercussions for the potato supply chain. *Potato Res.*, 51, 233–237.

Hay R.K.M. and Porter J.R. (2006). *The physiology of crop yield. 2nd ed.,* Blackwell Publishing, UK

Hijmans R.J., Condori B. and Carrillo R. (2003). The Effect of Climate Change on Global Potato Production. *American J. Potato Res.,* 80, 271–279.

Hodges T. (Ed.) (1991). *Predicting Crop Phenology*. CRC Press, Boca Raton, USA.

Hodges T., Johnson S.L. and Johnson B.S. (1992). A modular structure for crop simulation models: implemented in the SIMPOTATO model. *Agron. J.,* 84, 911–915.

Holden N. M., Brereton A. J., Fealy R. and Sweeney J. (2003). Possible change in Irish climate and its impact on barley and potato yields. *Agric. Forest Meteorol.,* 116, 181–196.

Hoogenboon G. (2000). Contribution of agrometeorology to the simulation of crop production and its applications. *Agric. Forest Meteorol*., 103, 137–157.

Hooker R.H. (1921). Forecasting the crops from the weather. *Quarterly Journal of the Royal Meteorological Society*, 47, 75–99.

Hu Q., Weiss A., Feng S. and Baenziger P.S. (2005). Earlier winter wheat heading dates and warmer spring in the US Great Plains. *Agric.Forest Meteorol.,* 135, 284–290.

Hulme M., Wigley T.M.L., Barrow E.M., Raper S.C.B., Centella A., Smith S.J. and Chipanshi A.C. (2000). *Using a Climate Scenario Generator for Vulnerability and Adaptation Assessments: MAGICC and SCENGEN Version 2.4 Workbook*. Climatic Research Unit, Norwich UK.

Hurrell J.W. (1995). Decadal trends in the North Atlantic oscillation: regional temperatures and precipitation. *Science,* 269, 676–679.

Hurrell J.W. and van Loon H. (1997). Decadal variations in climate associated with the North Atlantic Oscillation. *Clim. Change,* 36, 301–326.

Hurrell J.W., Kushnir Y., Visbeck M. and Ottersen G. (2003). An overview of the North Atlantic Oscillation. In: J.W. Hurrell, Y. Kushnir, G. Ottersen and M. Visbeck, Editors, *The North Atlantic Oscillation, Climatic Significance and Environmental Impact*, *AGU Geophysical Monograph* 134**,** 1–35.

Huth R. (2010). Synoptic-climatological applicability of circulation classifications from the COST733 collection: First results. *Phys. Chem. Earth*, 35, 388–394.

Huth R., Beck C., Philipp A., Demuzere M., Ustrnul Z., Cahynová M., Kyselý J. and Tveito O.E. (2008). Classifications of Atmospheric Circulation Patterns. Recent Advances and Applications. *Annals of the New York Academy of Sciences*, 1146, 105–152.

Ingram K.T. and McCloud D.E. (1984). Simulation of potato crop growth and development. *Crop Sci.,* 24, 21–27

IPCC (2007a). Climate Change 2007: The Physical Science Basis. In: Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor & H.L. Miller (Eds.). *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York.

IPCC (2007b). Climate Change 2007: Impacts, Adaptation and Vulnerability. In: Parry M.L., Canziani O.F., Palutikof J.P., van der Linden P.J. & Hanson C.E. (Eds.), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York.

Jaagus J. (2006). Climatic changes in Estonia during the second half of the 20th century in relationship with changes in large-scale atmospheric circulation. *Theor. Appl. Climatol.*, 83, 77–88.

Jaagus J. and Truu J. (2004). Climatic regionalisation of Estonia based on multivariate exploratory techniques. *Estonia. Geographical studies,* 9, 41–55.

Jacob D., Barring L., Christensen O.B., Christensen J.H, de Castro M., Deque M., Giorgi F., Hagemann S., Lenderink G., Rockel B., Sanchez E., Schar C., Seneviratne S.I., Somot S., van Ulden A. and van den Hurk B. (2007). An inter-comparison of regional climate models for Europe: model performance in present-day climate. *Clim. Change,* 81, 31–52.

Jackson L.E., Kurtz J.C. and Fisher W.S. (2000). *Evaluation Guidelines for Ecological Indicators*. Environmental Protection Agency, Washington, DC. Report No. EPA/620/R-99/005.

Jame Y.W. and Cutforth H.W. (1996). Crop growth models for decision support systems. *Canadian J. Plant Sci.***,** 76, 9–19.

Jones C.A. and Kiniry J. R. (1986). *CERES-maize: A simulation model of maize growth and development.* Texas A&M Univ. Press, College Station, USA.

Jones J.W., Keating B.A. and Porter C.H. (2001). Approaches to modular model development. *Agric. Syst.,* 70**,** 421–443.

Jones J.W., Hoogenboom G., Porter C.H., Boote K.J, Batchelor W.D., Hunt L.A., Wilkens P.W., Singh U., Gijsman A.J. and Ritchie J.T. (2003). The DSSAT cropping system model. *Europ. J. Agronomy,* 18, 235–265.

Jylha K., Fronzek S., Tuomenvirta H., Carter T. R., and Ruosteenoja K. (2008). Changes in frost, snow and Baltic sea ice by the end of the twenty-first century based on climate model projections for Europe. *Clim. Change,* 86, 441–462.

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, 139–149.

Kadaja J. (2004). Influence of fertilisation on potato growth functions. *Agronomy Res.*, 2, 49–55.

Kadaja J. (2006). Reaction of potato yield to possible climate change in Estonia. In: Fotyma M. and Kaminska B. (Eds.). *Book of proceedings. IX ESA Congress. Part I. Bibliotheca Fragmenta Agronomica, 11,* Pulawy–Warszawa, 297–298.

Kadaja J. and Tooming H. (1998). Climate change scenarios and agricultural crop yields. In: Tarand A. and Kallaste T. (Eds.). *Country case study on climate change impacts and adaptation assessments in the Republic of Estonia,* Ministry of the Environment Republic of Estonia, SEI, CEF, UNEP, Tallinn, 39–41.

Kadaja J. and Tooming H. (2004). Potato production model based on principle of maximum plant productivity. *Agric. Forest Meteorol.*, 127, 17–33.

Kadaja J., Saue T. and Viil P. (2009a). Crop modelling based on the principle of maximum plant productivity. E.J. van Henten, D. Goense, C. Lokhorst (Eds.). Precision Agriculture '09 (675–681). Wageningen: Wageningen Academic Publishers.

Kadaja J., Saue T. and Viil P. (2009b). Probabilistic yield forecast based on a production process model. Li D. and Zhao C. (Eds.). *Computer and Computing Technologies in Agriculture* II. Springer, 487–494.
Kallis A. and Tooming H. (1974). Estimation of the influence of leaf photosynthetic parameters, specific leaf weight and growth functions on yield. *Photosynthetica,* 8 (2), 91–103.
Karing P., Kallis A. and Tooming H. (1999). Adaptation principles of agriculture to climate change. *Clim. Res.*, 12, 175–183.
Kaukoranta T. (1996). Impact of global warming on potato late blight: Risk, yield loss and control. *Agr. Food Sci. Finland,* 5, 311–327.
Kaukoranta T. and Hakala K. (2008). Impact of spring warming on sowing times of cereal, potato and sugar beet in Finland. *Agr. Food Sci.* 17, 165–176.
Kitse E. (1978). *Soil water.* Tallinn, Valgus (in Estonian).
Kooman P.L. (1995). *Yielding ability of potato crops as influenced by temperature and daylength*. PhD thesis, Wageningen Agricultural University, Wageningen, The Netherlands.
Kooman P.L. and Haverkort A.J. (1995). Modelling development and growth of the potato crop influenced by temperature and daylength: LINTUL-POTATO. In: Haverkort A.J and MacKerron D.K.L. (Eds). *Potato ecology and modeling of crops under growth limiting conditions*. Boston: Kluwer Academic Publ., 41–60.
Kotkas K. (2006). Potato in Estonia: Production and research. In: Haase N.U. & Haverkort A.J. (Eds.). Potato developments in a changing Europe. Wageningen Academic Publishers, 250–258.
Kravchenko A.N., Thelen K.D. and Harwood R.R. (2005). Management, Topographical, and Weather Effects on Spatial Variability of Crop Grain Yields. *Agron. J.*, 97, 514–523.
Kreyling J. (2010). Winter climate change: a critical factor for temperate vegetation performance. *Ecolog.,* 91 (7), 1939–1948.
Kumar R. and Chaturevdi S. (2005) Crop modeling: A tool for agricultural research. *Phil. Trans. R. Soc. B,* 360 (1463), 2037–2047.
Laisk A. (1970). A model of leaf photosynthesis and photorespiration. In: Shetlik I. (Ed.) *Prediction and Measurement of Photosynthetic Productivity*, 295–306, PUDOC, Wageningen.
Laisk A. (1977). *Kinetics of Photosynthesis and Photorespiration in C_3 Plants*. Nauka, Moscow (in Russian).
Laisk A. (1982). Correspondence of photosynthetic system to environmental conditions. In: Nichiporovitch A.A. (Ed.), *Physiology of Photosynthesis*, Nauka, Moscow (in Russian).
Lamb J.A., Dowby R.H., Anderson J.L. and Rehm G.W. (1997). Spatial and temporal stability of corn grain yields. *J. Prod. Agric*., 10, 410–414.
Lehenbauer, P.A. (1914). Growth of maize seedlings in relation to temperature. *Physiol. Res*., 1, 247–288.
Lemon E.R. (1963). Energy and water balance of plant communities. In: L.T. Evans L.T. (Ed)., *Enviromental Control of Plant Growth*. Academic Press, New York, 55–78.
Lin E.D., Xiong W., Ju H., Xu Y.L., Li Y., Bai L.P. and Xie L.Y. (2005). Climate change impacts on crop yield and quality with CO2 fertilization in China. *Phil. Trans. R. Soc. B.*, 360, 2149–2154.
Linderholm H.W. (2006). Growing season changes in the last century. *Agric. Forest Meteorol.,* 137 (1–2), 1–14.

