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THE INFLUENCE OF THERMAL SHOCK AND PRE-SPROUTING ON FORMATION OF YIELD STRUCTURE ELEMENTS IN SEED POTATOES

TERMOŠOKI JA EELIDANDAMISE MÕJU KARTULI SEEMNEMUGULATE SAAGISTRUKTUURI ELEMENTIDE KUJUNEMISELE

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LIST OF ORIGINAL PUBLICATIONS

This thesis is a summary of the following papers, which are referred to by Roman numerals in the text. All papers are reproduced with due permission from publishers.

I Eremeev, V., Lõhmus, A., Lääniste, P., Jõudu, J., Talgre, L., Lauringson, E. 2007. The influence of thermal shock and pre-sprouting of seed potatoes on formation of some yield structure elements. *Acta Agriculturae Scandinavica, Section B - Plant Soil Science* (in press).

II Eremeev, V., Jõudu, J., Lääniste, P., Mäeorg, E., Makke, A., Talgre, L., Lauringson, E., Raave, H., Noormets, M. 2007. Consequences of pre-planting treatments of potato seed tubers on leaf area index formation. *Acta Agriculturae Scandinavica, Section B - Plant Soil Science* (in press).

III Eremeev, V., Jõudu, J., Lääniste, P., Mäeorg, E., Selge, A., Tsahkna, A., Noormets, M. 2007. The influence of thermal shock and pre-sprouting of seed potatoes on formation of tuber yield. *Spanish Journal of Agricultural Research* (in press).

IV Eremeev, V., Lõhmus, A., Jõudu, J. 2007. Effects to thermal shock and pre-sprouting of field performance of potato in Estonia. *Agronomy Research*, 5(1): 21–30.

V Eremeev, V., Jõudu, J., Lõhmus, A., Lääniste, P., Makke, A. 2003. The effect of preplanting treatment of seed tubers on potato yield formation. *Agronomy Research*, 2(1): 115–122.

ABBREVIATIONS

a.i.	active ingredient
CA	chronological age
DAP	day after planting
LAI	leaf area index
LSD$_{05}$	least significant differences
PA	physiological age
PAR	photosynthetically active radiation
P$_S$	pre-sprouting
RH	relative humidity
T$_0$	untreated variant
T$_S$	thermal shock

INTRODUCTION

The 1990 growing area of potato in Estonia was 45,500 ha (Statistics Estonia, 2003). Since then the growing area has suffered a remarkable decline to 30,900 ha in 2000 and to 10,200 ha in 2007 (Statistics Estonia, 2007). Concomittent to this decline has been the increase in imported potato which in recent years has reached 10–20 thousand tons per year.

The average consumption of potato, as foodstuff, per capita in developed countries, is usually 60–80 kg per year. Although the average consumption per capita of potato in Estonia has decreased by 28 kg, the annual figure remains in the 97–103 kg range (Statistics Estonia, 2003).

Global potato consumption trends indicate that consumers prefer locally grown tubers because of their freshness and taste. In order to satisfy the demand for locally grown potato, scientists are investigating the best agrotechnical measures to obtain high quality yield and to maintain the marketability and nutritional quality of potato throughout the storage and consumption period (Essah and Honeycutt, 2004; Struik, 2006).

The quality of seed tubers is affected by numerous factors, which depend mainly on the cultivar characteristics, environmental conditions and the effectivency of the plant protection measures used during growth and storage (Struik and Wieserma, 1999). Some of the most important quality indicators include: authenticity of the cultivar, tuber health and uniformity in the size of the seed tubers treated before planting (Wurr, 1974; Barry *et al*., 1990; Strange and Blackmore, 1990).

Various growing schedules are used in order to ensure the full maturation of different cultivars and especially late ones, but the sum of active temperatures in Estonia often remains low. At the same time it is vitally important for farmers to market the early potato as early as possible (Tartlan, 2000; Essah and Honeycutt, 2004). Yield increases of late potato cultivars are usually negatively affected by broad infestation of diseases, such as *Phytophthora infestans* (Mont. de Bary) and *Alternaria Solani*, occurring before full maturation. Therefore, measures to shorten the growth period of potato should be implemented, especially for seed potato cultivation.

Different methods are used to achieve an earlier potato yield, including the thermal treatment of seed tubers, which adds physiological age (PA) to the tubers and shortens the chronological time that is necessary for the tuber yield to become harvest-ripe (Allen *et al*., 1992; Struik and Wiersema, 1999; Caldiz *et al*., 2001; Essah and Honeycutt, 2004). This method boosts enzyme activity in tubers, stimulates faster development of sprouts from the eyes, reduces the sprouting period and accelerates plant development and tuber yield formation. The leaf area and tuber yield of potatoes may vary. After the breaking of dormancy, the seed tuber goes through different phases: apical dominance, normal sprouting, production of branched sprouts, senility and incubation (little tuber formation) (Schrage, 1999). Crops grown from seed tubers in different phases differ in canopy structure, tuber number, yield, tuber size distribution and quality (Ewing and Struik, 1992; Struik and Wiersema, 1999). If seed tubers are kept at a higher temperature for some time in spring, then the result is physiologically older tubers are achievable (Struik *et al*., 2006). An economically optimal tuber yield can also be harvested earlier. However, physiologically younger plants can be more viable and even form a higher tuber yield, although this will occur slightly later. The PA of the tuber affects not only the number of sprouts and the sprout behaviour, but also the growth pattern of the plant that originates from it and thus sometimes the tuber yield of the crop produced from it (Van der Zaag and Van Loon, 1987; Panelo and Caldiz, 1989; Caldiz, 1991). In considering these aspects, it should be kept in mind, that once sprouts are formed on a seed tuber during storage, not only the PA of the seed tuber is relevant, but also the physiological status of the sprout itself (Struik and Wiersema, 1999).