Lobell D.B. and Field C. B. (2007). Global scale climate–crop yield relationships and the impacts of recent warming. *Environ. Res. Lett.,* 2, 1–7.

Lobell D. B. and Burke M. (2008). Why are agricultural impacts of climate change so uncertain? The importance of temperature relative to precipitation. *Environ. Res. Lett*., 3, 1–8.

Lobell D.B. and Burke M.B. (2010). On the use of statistical models to predict crop yield responses to climate change. *Agric. Forest Meteorol.*, 150, 1443–1452.

Loomis R.S., Rabbinge R. and Ng E. (1979). Explanatory models in crop physiology. *Ann. Rev. Plant Physiol*., 30, 339–367.

Machado S., Bynum E.D. Jr., Archer T.L., Lascano R.J., Wilson L.T., Bordovsky J., Segarra E., Bronson K., Nesmith D.M. and Xu W. (2002). Spatial and temporal variability of corn growth and grain yield implications for site-specific farming. *Crop Sci.*, 42, 1564–1576.

MacKerron D.K.L. (2008). Advances in modelling the potato crop: sufficiency and accuracy considering users, data and errors. *Potato Res.*, 51, 411–427.

MacKerron D.K.L. and Waister P.D.A. (1985a). A simple model of potato growth and yield. Part I. Model development and sensitivity analysis. *Agric. Forest Meteorol.*, 34, 241–252.

MacKerron D.K.L. and Waister P.D.A. (1985b). A simple model of potato growth and yield. Part II. Validation and external sensitivity. *Agric. Forest Meteorol*., 34, 285–300.

Makra L., Horvath S., Pongracz R. and Mika J. (2002). Long term climate deviations: an alternative approach and application on the Palmer drought severity index in Hungary. *Phys. Chem. Earth*, 27, 1063–1071

McCree K.J. (1974). Equations for the rate of dark respiration of white clover and grain sorghum, as functions of dry weight, photosynthetic rate, and temperature. *Crop Sci.,* 14, 509–514.

McPherson R. (2007). A review of vegetation—atmosphere interactions and their influences on mesoscale phenomena. *Progress in Physical Geography*, 31, 261–285.

Mearns L.O. (2000). Climate change and variability. In: Reddy K.R. and Hodges H.F. (Eds.). *Climate Change and Global Crop Productivity.* CAB International Publishing, 7–35.

Meehl G. A., Karl T., Easterling D.R.Changnon S., Pielke R. Jr.,Changnon D., Evans J., Groisman, P.Ya., Knutson T.R., Kunkel K.E., Mearns L.O., Parmesan C., Pulwarty R., Root T., Sylves R.T., Whetton P. and Zwiers F. (2000). An introduction to trends in extreme weather and climate events: observations, socioeconomic impacts, terrestrial ecological impacts, and model projections. *B. Am.Meteorol. Soc.,* 81, 413–416.

Mela T. (1996). Northern agriculture: constraints and responses to global climate change. *Agric. Food Sci. Finland,* 5, 229–234.

Menzel A. (2003). Plant Phenological Anomalies in Germany and their Relation to Air Temperature and NAO. *Clim.Change*, 57, 243–263.

Menzel A. and Fabian P. (1999). Growing season extended in Europe. *Nature,* 397, 659.

Menzel A., Sparks T.H.,Estrella N., Koch E., Aasa A., Ahas R., Alm-Kübler K., Bissolli P., Braslavska O., Briede A., Chmielewski F.M., Crepinsek Z., Curnel Y., Dahl A., Defila C., Donnelly A., Filella Y., Jatczak K., Mage F., Mestre A., Nordli Ø., Penuelas J., Pirinen P.,Remišova V., Scheifinger H., Striz M., Susnik A., Van Vliet A.J.H., Wiegolaskii F-E., Zach S. and Zust A. (2006). European phenological response to climate change matches the warming pattern. *Global Change Biol.*, 12, 1969–1976.

Meyer-Aurich A. , Weersink A., Gandorfer M. and Wagner P. (2010). Optimal site-specific fertilization and harvesting strategies with respect to crop yield and quality response to nitrogen. *Agricult. Syst.,* 103, 478–485.

Miglietta F., Magliulo V., Bindi M., Cerio L., Vaccari F.P., Loduca V. and Peressotti A. (1998). Free air CO_2 enrichment of potato (*Solanum tuberosum* L.): development, growth and yield. *Global Change Biol.,* 4, 163–172.

Miglietta F., Bindi M., Vaccari F.P., Schapendonk A.H.C.M., Wolf J. and Butterfield R.E. (2000). Crop Ecosystem Responses to Climatic Change: Root and Tuberous Crops. In: Reddy K.R. and Hodges H.F. (Eds.), *Climate Change and Global Crop productivity*. CAB International Publishing.

Miraglia M., Marvin H.J.P., Kleter G.A., Battilani P., Brera C., Coni E., Cubadda F., Croci L., De Santis B., Dekkers S., Filippi L., Hutjes R.W.A., Noordam M.Y., Pisante M., Piva G., Prandini A., Toti L., van den Born G.J. and Vespermann A. (2009). Climate change and food safety: An emerging issue with special focus on Europe. *Food and Chemical Toxicology*, 47, 1009–1021.

Mize J.H. and Cox G.J. (1968). *Essentials of Simulation.* Prentice Hall, New York, USA.

Mkhabela M.S., Bullock P., Raj S., Wang S. and Yang Y. (2011). Crop yield forecasting on the Canadian Prairies using MODIS NDVI data. *Agric. Forest Meteorol.*, 151 (3), 385–393.

Monsi M. and Saeki T. (1953). Uber den Lichtfaktor in den Pflanzengesellschaften. *Jpn. J. Botany,* 14, 22–52 (In German).

Monteith J.L. (2000). Agricultural meteorology: Evolution and application. *Agric. Forest Meteorol.,* 103, 5–9.

Moriondo M. Bindi M., Kundzewicz Z.W., Szwed M., Chorynski A., Matczak P., Radziejewski M., McEvoy D. and Wreford A. (2010). Impact and adaptation opportunities for European agriculture in response to climatic change and variability. *Mitigation and adaptation strategies for global change*, 15 (7), 657–679.

Moss D. N., Musgrave R. B. and Lemon E. R. (1961). Photosynthesis under field conditions: II. Some effects of light, carbon dioxide, temperature, and soil moisture on photosynthesis, respiration, and transpiration of corn. *Crop Sci*., 1, 83–87.

Mpelasoka F., Hennessy K., Jones R. and Bates B. (2007). Comparison of suitable drought indices for climate change impacts assessment over Australia towards resource management. *Int. J. Clim.*, 28, 1283–1292.

Mueller L., Schindler U., Mirschel W., Shepherd T. G., Ball B. C., Helming K., Rogasik J., Eulenstein F. and Wiggering H. (2010). Assessing the productivity function of soils. A review. *Agron. Sustain. Dev*., 30, 601–614.

Murata Y. and Iyama J. (1963). Studies on the photosynthesis of forage crops. II. Influence of air-temperature upon the photosynthesis of some forage and grain crops. *Proc. Crop Sci. Soc. Japan*, 31, 315–322.

Nakicenovic N. and Swart R. (Eds.) (2000). *Special Report on Emissions Scenarios*. Cambridge University Press, Cambridge, UK.

Ng E. and Loomis R.S. (1984). *Simulation of Growth and Yield of the Potato Crop*, Pudoc, Wageningen.

Nichiporovich A.A. (1956). Photosynthesis and the theory of obtaining high crop yields. 15th Timiryazev lecture. USSR Acad. Sci., Moscow (in Russian).

Nichols N. (1991) Advances in long-term weather forecasting. In: Muchow R.C., Bellamy J.A. (Eds.), *Climatic Risk in Crop Production: Models and Management for the Semiarid Tropics and Subtropics*. CAB International, Wallingford, 427–444.

Nilson T. (1968). On the optimum geometrical arrangement of foliage in the plant cover. In: *Regime of photosynthetically active radiation in vegetation*. Inst. Phys. Astron., Estonian Acad. Sci., Tartu, 112–146 (in Russian).

Nilson T. (1971). A theoretical analysis of the frequency of gaps in plant stands, *Agric. Meteorol.* 7, 25–38.

Nordli Ø. (2001). Reconstruction of Nineteenth Century summer temperatures in Norway by proxy data from farmers' diaries. *Clim. Change*, 48, 201–218.

Nugis E., Kadaja J., Plakk T. and Saue T. (2008). Invention: *Method for determination of volumetric moisture content in soil layer*; Owner: Estonian Research Institute of Agriculture; Authors: Edvin Nugis, Jüri Kadaja, Tiit Plakk, Triin Saue; Priority number: P200800010; Priority date: 28.02.2008.

OECD (1993). *OECD Core Set of Indicators for Environmental Performance Reviews: A Synthesis Report by the Group on the State of the Environment*. Organisation for Economic Co-operation and Development, Paris, Report No. 83.

Oja V. and Laisk A. (1995). Gas system and method for CO_2 titration of intact leaves. *Photosynthetica*, 31, 37–50.

Olesen J.E., Jensen T. and Bøcher P.K. (2000). Modelling climate change impacts on wheat and potato in Denmark. In: T.E. Downing, P.A. Harrison, R.E. Butterfield and K.G. Lonsdale, Editors, *Climate Change, Climatic Variability and Agriculture in Europe: an Integrated Assessment. Research Report No. 21*, Environmental Change Institute, University of Oxford, 313–332.