Potato cultivars, which are able to provide high quality yields as early as possible in order to be market competitive are vital. Accumulated temperature, precipitation and radiation during the vegetation period favour the growth of early cultivars rather than late cultivars. Biologically active and potentially high-yielding seed must be prepared for planting according to the end usage. The pre-sprouting of seed tubers of early as well as late potato cultivars is, among the yield-increasing pre-planting measures, widely used in the Netherlands (Struik and Wiersema, 1999). Late-maturing cultivars are beneficial because of their higher yield potential and also their ability to maintain nutritional quality during storage (Struik, 2006). Another technique used for obtaining earlier yield is thermal treatment (otherwise known as thermal shock), which increases the PA of seed tubers and shortens the chronological time needed for the formation of harvestable tubers (Reust, 1986; Allen *et al.,* 1992; Van der Zaag, 1992a; Struik and Wieserma, 1999).

Only a few studies have addressed the research complexities of the influences of different methods of pre-planting treatments on the dynamics of tuber yield, the weight of the haulms, leaf area, the number of tubers per plant and the average weight of each tuber.

Previous pre-planting treatment methods needed some modifications to prevent the mechanical damaging of sprouts. The effectiveness of different pre-sprouting methods depends also on the prevailing climate conditions. Therefore many methods developed throughout the world may not be viable in Baltic weather conditions and with local cultivars.

I have focused my research at the Department of Plant Production at the Plant Biology experimental station of the Estonian University of Life Sciences (EMÜ), on the effects of seed tubers with different ages on the different parts of a potato plant. If the seed tubers are kept for certain time at higher temperatures before planting, physiologically older tubers are obtained (Lõhmus *et al*., 1999). This ageing of tubers is important for growing early or late potato cultivars because both the maximum weight of the haulms and the leaf area index (LAI) are attained faster and makes possible a much earlier harvest of the economically optimal tuber yield.

1. REVIEW OF THE LITERATURE

1.1. Physiological age of the seed potato and the effect on tuber yield

Physiological age is a well-known limiting factor in potato production (Caldiz and Gaspari, 1997). The PA of the seed tubers affects future crop performance, i.e., emergence rate, percentage of emergence, number of emerged stems per mother tuber, time to tuber initiation, crop vigour and growth, dry matter distribution and tuber yield (Vakis, 1986; Van Loon, 1987; Moll, 1994; O'Brein *et al*., 1998; Christiansen *et al*., 2006). The PA of a tuber at any given moment of its life depends on its chronological age (CA), measured from the date of its formation on the mother plant, and on the temperature conditions to which it has been subjected during growth and storage (Perennec and Madec, 1980). There have been numerous studies into the relationship between different cultivars and the effects of different environments, crop management, crop husbandry, and storage systems upon the PA of seed tubers, as measured by different biological (Hartmans and Van Loon, 1987; Wiersema and Booth, 1985; Van Ittersum *et al.,* 1990; Bohl *et al*., 2003; Knowles *et al*., 2003), biochemical (Reust and Aerny, 1985; Van Es and Hartmans, 1987; Biotto and Siegenthaler, 1991; Bohl *et al*., 1995; De Weerd *et al*., 1995; Bachem *et al*., 2000), or physical parameters (Scholte, 1987; Francl, 1989). Since the seminal work of Krijthe (1962), other researchers considered the possibility of using sprouting capacity as a measure of PA (Wurr, 1980; O'Brein *et al.,* 1983; Hagman, 2006). These studies have shown that genetic differences exist in cultivars' reactions to physiological aging when measured by sprouting capacity.

Environmental factors during storage affect PA and thereby sprouting capasity. Relevant factors include relative humidity (RH), temperature, photoperiod and diffuse light, of which temperature is a key effect being both highly complex and cultivar specific. As the metabolic processes and physiological events that occur before and after dormancy vary, the sensitivity of tubers towards environmental conditions, especially temperature, during the different stages of physiological development may also differ (Scholte, 1987; Struik and Wiersema, 1999; Struik *et al*., 2006). Heat shocks, cold shocks, and similar accumulated day-degrees achieved in different ways may all have their specific effects, depending on the cultivar (Van Ittersum, 1992; Struik and Wiersema, 1999; Struik *et al.*, 2006).

The other biological parameter widely used to measure PA is the length of the incubation period. This period, defined as the period between sprouting and new tuber formation on the sprouts, is also an important biological indicator of the PA of a seed tuber and can be used to indicate approximately the beginning end of the maximum growth vigor of a cultivar (Van Der Zaag and Van Loon, 1987; Van Ittersum *et al.*, 1990; Van Ittersum, 1992; Struik *et al.*, 2006). The duration of the incubation period has a direct influence on the tubers' sensitivity to physiological aging – longer results in a reduction while shorter leads to an increase in sensitivity. Moreover, this period is modified by temperatures during the bulking period of the seed and can, to a certain extent, determine yield (Caldiz, 1991).

Potato plants have an indeterminate growth pattern. Quantifying above and below-ground plant phenology in relation to different environmental factors (Ojala *et al.*, 1990) and cultivars (Van der Zaag *et al.*, 1990) is an important step toward an adequate understanding of potato growth and development. This quantification has been conducted in only a few environments, especially in relation to pre-planting thermal shock (T_S) and pre-sprouting (P_S) treatments (Jõudu *et al.*, 2004).

The PA is defined as the physiological status of a tuber that influences its productivity but could also be defined as the developmental level which has been modified by varying the CA (Caldiz *et al.*, 2001). The PA of a tuber is its CA that has been affected by storage conditions (Reust, 1986; Struik and Wiersema, 1999; Coleman, 2000).

Effects of PA differ between cultivars (Struik and Wiersema, 1999; Asiedu *et al.*, 2003) and are important because seed tubers are planted in different zones of the same country or are shipped to overseas areas with double or triple cropping, resulting in different age requirements (Fahem and Haverkort, 1988; Struik and Wiersema, 1999). Seed age can be modified by crop and storage management to make it suitable for different conditions (Van Ittersum *et al.*, 1993). There is general agreement that younger seed produces high yields in long growing seasons, while older seed is suitable to obtain high yields early in the season or in short cycle seasons (Wurr, 1979).

Yield of potatoes is related to several other characteristics of the crop, such as the duration of crop growth, the time of maturity and harvest, the plant density, the number of plants, and the weight of individual tubers (Sawant *et al.*, 1991). Most authors agree that the yield of physiologically older seed is markedly higher than that of younger seed, if harvested prematurely (Bean and Allen, 1980; Van der Zaag and Van Loon, 1987; Jõudu *et al.*, 2004; Mustonen, 2006). This agrees with the relationship between PA and yield suggested by O'Brein *et al.*, (1983), for progressively later harvests.

However, there is less agreement on the effect of PA on final tuber yields. Several authors have found lower final yields with physiologically old seed than with young seed (Iritani, 1968; Reust, 1986). There is some confusion as to whether these lower yields are a result of reduced plant vigour or of a reduced light intercepting capacity due to open spaces caused by seed tuber that have not emerged (e.g. because of 'little potato') or of a low number of stems per unit area. Other researchers found almost no effect of PA on final yield (Essah and Honeycutt, 2004). Yield differences between physiologically young and old seed might also depend on cultivar, length of the growing period and on climatic conditions because yield depends on the amount of foliage and of intercepted light, on the photosynthetic activity of the foliage and on the length of the vegetative period. Not only does older seed often emerge and initiate tubers early but also produces plants with a small maximum leaf area and early senescence. The accelerated emergence of tubers from old seed usually aids the plant's growth because the vegetative period is advanced and therefore benefits from the better water supply and higher light intensity earlier in the season (O'Brein *et al.*, 1983; Christiansen *et al.*, 2006).

Moll (1985) found that the final yield of early cultivars grown from old seed was lower than their final yield when grown from young seed, because of the reduced amount of foliage. Young seed gave better haulm development. Later cultivars, however, tended to give higher yields from old seed, because of early emergence and consequently more available light and water.

Studies have been conducted on the variation between yields and sites on the effect of PA of the seed to its response to climatic conditions (Perennec and Madec, 1980; O'Brein *et al.*, 1983; Johansen *et al.*, 2002; Christiansen *et al.*, 2006). Unfavourable weather conditions at the time of emergence will increase the effect of PA on final yield, because of the occurrence of 'little potato' in physiologically old seed. If the growing conditions later in the season are unfavourable, the crops from young seed will produce lower yields then crops from old seed. O'Brein *et al*., (1983) found that increasing age often increased yields at early harvests, but decreased them later. O'Brein *et al*., (1983) attributed the rate of change to effects of age on plant size and leaf area and to the prevailing moisture and light conditions and noted that the absence of moisture stress minimized the effects of age on LAI and yield.

Maturity in conjunction with date of planting determines the length of the growing season and is therefore a major agronomic trait. The longer the crop cycle, the more radiation can be intercepted, the higher is the yield (Allen and Scott, 1992). Compared with late cultivars, early potato cultivars divert a large part of the available assimilates to the tubers early in the growing season, leading to shorter growing periods and lower yields (Kooman and Rabbinge, 1996; Haverkort and Kooman, 1997). Thus, in principle, late cultivars are expected to have greater yields (Howard, 1963) and are therefore more desirable as a crop (Ewing and Struik, 1992). However, the fitness of a certain cultivar to be grown in a given climatic environment is for a great deal dictated by the earliness of maturation.

1.2. Leaf area as the basis of yield formation

Potato yield is strongly affected by the size of the leaf area and the duration of photosynthesis (Van Oijen, 1991; Boyd *et al*., 2001). The duration of photosynthesis is influenced by agro-climatic conditions and agrotechnics, e.g. night frosts can shorten the duration of photosynthesis. Rapid emergence (i.e., the formation of optimum-sized leaf area) and maintaining the plant's productivity for as long as possible are vital for obtaining high potato yields (Marschner, 1995; Van Delden, 2001). However, early development is also associated with the earlier senescence of the leaves (Allen *et al*., 1979; O'Brein *et al*., 1983). Plants that have emerged earlier have the benefit of using more sunlight. The rate of photosynthesis decreases with senescence because the respiration rate in young leaves is higher than in older leaves. The rate of photosynthesis is highest in leaves that have just reached their maximum leaf area but this rate declines in leaves older than 50 days (Van der Zaag, 1992a) and the ageing process progresses more rapidly at higher temperatures. Plants from P_S tubers develop faster and reach their maximum leaf area earlier but their leaves are also ageing more rapidly.

The rate of photosynthesis depends on the leaf area, which itself depends on the growing conditions and cultivar. These conditions and cultivars may vary widely and consequently the leaf areas of potato cultivars differ by a magnitude of three (Reich *et al*., 1998). However, a larger mass of top leaves (canopy) may be an indicator of a larger leaf area, a higher rate of photosynthesis or a higher yield only when the leaves are not overshadowed and all the necessary components are provided. Unilateral nitrogen fertilization significantly increases the weight of the haulms of the potato plant as well as the leaf area (Grindlay, 1997) and also reduces the effects of diseases and weeds (Jornsgard *et al*., 1996; Möller *et al*., 1998). The vigorous growth of haulms or the density of the plants after canopy closure will cause overshadowing of many of the leaves, especially those on the lower section of the plant (Tooming, 1977; Tooming, 1984). Under sufficient light intensity 320 µmol m^{-2} s^{-1} (Struik and Wiersema, 1999), the processes of photosynthesis and respiration in a plant are in balance. As light intensity decreases, a greater number of the lower leaves switch from net producers to net consumers of photosynthetic products. The production of organic matter from the whole plant therefore decreases and the tuber yield may be negatively affected.