Olesen J.E and Bindi M. (2002). Consequences of climate change for European agricultural productivity, land use and policy. *Eur. J. Agronomy*, 16, 239–262.

Olesen J.E., Carter T.R., Diaz-Ambrona C.H., Fronzek S., Heidmann T., Hickler T., Holt T., Minguez M. I., Morales P., Palutikof J. P., Quemada M., Ruiz-Ramos M., Rubæk G. H., Sau F., Smith B. and Sykes M. T. (2007). Uncertainties in projected impacts of climate change on European agriculture and ecosystems based on scenarios from regional climate models. *Clim. Change,* 81, 123–143.

Oleson K.W., Niu G.-Y., Yang Z.-L., Lawrence D.M., Thornton P.E., Lawrence P.J., Stöckli R., Dickinson R.E., Bonan G.B., Levis S., Dai A. and Qian T. (2008). Improvements to the Community Land Model and their impact on the hydrological cycle. *J. Geophys. Res*., 113, G01021.

Orlandini S., Nejedlik P., EitzingerJ., Alexandrov V., Toulios L., Calanca P., Trnka M. and Olesen J.E. (2008). Impacts of Climate Change and Variability on European Agriculture. Results of Inventory Analysis in COST 734 Countries. *Annals of the New York Academy of Sciences*, 1146, 338–353.

Osborne T.M., Lawrence D.M., Challinor A.J., Slingo J.M. and Wheeler T.R. (2007). Development and assessment of a coupled crop-climate model. *Global Change Biol.,* 13, 169–183.

Palmer W.C. (1965). *Meteorological drought*. Research Paper No. 45, U.S. Department of Commerce Weather Bureau, Washington, USA.

Parry M.L., Rosenzweig C., Iglesias A., Fischer G. and Livermore M. (1999). Climate change and world food security: a new assessment. *Global Environ. Change,* 9, 51–67.

Parry M.L., Rosenzweig C., Iglesias A., Livermore M. and Fischer, G. (2004). Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environ. Change*, 14, 53–67.

Parry M.L. (2007). The Implications of Climate Change for Crop Yields, Global Food Supply and Risk of Hunger. *SAT eJournal*, 4, 1–44.

Passioura J. B. (1973). Sense and nonsense in crop simulation. *J. Aust. Inst. Agric. Sci.*, 39, 181–183.
Peiris D.R., Crawford J.W., Grashoff C., Jefferies R.A., Porter J.R. and Marshall B. (1996). A simulation study of crop growth and development under climate change. *Agric. Forest Meteorol.*, 79, 271–287.
Peltonen-Sainio P., Jauhiainen L., Hakala K. and Ojanen H. (2009a). Climate change and prolongation of growing season: changes in regional potential for field crop production in Finland. *Agric. Food Sci.*, 18, 171–190.
Peltonen-Sainio P., Jauhiainen L. and Hakala K. (2009b). Are there indications of climate change induced increases in variability of major field crops in the northernmost European conditions? *Agric. Food Sci.*, 18, 206–222.
Penning de Vries F.W.T. (1977). Evaluation of simulation models in agriculture and biology: conclusions of a workshop. *Agric. Syst.* 2, 99–105
Penning de Vries F.W.T., Jansen D.M., Ten Berge H.F.M. and Bakema A. (1989). *Simulation of ecophysiological processes of growth in several annual crops*. Simulation Monographs 29, Pudoc, Wageningen.
Penning de Vries F.W.T. and van Laar H.H. (1982). *Simulation of plant growth and crop production*. Simulation Monographs, Pudoc, Wageningen.
Pensa M., Sepp M. and Jalkanen R. (2006). Connections between climatic variables and the growth and needle dynamics of Scots pine (Pinus sylvestris L.) in Estonia and Lapland. *Int. J. Biometeorol.* 50, 205–214.
Pereira A.B., Villa Nova N.A., Ramos V. J. and Pereira A.R. (2008). Potato potential yield based on climatic elements and cultivar characteristics. *Bragantia*, 67, 327–334.
Petr J. (ed.) (1991). Weather and Yield. (Developments in Crop Science 20.) Elsevier, Amsterdam – New York.
Philipp A., Bartholy J., Beck C., Erpicum M., Esteban P., Fettweis X., Huth R., James P., Jourdain S., Kreienkamp F., Krennert T., Lykoudis S., Michalides S.C., Pianko-Kluczynska K., Post P., Rasilla Álvarez D., Schiemann R., Spekat A. and Tymvios F.S. (2010). Cost733cat – A database of weather and circulation type classifications. *Phys. Chem. Earth*, 35, 360–373.
Plakk T. (1990). Correlation between availability of moisture to plants and dielectric constant of soil. *Soviet Soil Sci.*, Washington, Scripta Publications 22/21, 98–105.
Plentinger M.C. and Penning de Vries F.W.T. (1997). *Rotation models for ecological farming*. CAMASE/PE workshop report. Quantitative Approaches in Systems Analysis no. 10. DLO Research Institute for Agrobiology and Soil Fertility & C.T. de Wit Graduate School for Production Ecology, Wageningen, Netherlands.
Polevoy A.N. (1983). *Theory and calculation of the productivity of agricultural plants*. Gidrometeoizdat, Leningrad (in Russian, with English abstract).
Polevoy A.N. (1988). *Applied Simulation and Prediction of Crop Productivity.* Gidrometeoizdat, Leningrad (in Russian, with English abstract).
Poluektov R.A. (1991). *Dynamic models of agroecosystem.* Gidrometeoizdat, Leningrad (in Russian, with English abstract).
Pusey P.L. (1997). Crab apple blossoms as a model for research on biological control of fire blight. *Phytopathology*, 87, 1096–1102.
Rabbinge R. and Van Latesteijn H.C. (1992) Long term options for land use in the European Community. *Agricultural Systems,* 40, 195–210.
Raper S.C.B., Wigley T.M.L. and Warrick R.A. (1996). Global sea-level rise: past and future. In: *Sea-Level Rise and Coastal Subsidence: Causes, Consequences and Strategies*. Kluwer Academic Publishers, Dordrecht.

Rasmusson E. M. and Carpenter T.H. (1982). Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Nino. *Monthly Weather Rev.*, 115, 1606–1626.

Rasmusson E. M. and Wallace J.M. (1983). Meteorological aspects of the El Niňo/Southern Oscillation. *Science*, 222, 1195–1202.

Reidsma P. (2007). *Adaptation to climate change: European agriculture*. PhD thesis, Wageningen University, Wageningen. (http://edepot.wur.nl/121920).

Reidsma P., Ewert F., Lansink A.O. and Leemans R. (2009). Vulnerability and adaptation of European farmers: a multi-level analysis of yield and income responses to climate variability. *Reg. Environ. Change*, 9, 25–40.

Reilly J. (2003). US agriculture and climate change: new results. *Clim. Change,* 57, 43–69.

Rind D., Goldberg R. and Ruedy R. (1989). Change in climate variability in the 21st century. *Clim. Change*, 14, 5–37.

Ritchie J. T. (1991). Specifications of the ideal model for predicting crop yields. In:. Muchow R. C. and Bellamy J. A. (Eds). *Climatic risk in crop production: models and management for semiarid tropics and subtropics*. CAB International, Wallingford, UK, 97–122

Ritchie J.T. and Otter S. (1984). Description and performance of CERES-Wheat, a user-oriented wheat yield model. USDA-ARS-SR Grassland, Soil and Water Research Laboratory. Temple, USA, 159–175.

Ritchie J.T., Griffin T.S. and Johnson B.S. (1995). SUBSTOR functional model of potato growth, development and yield. In: Kabat P. et al., (Eds), *Modelling and Parameterization of the Soil–Plant–Atmosphere System: a Comparison of Potato Growth Models*, Wageningen Pers, Wageningen, 401–435.

Roberts E.H. and Summerfield R.J. (1987). Measurement and prediction of flowering in annual crops. In: J.G. Atherton (Ed.), *Manipulation of Flowering*, Butterworths, UK, 17–50.

Robinson D.A., Jones S.B., Wraith J.M., Or D. and Friedman S.O. (2003). A review of advances in dielectric and electrical conductivity measurement in soils using time domain reflectometry, *Vadose Zone J.,* 2, 444–475.

Robinson D.A., Campbell C.S., Hopmans J.W., Hornbuckle B.K., Jones S.B., Knight R., Ogden F., Selker J. and Wendroth O. (2008). Soil moisture measurements for ecological and hydrological watershed scale observatories: a review. *Vadose Zone J.,* 7, 358–389.

Robock A, Vinnikov K.Ya., Srinivasan G., Entin J.K,. Hollinger S.E., Speranskaya N.A., Liu S. and Namkhai A. (2000). The global soil moisture data bank, *B. Am. Meteorol. Soc.,* 81, 1281–1299.

Romanova E.N. (1966). Redistribution of the moisture on gentle slopes and at their foothills in a warm season. In: Goltsberg I.A. (ed.). *Microclimatology.* Hydrometeoizdat, Leningrad, 3–18 (In Russian).

Romanova E.N. (1977). *Microclimatic Variability of Main Elements of Climate.* Hydrometeoizdat, Leningrad (In Russian).

Root T.I. and Hughes L. (2005). Present and future phenological changes in wild plants and animals. In: Lovejoy T.E., Hannah L. (Eds). *Climate change and biodiversity*, 61–69.

Rosenzweig C., Parry M.L., Fischer G. and Frohberg K. (1993). *Climate Change and World Food Supply*, Research Report No. 3, Environmental Change Unit, Univ. of Oxford, Oxford.

Rosenzweig C. & Iglesias A. (1994). *Implications of Climate Change for International Agriculture: Crop Modeling Study*. U.S. Environmental Protection Agency. Washington, D.C.

Rosenzweig C. & Parry M.L. (1994). Potential impacts of climate change on world food supply. *Nature,* 367, 133–138.

Rosenzweig C., Phillips J., Goldberg R., Carroll J. and Hodges T. (1996). Potential impacts of climate change on citrus and potato production in the US. *Agric Syst.*, 52, 455–479.

Rosenzweig C. and Hillel D. (1998). *Climate Change and the Global Harvest*, Oxford University Press, New York.

Parry M., Rosenzweig C. and Livermore M. (2005). Climate change, global food supply and risk of hunger *Phil. Trans. R. Soc.* B., 360, 2125–2138.

Rosenzweig C. and Iglesias A. (2006). *Potential impacts of Climate Change on World Food Supply: Data sets from a major crop modelling study.* New York: Goddard institute for Space Studies, Columbia University.

Ross J. (1966). About the mathematical description of plant growth. *DAN SSSR* 171 (2b), 481–483 (in Russian).

Ross J. (1975). *The radiation regime and Architecture od Plant Stands.* Gidrometeoizdat, Leningrad (in Russian, with English abstract).

Ross J. (1981). *The Radiation Regime and Architecture of Plant Stands*. Dr. W. Junk Publishers, Hague.

Ross J. and Nilson T. (1963). On the theory of radiation regime of plant cover. In: Investigations of Atmospheric Physics, 4, 42–63 (in Russian).

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

Schapendonk A. H. C. M., van Oijen M., Dijkstra M., Pot S. C., Jordi W. J. R. M. and Stoopen G. M. (2000). Effects of elevated CO2 concentration on photosynthetic acclimation and productivity of two potato cultivars grown in open-top chambers. *Austr. J. Plant Physiol*., 7, 1119–1130.

Scheierling S.M., Cardon G.E. and Young R.A. (1997). Impact of irrigation timing on simulated water–crop production functions. *Irrig. Sci.,* 18, 23–31

Scheifinger H., Menzel A., Koch E., Peter C. and Ahas R. (2002). Atmospheric mechanisms governing the spatial and temporal variability of phenological phases in central Europe. *Int. J. Clim.*, 22, 1739–1755.

Schimel D. (2006). ECOLOGY: climate change and crop yields: beyond Cassandra. *Science,* 312, 1889–1890.

Schulze R.E., Kiker G.A. and Kunz R.P. (1993). Global climate change and agricultural productivity in southern Africa. *Global Environ. Chang*., 3, 330–349.

Schwarz M.D. and Reiter B.E. (2000). Changes in North American spring. *Int. J. Biometeorol.*, 20, 929–932.

Schwartz M.D, Ahas R., Aasa A. (2006). Onset of spring starting earlier across the Northern Hemisphere. *Global change biology*, 12, 343–351.

Seljaninov G. (1966) Agroclimatic Map of the World. Leningrad Publishing Center (in Russian).

Semenov M.A. (2009). Impacts of climate change on wheat in England and Wales. *J. Royal Society Interface*, 6, 343–350.

Semenov M.A. and Porter J.R. (1995). Climatic variability and the modelling of crop yields. *J. Agricult.Forest Meteorol.*, 73, 265–283.

Semenov M.A., Wolf J., Evans L.G., Eckersten H. and Iglesias A. (1996). Comparison of wheat simulation models under climate change. II. Application of climate change scenarios. *Clim. Res.*, 7, 271–281.

Semenov M.A. and Doblas-Reyes F.J. (2007). Utility of dynamical seasonal forecasts in predicting crop yield. *Clim. Res.*, 34, 71–81.

Seneviratne S.I., Corti T., Davin E.L., Hirschi M., Jaeger E.B., Lehner I., Orlowsky B. and Teuling A.J. (2010): Investigating soil moisture-climate interactions in a changing climate: A review. *Earth-Science Reviews*, 99, 125–161.

Sepaskhah A.R., Bazrafshan-Jahromi A.R., Shirmohammadi-Aliakbarkhani Z. (2006). Development and evaluation of a model for yield production of wheat, maize and sugarbeet under water and salt stresses. *Biosystems engineering*, 93, 139–152.

Sepp J. (1988). Impact of meteorological conditions of different periods on potato production and calculation of yield security. (Vliyanie meteorologicheskikh uslovij razlichnykh periodov na produktivnost' kartofelya i raschet obespechennosti urozhainosti). In: Karing P. and Prosvirkina A.G. (Eds), *Questions of Agroclimatology and Agrometeorology*. *Trudy VNIISKHM 23*, Gidrometeoizdat, Leningrad, 116–122 (in Russian).

Sepp J. and Tooming H. (1982). Production process and actually possible yield of potato (dynamic model). *Agricultural Biology*, 17 (1), 89–97 (in Russian).

Sepp J. and Tooming H. (1983). Estimation of climatological resources of potato production in the Baltic Republics. *Vestnik s-h nauki (Messenger of agricultural sciences)*, 8, 58–63. (In Russian).

Sepp J., Tooming H. and Shvetsova V.M. (1989). Comparative assessment of potato productivity in the Komi A.S.S.R. and in Baltic republics by the method of dynamic modeling. *Plant Physiology,* 36, 68–75 (In Russian with English summary).

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

Sepp M. (2005). *Influence of atmospheric circulation on environmental variables in Estonia.* PhD thesis, University of Tartu, Tartu University Press, Estonia.

Sepp M. (2009). Changes in frequency of Baltic Sea cyclones and their relationships with NAO and climate in Estonia. *Boreal Environment Research*, 14, 143–151.

Sirotenko O.D. (1981). *Mathematical modelling of water-warmth regime and productivity of the agroecosystem*. Gidrometeoizdat, Leningrad (in Russian, with English abstract).

Sirotenko O.D. (1996). Mathematical models in crop bioclimatology in the former USSR (history, achievements, and prospects). *Adv. Bioclimatol*., 4, 125–169

Sirotenko O.D. (2001). Crop Modeling – Advances and Problems. *Agronomy J.*, 93, 650–653.

Sivakumar M.V.K. (1992). Climate change and implications for agriculture in Niger. *Clim. Change,* 20, 297–312.

Sivakumar M.V.K., Gommes R. and Baier. W. (2000). Agrometeorology and sustainable agriculture. *Agricult. Forest Meteorol.,* 103, 11–26.

Skelsey P., Rossing W.A.H., Kessel G.J.T. and van der Werf W. (2010). Invasion of Phytophthora infestans at the Landscape Level: How Do Spatial Scale and Weather Modulate the Consequences of Spatial Heterogeneity in Host Resistance? *Phytopathology,* 100, 1146–1161.

Smeets E. and Weterings R. (1999). *Environmental Indicators: Typology and Overview*. European Environment Agency, Copenhagen. Report No. 25.

Smith J.W. (1914). The effect of weather upon the yield of corn. *Monthly Weather Rev.*, 42, 78–92.

Smith J.W. (1920). *Agricultural Meteorology: the effect of weather on crops*. New York, Macmillan.

Smith J.U. (1997). Constructing a nitrogen fertilizer recommendation system using a dynamic model: what do farmers want? *Soil Use Manage.,* 13, 225–228.

Sparks T. and Tryjanowski P. (2007). Patterns of spring arrival dates differ in two hirundines. *Clim.Res.*, 35, 159–164.

Sporleder M.J., Kroschel M.R., Gutierrez Q and Lagnaoui A. (2004). A temperature-based simulation model for the potato tuber worm, *Phthorimaea operculella* Zeller. Lepidoptera Gelechiidae. *Environ. Entomol*., 33, 477–486.

Szwed M., Karg G., Pinskwar I., Radziejewski M., Graczyk D., Kedziora A., Kundzewicz Z. W. (2010). Climate change and its effect on agriculture, water resources and human health sectors in Poland. *Natural hazards and earth system sciences,* 10, 1725–1737.

Stöckle C.O., Donatelli M. and Nelson R.L. (2003). CropSyst, a cropping systems simulation model. *Eur. J. Agron*., 18, 289–307.

Stöckle C.O., Nelson R.L., Higgins S., Brunner J., Grove G., Boydston R., Whiting M. and Kruger C. (2010). Assessment of climate change impact on Eastern Washington agriculture. *Clim. Change,* 102, 77–102.

Šťastná M., Toman F. and Dufková J. (2010). Usage of SUBSTOR model in potato yield prediction. *Agricultural Water Management*, 97, 286–290.

Streck N.A., de Paula F. L. M., Bisognin D. A., Heldwein A.B and Dellai J**.** (2007). Simulating the development of field grown potato (*Solanum tuberosum* L). *Agricult. Forest Meteorol.*, 142, 1–11.

Supit I, van Diepen C.A., de Wit A. J. W., Kabat P., Baruth B. and Ludwig F. (2010). Recent changes in the climatic yield potential of various crops in Europe. *Agricult. Syst.*, 103, 683–694.

Sun J, Yang L., Wang Y and Ort D.R. (2009). Review. FACE-ing the global change: Opportunities for improvement in photosynthetic radiation use efficiency and crop yield. *Plant Sci.*, 177, 511–522.

Szep I.J., Mika J. and Dunkel Z. (2005). Palmer drought severity index as soil moisture indicator: Physical interpretation, statistical behaviour and relation to global climate. *Phys. Chem. Earth*, 30, 231–243.

Tagami Y. (1993). Climate change reconstructed from historical data in Japan. In: Proc Int Symp Global Change by IGBP March 27–29 1992, Tokyo. International Geosphere- Biosphere Programme-IGBP, Tokyo, 720–729.