Leaf area index indicates the ratio of the assimilative area of the leaf and the surface area (Watson, 1947). For optimal photosynthetic rate it is necessary that LAI should be over 4.0 for as long a period as possible, otherwise the use of photosynthetically active radiation (PAR) and thus the production of organic matter, decreases (Scott and Wilcockson, 1978; Allen and Scott, 1980; Khurana and McLaren, 1982).

Several plant deseases affect the photosynteticlli active leaf area. For example in Estonian climatic conditions, in 8 out of 10 years, late blight will cause significant yield loss. Resistance against potato late blight is less important for early cultivars, because these will mainly form yield before any large-scale spread of the disease (Koppel, 2001). The same climatic conditions that contribute to the rapid development of potato tubers, favour also the distribution of late blight. The use of fungicides to control late blight is still at a high level as the population of *Phytophthora infestans* (Mont. de Bary) has shown an increase in virulence (Smart and Fry, 2001; Fry *et al*., 2001), adaptability (Allefs *et al*., 2005) and resistance to some biocides (Cooke and Deahl, 2005).

1.3. Number of tubers

Tuber formation is a complex physiological phenomenon (see e.g. review by Vreugdenhil and Struik, 1989; Ewing and Struik, 1992; Jackson 1999). Tuber formation usually takes place in a short period of time (one or two weeks), but the duration of this period depends on the maturity class of the cultivar. Moreover, the period between the start of tuberisation and the onset of rapid tuber bulking is also variable. Often there is little correlation between final tuber size and its time of initiation (Struik *et al*., 1991; Struik, 1991).

The number of tuber set by plants is determined by stem density, spatial arrangement, cultivar and season (Wurr *et al*., 2001). There are strong relationships between tuber yield and stem density (Bleasdale, 1965; Jarvis, 1977) and between tuber yield distribution in different size grades and stem density (Wurr, 1974). Thus, control over stem numbers is a fundamental requirement if growers are to control tuber size to meet market requirements. While it is known that the number of stems produced can be affected by the origin of seed (O'Brein and Allen, 1986; Gill and Waister, 1987) and cultural factors during seed production (O'Brein and Allen, 1992) there seems to be little explanation of exactly why this occurs. The likliest reasons are morphological differences between seed lots, inherent physiological differences in tuber dormancy and apical dominance or because of effects imposed between sprouting and stem emergence in the field.

The best way of manipulating tuber number is by manipulating seed rate, size of the seed tubers and their PA. Storage conditions and P_S treatments strongly influence the number of tubers per plant (Struik and Wiersema, 1999). Wurr (1979) suggested that differences in tuber number for different genotypes do not result from a difference in the number of potential tuber sites, but from some control over tuber initiation. Struik *et al*., (1990) claimed that tuber set, rather than tuber initiation, determined total tuber number. After the tubers have been set, the growth into various size grades is the result of competition among the tuber settings and growth rate of the individual tubers (Struik *et al*., 1990; 1991).

2. THE HYPOTHESIS AND AIMS OF THE STUDY

The hypothesis for this research experiment is that a short-term high temperature treatment of seed tubers of potato cultivars with various length of growing period has an influence on the LAI, weight of the haulms, tuber number per plant and tuber weight development and tuber size.

The aims of the present research are to discover:
(1) how thermal shock and pre-sprouting influence the development of the different parts and characteristics of a potato plant (tuber yield, the weight of the haulms, leaf area, the number of tubers per plant and the average weight of each tuber) for ensuring the formation of a large high quality tuber yield as early as possible in Baltic weather conditions.

(2) whether there is any possibility of replacing the long and energy-consuming pre-sprouting treatment period with the shorter, more energy efficient thermal shock treatment.

3. MATERIAL AND METHODS

3.1. Experimental site and design

The experiment was carried out during the 2000–2002 growing seasons at the Department of Plant Production at the Plant Biology experimental station (58°23′N, 26°44′E) of the EMÜ. Random block placement in four replications was used (Hills and Little, 1972). The size of a test plot was 21 m^2. The distance between seed tubers was 25 cm and distance between furrows 70 cm. Seed tubers with a diameter of 35–55 mm were used in the experiment. The dynamics of the tuber yield, the weight of the haulms, leaf area, the number of tubers per plant and the average weight of each tuber were determined with an interval of 3–5 days and each sample consisted of four plants from the test plot.

3.2. Plant material

The late cultivar 'Ants' and the mid-maturing cultivar 'Piret', both bred at the Jõgeva Plant Breeding Institute in Estonia, and the early cultivar 'Agrie Dzeltenie', bred at Latvia's Priekuli State Plant Breeding Station, were used in the experiments. These cultivars were chosen because local cultivars are better adapted to Estonian climatic conditions and are, therefore, able to give reasonably high yields of good quality tubers.