Tagami Y. (1996). Some remarks on the climate in the Medieval Warm Period of Japan. In: Mikami T., Matsumoto E., Ohta S. and Sweda T. (Eds), *Paleoclimate and environmental variability in Austral-Asian transect during the past 2000 years (IGBP Proceedings).* International Geosphere-Biosphere Programme-IGBP, Nagoya, 115–119.

Tao F., Yokozawa M., Xu Y., Hayashi Y. and Zhang Z. (2006). Climate changes and trends in phenology and yields of field crops in China, 1981–2000. *Agricult. Forest Meteorol.,* 138, 82–92.

Tao F., Yokozawa M. and Zhang. Z. (2009). Modelling the impacts of weather and climate variability on crop productivity over a large area: A new process-based model development, optimization, and uncertainties analysis. *Agricult. Forest Meteorol.*, 149, 831–850.

Tarand A. and Kuiv P. (1994). The beginning of the rye harvest – a proxy indicator of summer climate in the Baltic Area. *Paleoclimatic Res.,* 13, 61–72.

Thompson L.M. (1969). Weather and Technology in the Production of Corn in the U.S. Corn Belt. *Agronomy J.,* 61, 453–456.
Thompson L.M. (1970). Weather and Technology in the Production of Soybeans in the Central U.S. *Agronomy J.,* 62, 232–236.
Thornton P.K. and Wilkens P.W. (1998). Risk Assessment and Food Security. *In*: Tsuji G.Y., Hoogenboom G. and Thornton P.K. (Ed.) *Understanding Options for Agricultural Production.* Kluwer Academic Publishers, Dordrecht, The Netherlands.
Timmermans B. G. H., Vos J. And Stomph T. J. (2009). The development, validation and application of a crop growth model to assess the potential of *S. sisymbriifolium* as a trap crop for potato cyst nematodes in Europe. *Field Crops Res.*, 111, 22– 31.
Tomingas O. (2002). Relationship between atmospheric circulation indices and climate variability in Estonia. *Boreal Env. Res.* 7, 463–469.
Tooming H. (1959). On some questions pertaining to the distribution of total radiation in vegetation. In: Niilisk H. (Ed.). *Issledovanija po fizike atmosfery*. Tartu, 83–108 (In Russian with an English summary).
Tooming H. (1961). *Reflection and absorption of short-wave solar radiation by some natural surface*. Candidate's thesis. Tartu University (In Russian).
Tooming H. (1967a). Mathematical model of plant photosynthesis considering adaptation. *Photosynthetica,* 1, 233–240.
Tooming H. (1967b). An approximate method for determining the attenuation and reflection of PAR and of near infrared radiation in a maize stand from the measurements of total radiation In: Monteith J. (Ed). *Photosynthesis of Productive Systems*. Israel Program of Scientific Translations, Jerusalem, 100–113.
Tooming H. (1968). Adaptation of plant communities to light intensity and its mathematical modelling. *Journal of General Biology*, 29, 549–563 (in Russian).
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, 103–114.
Tooming H. (1975). Prospects in forecasting the efficiency of changing the plant parameters and the estimation of maximum yield. In: *Programming of agricultural crops yield*. Kolos, Moscow, 403–414 (In Russian).
Tooming H. (1977). *Solar radiation and yield formation*. Gidrometeoizdat, Leningrad [In Russian with English abstract].
Tooming H. 1984. *Ecological principles of maximum crop productivity.* Gidrometeoizdat, Leningrad [in Russian with English summary].
Tooming H. (1988). Principle of maximum plant productivity. In: Kull K., Tiivel T. (Eds.). *Lectures in Theoretical Biology*. Valgus, Tallinn, 129–138.
Tooming H. (1993). Evaluation of agrometeorological resources based on the potential productivity of crops. *Journ. Agric. Met*., 48, 501–507.
Tooming H. (1998). Climate change and estimation of ecologically founded yields. In: Kallaste T. And Kuldna P. (Eds). *Climate change studies in Estonia.* Stockholm Environment Institute Tallinn Centre – Ministry of environment, Republic of Estonia, Tallinn, 141–152.
Tooming H. and Ross J. (1964). Radiation regime of maize crop by levels of describing its approximate formula. *Issledovaniya Po Fizike Atmosfery* 6**,** 63–80 (in Russian with English summary).
Tooming H. and Nilson T. (1967). Basis of energetic adaptation of vegetation on light. In: *Phytoactinometrical Investigations of Vegetation*. Tallinn, Valgus, 35–63 (in Russian).

Tooming H. and Kallis A. (1972). Productivity and growth calculations of plant stands. In: *Solar radiation and productivity of plant stands*. Estonian Academy of Science, Tartu, 5–120 (in Russian).

Tooming H. and Kadaja J. (2006). Relationships of snow cover in Estonian climate – relations from winter to spring. In: Tooming H. and Kadaja J. (Compilers), Kallis A. (Ed.). *Handbook of Estonian snow cover.* Estonian Meteorological and Hydrological Institute – Estonian Research Institute of Agriculture, Tallinn – Saku, 112–133.

Topp G.C. (2003). State of the art of measuring soil water content, *Hydrol. Process.*, 17**,** 2993–2996.

Topp G.C. and Reynolds W.D. (1998). Time domain reflectometry: a seminal technique for measuring mass and energy in soil. *Soil Till. Res.,* 47 (1–2), 125–132.

Torriani D.S., Calanca P., Schmid S., Beniston M. and Fuhrer J. (2007). Potential effects of changes in mean climate and climate variability on the yield of winter and spring crops in Switzerland. *Clim. Res.,* 34 (1), 59–69.

Trnka M., Eitzinger J., Hlavinka P., Dubrovsky M., Semeradova D., Stepanek P., Thaler S., Zalud Z., Mozny M. and Formayer H. (2009). Climate-driven changes of production regions in Central Europe. *Plant soil and environment,* 55, 257–266.

Tubiello F.N., Rosenzweig C., Goldberg R.A., Jagtap S and Jones J.W. (2002). Effects of climate change on US crop production: simulation results using two different GCM scenarios. Part I: wheat, potato, maize, and citrus. *Clim. Res.,* 20, 259–270.

Van den Broek B.J. and Kabat P. (1995). SWACROP: dynamic simulation model of soil water and crop yield applied to potatoes. In: Kabat P., Marshall B., van der Broek B.J., Vos J. And van Keulen H. (Eds). *Modelling and parametrisation of the soil-plant-atmosphere system – a comparision of potato growth models*. Pudoc, Wageningen, 299–333.

Van der Velde M., Wriedt G. and Bouraoui F. (2010). Estimating irrigation use and effects on maize yield during the 2003 heatwave in France. *Agricult. Ecosyst. Environ.*, 135, 90–97.

Van Diepen C.A, Wolf J., Van Keulen H. and Rappoldt C. (1989). WOFOST – a simulation-model of crop production. *Soil use and management*, 5, 16–24.

Van Ittersum M.K., Leffelaar P.A., Van Keulen H., Kropff M.J., Bastiaans L., Goudriaan J. (2003). On approaches and applications of the Wageningen crop models. *European Journal of Agronomy,* 18, 201–234.

Van Keulen H. and Wolf J. (1986). *Modelling of Agricultural production: weather, soils and crops*. Simulation Monographs. Pudoc, Wageningen, The Netherlands.

Viil P. and Nugis E. (2002). Some aspects of differentiation of soil tillage. In: *Proceedings of the 3rd Scientific and Practical Conference on Ecology and Agricultural Machinery*, N-WRIAEE, 2. St-Petersburg, Russia, 66–72.

Viil P. and Võsa T. (2006). Diferentseeritud põhimullaharimise mõju põllukultuuride saagile. In Kadaja, J; Siim, J; Tamm, U; Jõgeva; H. (Eds.). *Transactions of ERIA* LXXI (71), Saku, 315–326 (in Estonian with English abstract).

Vinnikov K.Y., Robock A., Speranskaya N.A. and Schlosser A. (1996). Scales of temporal and spatial variability of midlatitude soil moisture. *J. Geophys. Research-atmospheres,* 101, 7163–7174.

Visser M.E. and Both C. (2005). Shifts in phenology due to global climate change: the need for a yardstick. *Proc. R. Soc. B.,* 272, 2561–2569.

Walther G.R., Post E., Convey P., Menzel A., Parmesan C., Beebee T.J.C., Fromentin J.M., Hoegh-Guldberg O. and Bairlein F. (2002). Ecological responses to recent climate change. *Nature,* 416, 389–395.

Wanner H.S., Brönnimann S., Casty C., Gyalistras D., Luterbacher J., Schmutz C., Stephenson D.B. and Xoplaki E. (2001). North Atlantic Oscillation – concepts and studies. *Survey Geophys,* 22, 321–381.

Weir A.H., Bragg P.L., Porter J.R. and Rayner J.H. (1984). A winter wheat crop simulation model without water or nutrient limitation. *J.Agricult. Sci. Cambridge,* 102, 371–382.

Went F. W. (1958). The physiology of photosynthesis in higher plants. *Preslia*, 1, 225–240.

Wheeler R.M. and Tibbitts T.W. (1997). Influence of changes in daylength and carbon dioxide on the growth of potato. *Ann. Bot.* 79, 529–533.

Whisler F.D., Acock B., Baker D.N., Fye R.E., Hodges F.H., Lambert J.R., Lemmon H.E., Mckinion J.M. and Reddy V.R. (1986). Crop simulation models in agronomic systems. *Adv. Agron*., 40, 141–208.

Wigley T.M.L. and Raper S.C.B. (1992). Implications for climate and sea level of revised IPCC emissions scenarios. *Nature* 357, 293–300.