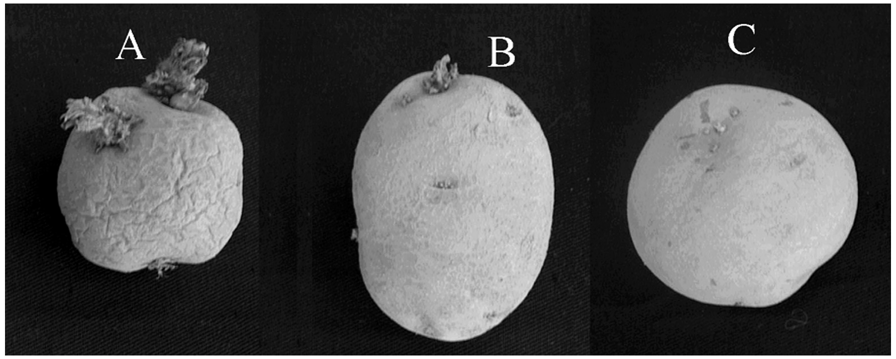
3.3. Pre-planting treatments

Until the 30th of March all seed tubers were kept in the same conditions in a storage room where the temperature was kept at 4°C. Seed tubers were treated before planting as follows:

1. Untreated variant (T_0) – the seed tubers were stored in darkness at a temperature of 4°C (C in Photo 1). An additional 148 degree days (the average accumulation of the three experimental years) was applied to this variant from March 30th until planting.

2. Thermal shock (T_S) – the seed tubers were stored in darkness at a temperature of 4°C. A week before planting the tubers were kept in a brightly lit room for two days at 30°C and then a in a dimly lit room for a further five days at 12°C (B in Photo 1) (Lõhmus *et al.*, 1999; Eremeev, 2000). An additional 240 degree days (the average accumulation of the three experimental years) was applied to this variant from March 30th until planting. Compared to the tubers from a cellar, strong (3–4 mm) sprouts appear on the tubers treated with T_S. Under certain conditions the T_S treatment may be less labour and energy-consuming than P_S, for example by using thermo-regulated storehouses (Jõudu *et al.,* 2002).

3. Pre-sprouting (P_S) – the seed tubers were stored in darkness at a temperature of 4°C, then 37 days before planting were kept in a sufficiently humid (85–90% RH) and in a dimly lit room at 12°C. (A in Photo 1). Seed tubers were P_S in wooden boxes (in one or two layers). An additional 444 degree days (the average accumulation of the three experimental years) was applied to this variant from March 30th until planting.



A – pre-sprouted, B – thermal shock, C – untreated variant

Photo 1. Seed tubers after treatment

3.4. Agrotechniques of experimental field

Agromonic measures were typical for potato experiments. Composted manure (60 t ha^{-1}) before autumn ploughing was used as organic fertilizer. Mineral fertilizers were applied locally at the same time as planting of potatoes in the spring. In 2000–2002, a compound mineral fertilizer (78 kg N, 72 kg P, 117 kg K ha^{-1}) was applied at planting.

For plant protection, the insecticide Fastac and fungicides Ridomil Gold, Acrobat Plus and Shirlan were used. The insecticide Fastac 50 (BASF Ag, Germany) had the active ingredient (a.i.) alpha-cypermethrin 100 g l^{-1}. The fungicide Ridomil Gold MZ 68 WG (Syngenta, Switzerland) contained Mankozeb (64%) and metalaksyl-M (4%) as a.i. Acrobat Plus (BASF Ag, Germany) contained dim ethomorph 90 g kg^{-1} and Mankozeb 600 g kg^{-1} for a.i. Shirlan 500 SC (ISK Bioscience Europe S.A, Belgium) contained the a.i. fluazinam 500 g l^{-1}. All a.i. for plant protection were used with 400 litres of water per ha.

3.5. Measurements

LAI was determined at 3–5 day intervals. Each sample consisted of 4 plants from the test plot. The time of sample collection, and the number of samples collected, varied among treatments and years due to differences in emergence dates and durations of the vegetative period (e.g., in 2001 the vegetation period was lengthy, lasting 118 days).

Leaf area can be measured in various ways including portable devices (Gordon *et al*., 1994; Lusk, 2002; Veteli *et al*., 2002) or manual methods (Tammets *et al*., 1989; Haverkort *et al*., 1991; Burstall and Harris, 1983; Khurana and McLaren, 1982). The so-called 'copy-method' was selected for determining the leaf area in this research experiment. The weight of the haulm and leaves of the sample plants were weighed together. Randomly selected leaf segments were then scanned at 100 dpi resolution and saved as black-and-white Windows Bitmap images (*.bmp). A special software program written by the Department of Botany EMÜ was used to calculate the areas of the scanned leaves.

3.6. Meteorological conditions

The Estonian climate is a transition climate from maritime to continental. It is mainly influenced by the Baltic Sea and the north-eastern part of the Atlantic Ocean. Year-round intensive cyclonic activity causes moist and continuously changing weather conditions. Summer is relatively short and cool, autumn is long, and winter mild. The vegetation period (average diurnal temperature continuously above 5°C) begins usually in the second half of April, lasts 170–180 days and ends in September or October. The period of active plant growth (average diurnal temperature continuously above 10°C) ranges usually from 115 to 135 days (Tarand, 2003). The experimental area belongs to the south Estonian upland agroclimatic region, where the sum of active air temperatures of the year is on average 1750–1800°C and total precipitation is 550–650 mm (Timothy and Granscog, 2001).

During the trial years, in the vegetation period (from May to September) the amount of precipitation was greater than average in June and July, and less than average in May, August and September (Table 1 in **I**). Air temperature remained similar to that of the average of 32-years (1966–1998); only July was significantly warmer.

3.7. Soil conditions and analysis

The soil of the experimental field was *Stagnic Luvisol* by World Reference Base for Soil Resources 1998 classification with a texture of sandy loam and a humus layer of 20–30 cm (Reintam and Köster, 2006). This is considered to be the very suitable soil for potato cultivation in Estonia (Viileberg, 1986). When using the 10-level scale, (0–10 points), such soil can be given 9 points for potato cultivation (Kõlli and Lemetti, 1999). Soil analyses were carried out at the laboratories of the Department of Soil Science and Agrochemistry, EMÜ. Air-dried soil samples were seeved through a 2 mm sieve. The following characteristics were determined: pH (in 1 *M* KCl and in 0.01 *M* $CaCl_2$ 1: 2.5 w: v); organic carbon by Tjurin, Ca and Mg in NH_4OAc at pH 7 (Soil Survey Laboratory Staff, 1996), P and K after the Mehlich-3 method (Handbook on Reference Methods for Soil Analysis, 1992). The Kjeldahl method was used to determine the content of total N of the soil (Procedures for Soil Analysis, 1995).