Winkler E. (1971). Karetoffelbau in Tirol II. Photosynthesevermögen und Respiration von verschiedenen Kartoffelarten. *Potato Res.,* 14, 1–18.

Wolf J. (1999a). Modelling climate change impacts at the site scale on potato. In: Downing, T.E.; Harrison, P.A.; Butterfield, R.E.; Lonsdale, K.G. (Eds.). *Climate Change, Climate variability and Agriculture in Europe: an integrated assessment*. Report No. 21., Environmental Change Unit, University of Oxford, Oxford, UK, 135–154.

Wolf J. (1999b). Modelling climate change impacts on potato in central England. In: Downing, T.E.; Harrison, P.A.; Butterfield, R.E.; Lonsdale, K.G. (Eds.). *Climate Change, Climate variability and Agriculture in Europe: an integrated assessment*. Report No. 21., Environmental Change Unit, University of Oxford, Oxford, UK, 239–261.

Wolf J. (2002) Comparison of two potato simulation models under climate change. II. Application of climate change scenarios. *Clim Res*, 21, 187–198.

Wolf J. and van Oijen M. (2002). Modelling the dependence of European potato yields on changes in climate and CO_2. *Agricult.Forest Meteorol.,* 112, 217–231.

Wolf J. and van Oijen M. (2003). Model simulation of effects of changes in climate and atmospheric CO_2 and O_3 on tuber yield potential of potato (cv. Bintje) in the European Union. *Agriculture, Ecosystems & Environment*, 94, 141–157.

Wolf J. and van Ittersum M. (2009). Crop models: main developments, their use in CGMS and Integrated modeling. *Agro Informatica*, 22, 15–18.

Woodward F.I. (1988). Temperature and the distribution of plant species and vegetation. In: Long S.P and Woodward F.I. (Eds). *Plants and Temperature*. Society of Experimental Biology by The Company of Biologists Limited, Cambridge, 59–75

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. and Tooming H. (1989). On the possibility of the yield calculation forecasting calculation. *Vestn. S.-H. Nauki (Messenger of agricultural sciences)*, 68–79 (In Russian with English abstract).

Zhukovsky E.E., Sepp J. and Tooming, H. (1990). Probabilistic forecasts of possible yield. *Meteorology and Hydrology,* 1, 95–102 (In Russian with English abstract).

SUMMARY IN ESTONIAN

Modelleeritud kartulisaak kui kliima varieeruvuse näitaja Eestis

Viimastel aastakümnetel oleme sattunud küllaltki intensiivsesse kliima muutumise perioodi. Globaalses mastaabis on üsna kindel, et kliima soojeneb ja et see soojenemine jätkub ka käesoleval sajandil; kohalikul tasandil seevastu ei ole globaalne soojenemine ja selle tagajärjed alati üks-üheselt määratavad. Ometi on just kohalikud muutused need, millega me igapäevaelus arvestama peame. Põllumajandus on üks regionaalsest kliimast, selle muutlikkusest ja muutumisest kõige enam mõjutatud olev majandusharu. See, milliseid põllukultuure mingis piirkonnas tulevikus kasvatatakse, sõltub olulisel määral sellest, millised on ilmastiku muutused just selles konkreetses piirkonnas. Samuti on põllumajanduse seisukohalt olulised mitte ainult aasta keskmised näitajad, vaid eelkõige temperatuuri ja sademete sessoonne jaotus ja varieeruvus.

Viimastel aastakümnetel on kliima varieeruvus ja muutused juba avaldanud põllumajandusele märkimisväärset mõju – nt. on nii Euroopas kui Põhja-Ameerikas toimunud mitmete taimeliikide, s.h. põllukultuuride fenoloogiliste faaside varasemaks nihkumine, mida võib seostada regionaalse soojenemisega. Lisaks on parasvöötmes täheldatud öökülmaohu vähenemist, kasvuperioodi pikenemist jm. paikse soojenemisega seostatavaid nähtusi. Kuna taimekasv ja -produktiivsus on otseselt ilmastikust mõjutatud, oleks loogiline seda seost ka teistpidisena vaadelda ja kasutada nt. põllumajanduskultuuride saagikust kui arvukalt mõõdetavat näitajat regionaalse kliima ja selle pikaajalise muutumise indikaatorina. Ometi ei ole tegelikult lihtne eristada kliima muutlikkuse ja muutumise otsest mõju taimede produktsioonile ja saagile ja eraldada seda nt. maastiku ja mullastiku erinevustest, muutuvatest põlluharimisviisidest, uute sortide kasutuselevõtust või paremini korraldatud väetamisest tulenevatest mõjudest. Nii näiteks võib muutusi põllukultuuride fenoloogias küll seostada kõrgemate talviste/kevadiste temperatuuridega, teisalt võib siin aga oma osa mängida ka muutunud põlluharimistehnoloogia, sellest tulenev põllutööde ajastatus kui ka kõigi eelnimetatud tegurite omavahelised vastasmõjud. Viimastel aastakümnetel toimunud pidev saagikuse kasv tänu tehnoloogia, sordiaretuse ja kahjuri/haigusetõrje täiustumisele (mis on küll viimasel ajal pidurdunud) muudab samuti kliimamuutuste otsese signaali tuvastamise keeruliseks.

Kõige eelnimetatu tõttu ei ole kuigi palju pikki homogeenseid saagiridu, mida kliima iseloomustamise aluseks võtta. Seega on kliimaarvutuste tarbeks mugavam ja efektiivsem kasutada pikkade saagiridade mudelarvutusi. Käesolevas väitekirjas kasutatakse kliima mõju hindamiseks maksimaalses produktiivsuse printsiibist ja etalonsaakide meetodist tulenevat meteoroloogiliselt võimaliku saagi mõistet (MVS, suurim võimalik saak olemasolevate meteoroloogiliste tingimuste korral). See kontseptsioon tähendab põllumajandustaimede saagikuse arvutamist matemaatilise mudeli abil ja võimaldab vaadelda meteoroloogiliste tingimuste ja nende muutlikkuse otsest mõju saagile. Lisaks on võimalik tõlgendada saadud tulemusi ka teisipidi ja kasutada arvutatud saagirida integraalse muutujana, mille abil on võimalik hinnata kokkuvõtlikult suvekuude ilmastikku ja kliimat erinevatel aastatel ja erinevates piirkondades. Võrreldes keskmiste või summeeritud meteoroloogiliste näitajatega seisneb selliselt arvutatud saagi eelis integraalse karakteristikuna selles, et ta integreerib ilmastiku erinevad seisundid nende ajalises järnevuses, keskmised ilmanäitajad aga siluvad.

Käesoleva väitekirja peamine eesmärk oli hinnata Eesti suvise kliima varieeruvust ja võimalikku muutust läbi kartulisaagile avalduva mõju. On püütud hinnata, kas ja kuivõrd annab MVS kliima varieeruvuse kohta lisainformatsiooni võrreldes traditsiooniliste individuaalsete meteoelementidega. Sel eesmärgil arvutati kartuli produktsiooniprotsessi mudeli POMOD abil pikaajalised MVS read ühe hilise ja ühe varase kartulisordi jaoks kolmes Eesti meteojaamas, mis iseloomustavad mõnevõrra erinevaid kliimatingimusi. Arvutused teostati nii olemasoleva kliima kohta kui ka võimalikku kliimamuutust arvestades. MVS pikki ridu võrreldi nii summeeritud meteoelementidega kui ka mõnede atmosfääri tsirkulatsiooni iseloomustavate näitajatega. Võrdlusena on toodud analüüs, kus meteoelementidega võrreldakse pikaajalises katses mõõdetud tegeliku kartulisaagi andmeid.

Tegelikult saadud kartulisaak leiti olevat määratud peamiselt ilmastikutingimuste poolt. Mõju avaldas ka erinev väetustase, kusjuures väetamise soodne mõju avaldus eelkõige ilmastiku poolest soodsatel aastatel. Mullaharimisviisil ei leitud statistiliselt usaldusväärset mõju kartuli saagikusele. Siiski, pikemas perspektiivis mõjutab ilmastik omakorda nii väetamine kui mullaharimine mõju ja need osutuvad oluliseks.

Tegelikku kartulisaaki mõjutavad eelkõige kevadised (aprill-mai) ilmastikutingimused. Positiivne seos esines saagi ja temperatuuride vahel, negatiivne saagi ja sademete summa vahel. Suuresti toimib see seos mullatemeratuuri ja -niiskuse kaudu, kuna kartuli mahapanek toimub alles maikuus ja aprilli-mai meteoelementide mõju taimekasvule ei ole seetõttu otsene. Sademete positiivne mõju avaldub saagile alates õitsemise faasist, mil hakkab toimuma mugulate moodustumine.

Sajandipikkustes modelleeritud MVS ridades esinevad vaid nõrgad ja statistiliselt mitteolulised trendid, kuigi statistiliselt usaldusväärseid trende võib leida üksikute lühemate perioodide kohta. Kõigis kolmes jaamas esinevad statistiliselt olulised polünomiaalsed seosed MVS ja summeeritud meteoelementide vahel, kuid lineaarsed seosed on usaldusväärsed ainult Eesti läänerannikul (Kuressaares). MVS varieeruvuse usaldusväärne suurenemine, mis määrati Tartus uuritava perioodi teises pooles, esines vaid nõrgalt sademete reas ja puudus täiesti temperatuuri ja kiirguse andmetes. Lineaarse seose puudumine, kõrge varieeruvus teise astme polünomiaalse seose ümber ja muutused saagi varieeruvuses, mida ei saa otseselt seostada ainult ühe meteoelemendiga, lubavad väita, et arvutatud MVS annab tõepoolest kliima varieeruvuse kohta lisainformatsiooni, sünteesides erinevate üksikute elementide mõju.