The soil data of the humus layer of the experimental field were as follows: pH ≈6.2; C, 1.4%; Ca, 674 mg kg^{-1}; Mg, 101 mg kg^{-1}; P, 183 mg kg^{-1}; K, 164 mg kg^{-1}; N, 0.11%; 56% sand; 35% silt and 9% clay.

3.8. Statistical analysis

Regression analysis was conducted using the following formula: $y = a + bx + cx^2$; where 'y' is the argument function – tuber yield, the weight of the haulms, LAI, the number of tubers per plant or the average weight of a tuber, 'a' is the constant term of the equation, 'b' and 'c' are regression coefficients and 'x' is the argument, the number of days after planting

(DAP). The derivative of the given function (*b* – *2c*) indicates the increase of value calculated according to the formula for each following day.

For every variant, separate regression formulas were found, and based on their differentials, it was possible to calculate the average formulas for multple years. Standard errors (SE) and confidence limits (CL_{05} – level of statistical significance $p = 0.05$) were calculated. The calculation of confidence limits was based on Student's theoretical criterion (Mead *et al.,* 1993).

To assess the probability of differences between the three treatments, the three potato cultivars and the three-year average, the least significant differences (LSD_{05}) were calculated. Statistica 7 (Statsoft Inc, 2005) was used for the statistical analysis. Vertical bars denote confidence intervals at 95% probability.

Correlation analysis was used to study correlation between different parts of potato plants and pre-planting treatment of seed tubers. Linear correlation coefficients between variables were calculated, the significance of coefficients being $p<0.001$, $p<0.01$, $p<0.05$, NS = non-significant ($p>0.05$).

The results are expressed as not only a three-year average but also for separate seasons to indicate the effect of years.

4. RESULTS AND DISCUSSION

4.1. The emergence of potato plants

Physiological aging advanced sprout growth, crop emergence, crop establishment and usually improved tuber yield (Burke and O'Donovan, 1998; Van der Zaag and Van Loon, 1987; Caldiz *et al*., 2001). Transition of developmental stages and their duration is often quite different. It depends on the biological characteristics of a cultivar, quality of seed potato, climatic and soil conditions and also agronomic measures used (Kuill, 2002; Christiansen *et al*., 2006). Some authors have found that physiologically older seed has a faster emergence than younger seed (Iritani, 1968; O'Brein *et al.,* 1983), others have found no difference (Bus and Schepers, 1978). Van Loon (1987) showed experimentally that the physiologically older seed emerged more slowly in all years. In our experiments the physiologically older seed emerged faster in all years (Figure 1 in **IV**). It usually takes 20–35 days for a potato plant to emerge in Estonian climatic conditions (Jõudu *et al*., 2002), depending on the treatment of seed tubers.

Earlier studies at the Department of Plant Production indicated that P_S and T_S increased the PA of seed tubers and initiated earlier emergence (Jeremejev *et al*., 1998; Jeremejev *et al*., 1999; Lõhmus *et al*., 1999). Plants from seed tubers of late cultivars treated with T_S emerged 1–4 days earlier than T_0 plants (Jeremejev *et al*., 1998; Jeremejev *et al*., 1999; Eremeev *et al*., 2001) whereas seed tubers of early cultivars treated with T_S emerged 1–7 days ealier than T_0 plants (Säga, 2000). In present study, the preplanting treatment of seed tubers ensured earlier field sprouting in the T_S variant by 2–5, and in the P_S variant by 7–12, days earlier than in vatiant T_0 (Figure 1 in **IV**). Thermal shock had a positive effect on potato plant during its early developmental phases (Eremeev *et al*., 2005a). The length of periods from planting to emergence depended on the PA of seed tubers (Struik and Wiersema, 1999). The faster growth of the haulms of the plants that developed from thermally treated seed tubers provided furrow coverage nearly a week earlier, as a result of which the last interrow tillage could be omitted at just the critical time when there were very favourable conditions for the growth of weeds.

4.2. The effect of preplanting treatment of seed tubers on formation of some yield structure elements

4.2.1. Weight of the haulms

The pre-planting treatment of seed tubers (P_S and T_S) accelerated the development of the haulms, and the weight of the latter was higher than in variant T_0 up to 50 DAP (Figure 1 in **I**). The weight of the haulms reached its maximum in variant P_S by 76 DAP, in T_S by 77 DAP and in T_0 by 81 DAP (Figure 1 in **I**). The later the maximum weight of the haulms was achieved, the bigger it was because the visible signs of ageing appeared earlier in physiologically older plants. Thus, the maximum weight of the haulms in variant T_0 was 31.9 t ha^{-1}, exceeding P_S and T_S, respectively, by 4.2 and 2.9 t ha^{-1} (Figure 1 in **I**). Therefore, the weight of the haulms in plants formed from physiologically older seed tubers developed faster and was lower.

Both P_S and T_S had a stronger effect on the deevelopment of the weight of the haulms in cultivars with a longer growth period. 'Ants' achieved the maximum weight of the haulms in thermally treated variants (P_S and T_S) 7–8 days earlier than in T_0. It occurred in 'Piret', five days earlier and practically at the same time as 'Agrie Dzeltenie' in all variants.