MVS ja NAO indeksi vahelised korrelatsioonid olid üldiselt nõrgad, kuid mõne sügis- ja talvekuu korral siiski usaldatavad. Kõrgeim, negatiivne korrelatsioonikordaja esines saagi ja eelneva novembri indeksi vahel, tähistades antitsüklonaalsete ilmade negatiivset seost. Positivsed seosed esinesid jaanuaris sisemaal hilise sordi korral.

Tsirkulatsioonitüüpide sageduse ja MVS vaheliste seoste analüüs näitas, et negatiivse mõjuga tsirkulatsioonitüübid tulevad selgemalt esile kui positiivse mõjuga tüübid. Tsirkulatsioon mõjutab saaki rohkem merelise kliimaga Kuressaares, kus sagedane põud toimib saaki limiteeriva tegurina. Tartus ja Tallinnas jääb tsirkulatsiooni mõju nõrgemaks. Mereäärsetes kohtades leiti MVS rohkem sõltuvat neist tüüpidest, mis toovad põuast ilma, samas Mandri-Eestis on saagikus rohkem mõjutatud liigsetest sademetest ja vähesest soojusest.

Hindamaks reljeefist tulenevaid mullaniiskuse erinevusi ja nende mõju kartulisaagile, täiendati POMOdit alamprogrammiga, mis võimaldab hinnata sademetevee ümberjaotumist nõlval. Tulemusena leiti, et Kuressaares on mullaniiskuse positiivne mõju iseloomustatav MVS muutuse kaudu nõlva ülaosast allapoole – mida rohkem lisavett on taimedele juurdevoolu tulemusena kättesaadav, seda parem saak. Tallinnas on olukord teistsugune, kõige halvemad kasvutingimused esinevad kõige rohkem lisaniiskust saaval nõlvajalamil, kuid soodsas olukorras ei ole ka ka kõige rohkem niiskust kaotav nõlva ülaosa. Tallinnas olid topograafiast tulenevad saagikaod oluliselt suuremad kui Kuressaares; eriti halvasti mõjusid ekstreemsete sademetega aastad.

Hindamaks võimaliku kliimamuutuse mõju kartuli kasvatamiseks vajalikele agrometeoroloogilistele ressurssidele, kaasati arvutustesse neli erinevat kliimamuutuste stsenaariumit. Nende põhjal arvutati MVS käesoleva sajandi keskpaigale ja lõpule vastavaks 30 aastaseks perioodiks, lähtudes Tartu, Tallinna ja Kuressaare andmetest. Varase sordi jaoks ennustavad kõik kasutatud stsenaariumid kasvutingimuste halvenemist kõigis kolmes vaadeldud asukohas, kusjuures tugevamat soojenemist lubavad stsenaariumid põhjustavad suuremat saagikadu, eelkõige tänu kiirenenud arengule, maksimaalse lehepinna vähenemisele ja sellest tulenevale kasvuperioodi lühenemisele. Hilise sordi jaoks võib esialgu oodata kasvuperioodi pikenemisest tulenevat saakide vähest suurenemist, kusjuures leebematest stsenaariumitest tingitud väiksem soojenemine on soodsmama mõjuga. Sajandi lõpuks ennustavad siiski Kuressaares ja Tartus kõik stsenaariumid saakide vähenemist. Tallinn tundub olevat kõige soodsamas seisus, kuna ainult kõige tugevamat soojenemist lubav stsenaarium põhjustab saakide vähenemist. Põhiliselt on nimetatud saagikaod seotud temperatuuri tõusuga, sademete hulga suurenemine omab nõrka kompensatoorset efekti.

Nagu kirjeldatud tulemustest näha, omab taimedele kättesaadav niiskus kartulisaagi kujunemisel Eestis olulist mõju. Seetõttu testiti põldkatsete käigus elektroonilist mullaniiskuse mõõturit, mis võimaldab tulevikus kohtspetsiifilisi mullaniiskuse erinevusi lihtsamalt mõõta ja ka mudelis arvestada. Tulemusena koostati logaritmiline seos dielektrilise konstandi ja mahulise mullaniiskuse vahel; lisaks viidi valemisse sisse kivisust arvestav parand.

ACKNOWLEDGEMENTS

I sincerely thank my supervisors – prof. Jaak Jaagus, for his stubborn faith in me and Jüri Kadaja, for his knowledge, soundness, patience, full support and stand throughout all those years. I would not had made it by myself.

I have enjoyed the assistance from my co-workers at the Estonian Research Institute of Agriculture. Thank you for taking me more seriously than I did myself. Special thanks to Peeter Viil and Marje Särekanno for the opportunity to work within their field trials and Helena Pärenson for perpetually correcting my English.

I feel that also my bosses deserve a bow for their impatient suspense. I do understand your pain.

Special thanks to Julia Sander and Eeva-Liisa Alanen for understanding how I feel and Mait Sepp for Georgian vine and Polish strawberries. My apologies to everyone to whom my recent ignorance in earthly subjects has caused any inconvenience.

Finally, I am so very grateful to my kids for surviving my studies: to my older son for learning to cook (thank you, YouTube.com), to my my younger son for actually eating it and to my baby daughter for her convenient sleeping pattern.

The thesis has been supported by ETF grants 5020, 6092 and 7526, Target Funding Projects SF0180127s08 of the Ministry of Education and Science of Estonia and Estonian Ministry of Agriculture through the project "The effect of soil tillage intensity on the yield and quality of slurry-fertilised crops and soil condition" of the State Program "Applied Agricultural Research and Development in 2009–2014".

PUBLICATIONS

CURRICULUM VITAE

TRIIN SAUE

Time and place of birth: 21.02.1976 Kärdla
Citizenhip: Estonian
Address, phone, e-mail: Raplamaa, Kohila vald, Aespa küla, Marja 27,
+372 5522822, triin.saue@eria.ee

Education

2006–2011	PhD studies at Geography, University of Tartu.
2004–2006	MSc at Environmental protection, Eurouniversity.
2000–2001	BSc at Hydrometeorology and environmental protection, University of Tallinn.
1994–1998	Diploma at Hydrometeorology and environmental protection, Estonian Marine Academy.
1991–1994	Kärdla High School.

Professional employment

2005–...	Estonian Research Institute of Agriculture, researcher at the department of Agricultural Engineering and Technology
2005–2008	Estonian Marine Academy, assistant at the Faculty of Hydrometeorology.
2000–2001	Estonian Meteorlogical and Hydrological Institute, technician at the Department of Research and Development.

Publications

Saue, T., & Kadaja, J. (201X). Possible effect of climate change on potato crops in Estonia. Boreal Environment Research (in print).

Sepp, M., & **Saue, T.** (201X). Connections between circulation type incidence and the modelled potato crop yield in Estonia. International Journal of Biometeorology (submitted).

Kadaja, J., & **Saue, T. (2011).** Ilmastikuressursid kartuli kasvatuseks kliima-muutuste tingimustes. In; Kadaja, J. (Ed.). Agronoomia 2010/2011 (87–94). Saku: Eesti Maaviljeluse Instituut (in Estonian with English abstract).

Saue, T., & Kadaja, J. (2010). Simulated Potato Crop Yield – an Indicator of Climate Variability in Estonia. In: Simard, S. (Ed.). Climate Change and Variability (365–388). Sciyo

Saue, T., & Kadaja, J. (2010). Meteorologically possible potato yields for Estonia, derived from climate change scenarios. 6th Study Conference on BALTEX; Miedzyzdroje, Island of Wolin, Poland; 14–18 June 2010. (Eds.) Reckermann, Marcus; Isemer, Hans-Jörg. Geesthacht, Germany: GKSS Forschungszentrum Geesthacht GmbH, 2010, (International BALTEX Secretariat Publication; 46), 171– 172.

Saue, T., Viil, P., & Kadaja, J. (2010) Do different tillage and fertilization methods influence weather risk on potato yield? Agronomy Research, 427–432.

Sepp, M., & **Saue, T**. (2010). Connections between the atmospheric circulation type and the modelled potato crop yield in Estonia. 6th Study Conference on BALTEX; Miedzyzdroje, Island of Wolin, Poland; 14–18 June 2010. (Eds.) Reckermann, Marcus; Isemer, Hans-Jörg. Geesthacht, Germany: GKSS Forschungszentrum Geesthacht GmbH, 2010, (International BALTEX Secretariat Publication; 46), 173–174.

Särekanno, M., Kadaja, J., Kotkas, K., Rosenberg, V., Vasar, V., **Saue, T**., & Eremeev, V. (2010). Potato seed from meristem plants using EVIKA multiplication methods. Acta Agriculturae Scandinavica, Section B – Plant Soil Science, 60(2), 101–109.

Särekanno, M., Kadaja, J., Kotkas, K., Rosenberg, V., Vasar, V., **Saue, T**., & Eremeev, V. (2010). Yield potential and tubers size distribution using EVIKA multiplication methods. Acta Agriculturae Scandinavica, Section B – Plant Soil Science, 60(4), 297–306.

Kadaja, J., **Saue, T**., & Viil, P. (2009). Probabilistic yield forecast based on a production process model. Li, Daoliang; Zhao, Chunjiang (Eds.) Computer and Computing Technologies in Agriculture II (487–494). Springer.

Kadaja, J., **Saue, T**., & Viil, P. (2009). Crop modelling based on the principle of maximum plant productivity. E.J. van Henten, D. Goense, C. Lokhorst (Eds.). Precision Agriculture '09 (675–681). Wageningen: Wageningen Academic Publishers.

Kadaja, J., Plakk, T., **Saue, T**., Nugis, E., Viil, P., & Särekanno, M. (2009). Measurement of soil water and nutrients by its electrical properties. Acta Agriculturae Scandinavica: Section B, Soil and Plant Science, 59, 447–455.