Thus, the weight of the plant haulms developed from physiologically older seed tubers, formed more quickly and remained lower. Pre-planting treatment of seed tubers (i.e., increasing the PA) gave earlier field emergence. The later the potato plants attained the maximum weight of the haulms, the higher it was. In physiologically older plants obvious signs of senescence started to appear earlier (partial wilting and yellowing of the lower leaves). According to Putz (1986), after the death of the haulms, growth of tubers ceases, the skin hardens and starts to tuberizate.

There were positive correlations between the weight of the haulms and the LAI and the number of stems, both as the average for all experimental variants ($r = 0.95$; $p < 0.001$ and $r = 0.53$; $p < 0.001$) and at the level of cultivars and the pre-planting treatment of seed tubers. The number of tubers per plant ($r = 0.79$; $p < 0.001$) and the average tuber weight ($r = 0.45$; $p < 0.05$) increased with the development of the weight of the haulms.

4.2.2. Leaf area index

The dynamics of LAI depending on the year (II).
At the start of the growing cycle of the potato plant, the increase in LAI was highest in 2002 when the increase was statistically significant (LSD_{05} 0.3) until 55 DAP. Evidently the weather of this period of the growing season was most favourable for haulm growth. The LAI started to decrease slowly, after 55 DAP, because the soil water supply decreased and nearly reached wilting point. The haulms turned yellow and dried up. The LAI was lower (LSD_{05} 0.4) during the 2000 vegetation period, in the periods 45–50 DAP and 80–100 DAP, than compared to the average LAI of the three experiment years. This was due to the cool weather conditions during the vegetation period.

According to Jõudu and Roostalu (1999), 1% infection of the leaf area with late blight decreases potato yield by an average of 100–300 kg ha^{-1}. In the present experiment, the measures against late blight infection were very effective and in accordance with the disease's development throughout the whole growth cycle both the combined and contact fungicides were used. The same recommendations for potato late blight protection are proposed by scientists of the Plant Biotechnological Research Centre EVIKA (Särekanno *et al.*, 2004). In our experiment, the protection against late blight provided long-term preservation of the potato leaves and enabled us to investigate the development of the haulms until 110 DAP.

The good weather in 2001 was a significant factor in the highest LAI of the experimental years, from the period of 65 DAP (LSD_{05} 0.3) until the harvest. The value of LAI should be at least 3.0, in order to considerably reduce the evaporation from the soil surface, and this level of shadowing also reduces the amount of radiation into the soil by 95–98% (MacKerron and Waister, 1985).

Earlier experiments (Eremeev, 2000; Eremeev *et al.*, 2001) with late potato cultivars have shown that LAI reaches the maximum value (average 3.7 units) by 72 DAP, and then starts to decrease. The Norwegian scientist Eltun (1996) concluded that the maximum LAI was formed 68 DAP. Our experiment records that the highest LAIs were reached 68–81 DAP (**I**, **II**); in 2002 the maximum LAI (3.7 units) was attained at 68 DAP, in 2000 at 73 DAP (3.6 units) and in 2001 at 81 DAP (4.5 units). The weather conditions were most favourable for the growth of potato plants and development of the leaf area in 2001. The water supplies were sufficient in the period of intensive growth and tuber formation, and were also efficient protection against late blight, providing effective photosynthesizing foliage until the harvest.

The dynamics of LAI depending on the seed tuber treatment.
The pre-planting treatment of the seed tubers had a different effect on the leaf area formation of the different potato cultivars. The initial slower development of the T_0 variant caused the prolongation of its growing period. The LAI in T_0 variants could be determined until 110 DAP while the assimilative leaf area of treated variants was destroyed by 105 DAP (Table 2 in **II,** Figure 1 in **IV**). Jõudu *et al.*, (2002) indicate that plants developed from P_S tubers have a better ability to assimilate nutrients from the mother tuber. The pre-planting treatment of seed tubers (P_S and T_S) stimulated the development of the haulms and their weight exceeded the same characteristic of the T_0 variants until 60 DAP. Later on the weight of the haulms of the plants developed from the T_0 variant exceeded both T_S and P_S until the leaves perished. In the current experiment both of the pre-planting treatments of potato seed resulted in larger LAI.

The LAI maximum was reached, in all variants, 72–76 DAP (Table 2 in **II,** Figure 1 in **IV**). The maximum LAI in the variant P_S was achieved by 72 DAP (3.7 units), in T_S (3.8 units) and T_0 (4.1 units), respectively, by 73 and 76 DAP. The LAI of the P_S variant plants, starting from 75 DAP, was significantly (LSD_{05} 0.4) lower than in the T_0 variants and from 80 DAP in T_S variants (LSD_{05} 0.4).

The leaf areas increased most intensively in all variants at 40 DAP, whereas in the variants that sprouted later the increment of the LAI was bigger (in T_0 variant – 0.22 units, in T_S – 0.20 units, in P_S – 0.17 units per day) (Figure 1 in **IV**). After 40 DAP the increment of the LAI gradually decreased. All cultivars that were used in the experiment demonstrated relatively even speed of the growth of the LAI throughout the vegetation period.

Dynamics of LAI depending on the cultivar
Comparison of different potato cultivars indicated that from the start of the haulm development until 90 DAP, the LAI was quite stable in all variants (Table 3 in **II**). The earliest leaf development was observed in the early cultivar 'Agrie Dzeltenie': its LAI exceeded the mid-maturing

cultivar 'Piret' until 85 DAP (0.2–0.4 units) and the late cultivar 'Ants' until 70 DAP (0.1–0.2 units). The LAIs of 'Piret', from 95 DAP, and of 'Agrie Dzeltenie', from 85 DAP, were in comparison with 'Ants' statistically lower (LSD_{05} 0.4) (Table 3 in **II**).