Kadaja, J.; **Saue, T.** (2009). Crop modelling based on the principle of maximum plant productivity. In: Lokhorst, C.; Huijsmans, J.F.M.; de Louw R.P.M. (Eds.), *JIAC2009, Book of abstracts, ECPA-ECPLF-EFITA: Joint International Agricultural Conference; Wageningen; 5–9 July 2009*. Wageningen: Wageningen Academic Publishers, 2009, 81.

Saue, T., & Kadaja, J. (2009). Modelling crop yield response to precipitation redistribution on slopes. Biologia, 64(3), 502–506.

Saue, T., & Kadaja, J. (2009). Simulated crop yield – an indicator of climate variability. Boreal Environment Research, 14(1), 132–142.

Nugis, E., Kadaja, J., Plakk, T., & **Saue, T**. (2008). Invention: *Method for determination of volumetric moisture content in soil layer*; Owner: Estonian

Research Institute of Agriculture; Authors: Edvin Nugis, Jüri Kadaja, Tiit Plakk, Triin Saue; Priority number: P200800010; Priority date: 28.02.2008

Saue, T., Kadaja, J. & Plakk, T. (2008). Measurement of soil water content by percometer. In: Workshop Program & Papers: 1st Global Workshop on High Resolution Digital Soil Sensing & Mapping, 5–8 veebruar, Sydney. Sydney, Australia: International Union of Soil Sciences, The Australian Centre for Precision Agriculture, 2008, 184–192.

Saue, T., ja Kadaja, J. (2007). Simulated crop as an indicator for climate variablity. Fifth Study Conference on BALTEX. Conference Proceedings, International BALTEX Secretariat, No38, 178–179.

Saue, T., & Kadaja, J. (2006). Percomeetri abil saadud tulemusi mulla parameetrite määramisel. Eesti Maaviljeluse Instituudi teaduslike tööde kogumik. LXXI (71), 247–256. (In Estonian with English abstract)

Saue, T., Kadaja, J., & Nugis, E. (2006). Mulla dielektrilise läbitavuse mõõtmisel saadud tulemusi. Publicationes Geophysicales Universitatis Tartuensis*,* 50, 155–160. (In Estonian with English abstract)

Saue, T., & Kadaja, J., (2005). Growth Stages of Winter Rye and Accumulated Temperatures. Baltic Horizons, EuroUniversity Series Environment Protection & Ecology, No4 (103), 63–78.

Saue, T., & Kadaja, J. (2005). Talirukki arengufaasid ja temperatuurisummad. Agraarteadus, XVI, 1, 44–52. (In Estonian with English abstract).

Saue, T., Kadaja, J., & Järvenoja, S. (2005). Comparison of HIRLAM Predicted Soil Moisture with Observed Data in Estonia. Baltic Horizons, EuroUniversity Series Environment Protection & Ecology, No4 (103), 79–88.

ELULOOKIRJELDUS

TRIIN SAUE

Sünniaeg ja -koht: 21.02.1976 Kärdla
Kodakondsus: Eesti
Aadress, telefon, e-mail: Raplamaa, Kohila vald, Aespa küla, Marja 27,
+372 552 2822, triin.saue@eria.ee

Haridus

2006–2011	Doktorantuur geograafia erialal, Tartu Ülikool.
2004–2006	Magistrantuur keskkonnakaitse erialal, Euroülikool (praegune Euroakadeemia).
2000–2001	Bakalaureuseõpe keskkonnakaitse ja hüdrometeoroloogia erialal, Tallinna Pedagoogikaülikool (praegune Tallinna Ülikool).
1994–1998	Diplomiõpe keskkonnakaitse ja hüdrometeoroloogia erialal, Eesti Merehariduskeskus (praegune Mereakadeemia).
1991–1994	Kärdla Keskkool (praegune Kärdla Ühisgümnaasium).

Töökogemus

2005–...	Eesti Maaviljeluse Instituut, Põllumajandustehnika ja -tehnoloogia osakonna teadur.
2005–2008	Eesti Mereakadeemia, Hüdrometeoroloogia õppetooli assistent.
2000–2001	Eesti Meteoroloogia ja Hüdroloogia Instituudi Teadus- ja arendusosakonna tehnik.

DISSERTATIONES GEOGRAPHICAE UNIVERSITATIS TARTUENSIS

1. Вийви Руссак. Солнечная радиация в Тыравере. Тарту, 1991.
2. Urmas Peterson. Studies on Reflectance Factor Dynamics of Forest Communities in Estonia. Tartu, 1993.
3. Ülo Suursaar. Soome lahe avaosa ja Eesti rannikumere vee kvaliteedi analüüs. Tartu, 1993.
4. Kiira Aaviksoo. Application of Markov Models in Investigation of Vegetation and Land Use Dynamics in Estonian Mire Landscapes. Tartu, 1993.
5. Kjell Weppling. On the assessment of feasible liming strategies for acid sulphate waters in Finland. Tartu, 1997.
6. Hannes Palang. Landscape changes in Estonia: the past and the future. Tartu, 1998.
7. Eiki Berg. Estonia's northeastern periphery in politics: socio-economic and ethnic dimensions. Tartu, 1999.
8. Valdo Kuusemets. Nitrogen and phosphorus transformation in riparian buffer zones of agricultural landscapes in Estonia. Tartu, 1999.
9. Kalev Sepp. The methodology and applications of agricultural landscape monitoring in Estonia. Tartu, 1999.
10. Rein Ahas. Spatial and temporal variability of phenological phases in Estonia. Tartu, 1999.
11. Эрки Таммиксаар. Географические аспекты творчества Карла Бэра в 1830–1840 гг. Тарту, 2000.
12. Garri Raagmaa. Regional identity and public leaders in regional economic development. Tartu, 2000.
13. Tiit Tammaru. Linnastumine ja linnade kasv Eestis nõukogude aastatel. Tartu, 2001.
14. Tõnu Mauring. Wastewater treatment weltlands in Estonia: efficiency and landscape analysis. Tartu, 2001.
15. Ain Kull. Impact of weather and climatic fluctuations on nutrient flows in rural catchments. Tartu, 2001.
16. Robert Szava-Kovats. Assessment of stream sediment contamination by median sum of weighted residuals regression. Tartu, 2001.
17. Heno Sarv. Indigenous Europeans east of Moscow. Population and Migration Patterns of the Largest Finno-Ugrian Peoples in Russia from the 18th to the 20th Centuries. Tartu, 2002.
18. Mart Külvik. Ecological networks in Estonia — concepts and applications. Tartu, 2002.
19. Arvo Järvet. Influence of hydrological factors and human impact on the ecological state of shallow Lake Võrtsjärv in Estonia. Tartu, 2004.
20. Katrin Pajuste. Deposition and transformation of air pollutants in coniferous forests. Tartu, 2004.

21. Helen Sooväli. *Saaremaa waltz*. Landscape imagery of Saaremaa Island in the 20th century. Tartu, 2004.
22. Antti Roose. Optimisation of environmental monitoring network by integrated modelling strategy with geographic information system — an Estonian case. Tartu, 2005.
23. Anto Aasa. Changes in phenological time series in Estonia and Central and Eastern Europe 1951–1998. Relationships with air temperature and atmospheric circulation. Tartu, 2005.
24. Anneli Palo. Relationships between landscape factors and vegetation site types: case study from Saare county, Estonia. Tartu, 2005.
25. Mait Sepp. Influence of atmospheric circulation on environmental variables in Estonia. Tartu, 2005.
26. Helen Alumäe. Landscape preferences of local people: considerations for landscape planning in rural areas of Estonia. Tartu, 2006.
27. Aarne Luud. Evaluation of moose habitats and forest reclamation in Estonian oil shale mining areas. Tartu, 2006.
28. Taavi Pae. Formation of cultural traits in Estonia resulting from historical administrative division. Tartu, 2006.
29. Anneli Kährik. Socio-spatial residential segregation in post-socialist cities: the case of Tallinn, Estonia. Tartu, 2006.
30. Dago Antov. Road user perception towards road safety in Estonia. Tartu, 2006.
31. Üllas Ehrlich. Ecological economics as a tool for resource based nature conservation management in Estonia. Tartu, 2007.
32. Evelyn Uuemaa. Indicatory value of landscape metrics for river water quality and landscape pattern. Tartu, 2007.
33. Raivo Aunap. The applicability of gis data in detecting and representing changes in landscape: three case studies in Estonia. Tartu, 2007.
34. Kai Treier. Trends of air pollutants in precipitation at Estonian monitoring stations. Tartu, 2008.
35. Kadri Leetmaa. Residential suburbanisation in the Tallinn metropolitan area. Tartu, 2008.
36. Mare Remm. Geographic aspects of enterobiasis in Estonia. Tartu, 2009.
37. Alar Teemusk. Temperature and water regime, and runoff water quality of planted roofs. Tartu, 2009.
38. Kai Kimmel. Ecosystem services of Estonian wetlands. Tartu, 2009.
39. Merje Lesta. Evaluation of regulation functions of rural landscapes for the optimal siting of treatment wetlands and mitigation of greenhouse gas emissions. Tartu, 2009.
40. Siiri Silm. The seasonality of social phenomena in Estonia: the location of the population, alcohol consumption and births. Tartu, 2009.
41. Ene Intermitte. Exposure to fluorides in drinking water and dental fluorosis risk among the population of Estonia. Tartu, 2010.

42. Kaido Soosaar. Greenhouse gas fluxes in rural landscapes of Estonia. Tartu, 2010.
43. Jaan Pärn. Landscape factors in material transport from rural catchments in Estonia. Tartu, 2010.