Maximum LAI was attained by all cultivars 72–75 DAP. 'Agrie Dzeltenie' reached its maximum LAI (4.0 units) at 72 DAP, followed by the mid-maturing cultivar 'Piret' (3.7 units) and the late cultivar 'Ants' (3.9 units) at 74 DAP and 75 DAP, respectively. Thus, the difference between cultivars in attaining the maximum LAI was 1–3 days and 0.1–0.3 units.

Dynamics of LAI in 'Ants'
According to Putz (1986), rapid development and growth of assimilative leaf area occurs from emergence to the start of tuber formation. The pre-planting treatments of 'Ants' seed tubers had a different effect on the leaf area development. The T_0 variant of 'Ants' had a slow initial development which meant that the vegetation period was longer. The LAI at 40 DAP, of the T_0 variant and the T_S variant were 0.5–0.6 units lower than that of the P_S variant (Table 4 in **II**).

The LAI of all the T_0 variants could be determined at 115 DAP, whereas those for T_S and P_S variants the assimilative area had perished by 105 DAP. Plants developed from tubers treated with T_S had a smaller leaf area during the vegetation period in comparison with the T_0 variant. The P_S variant of 'Ants' had a higher LAI (LSD_{05} 0.4) until 45 DAP and then, from 70 DAP until the end of vegetation, its LAI was lower than for the T_0 variant.

All the variants of 'Ants' reached their maximum LAI, 72–79 DAP. The P_S variant reached maximum LAI (3.7 units) at 72 DAP, followed by the T_S variant (3.9 units) and the T_0 variant (4.3 units), at 74 DAP and 79 DAP respectively. Consequently, the optimum leaf area needed for the photosynthesis of 'Ants' in the T_S variant perished two days later than in the P_S variant and five days earlier than in the T_0 variant.

Dynamics of LAI in 'Piret'
The LAI of T_S (0.3 units) and P_S (0.7 units) variants of 'Piret' exceeded the T_0 variant at 40 DAP (Table 5 in **II**). Due to the fast initial development, the LAI of treated variants exceeded that of T_0 variants, from the

beginning of the vegetation until 60 DAP for T_S treatment and until 55 DAP for P_S.

All the variants of 'Piret' reached their maximum LAI value, 72–77 DAP. The P_S variant reached 3.5 units at 72 DAP, followed by the T_S variant's 3.7 units at 73 DAP, and the T_0 variant's 4.0 units at 77 DAP. The LAI subsequently decreased gradually on a daily basis due to the loss of leaves. This decrease was clearly observed in the T_S and P_S variants since they reached their maximum LAI earlier, by 4 and 5 days respectively, than the T_0 variants. The LAI of the T_S variant started to decrease from 85 DAP (LSD_{05} 0.6) and that of the P_S variant from 65 DAP (LSD_{05} 0.5) until the end of the vegetation period.

Dynamics of LAI in 'Agrie Dzeltenie'
As with other cultivars, the T_S and P_S variants of 'Agrie Dzeltenie' emerged earlier. The LAI of these two variants proved higher than the T_0 variant at the start of the vegetation period. The LAI of the T_S variant increased until 40 DAP (LSD_{05} 0.5) and the P_S variant until 45 DAP (LSD_{05} 0.6) (Table 6 in **II**). Moreover, P_S variant plants reached their LAI maximum (3.7 units) at 72 DAP, followed by the T_S variant (3.8 units) and at 73 DAP and the T_0 variant (4.1 units) at 76 DAP. The LAI of the thermally treated variants was subsequently lower than in the T_0 variants from 60 DAP in the T_S variants and from 65 DAP in the P_S variants. The lower LAI in the thermally treated variants could be explained by the fact that a plant uses a larger amount of energy for better development of its underground organs. The LAI, in all cultivars, was fairly stable from the start of haulm development until 90 DAP. As a three-years' average, maximum LAI (3.9 units) formed at 74 DAP and on the 50th day after emergence. In all variants of 'Agrie Dzeltenie', the LAI formed relatively steadily during the whole vegetation period, reaching its maximum 72–73 DAP. The maximum LAI of T_S variant (3.9 units) and P_S variant (4.0 units) were attained by 72 DAP and in the T_0 variant (4.1 units) by 73 DAP.

4.2.3. The number of tubers per plant

The number of T_S treated tubers significantly exceeded the number of tubers of the T_0 variants, until 60 DAP (Table 2 in **III**). At the same time the number of P_S treated tubers exceeded the 50–60 DAP numbers of tubers for the T_0 plants. The significant differences between the P_S and

T_0 treatments occurred on 50 DAP (LSD_{05} 2.2) to 55 DAP (LSD_{05} 1.6). In the period of 85–105 DAP fewer tubers in the case of T_S treatment were observed, LSD_{05} 1.4, than for P_S treatment. Based on the average results of the three-year experiment, T_S increased the number of tubers per plant from the start of tuber formation until the harvest (statistically significantly until 60 DAP). P_S increased the average number of tubers per plant until 55 DAP (statistically significantly until 55 DAP). The greatest number of tubers per plant occurred on average at 94 DAP; in P_S treatment the greatest numbers occurred at 93 DAP (12.6 tubers), followed by T_S (14.0 tubers) and T_0 treatment (13.2 tubers), at 94 and 95 DAP, respectively.

The cultivars 'Piret' and 'Agrie Dzeltenie' started to form tubers early but had a lower average number of tubers per plant compared to 'Ants' (**I**). In 'Agrie Dzeltenie' the maximum number of tubers was formed at 92 DAP (12.8 tubers), in 'Ants' (14.6 tubers) and 'Piret' (12.1 tubers), respectively, at 93 and 97 DAP.

The number of tubers per plant has strong correlation with the number of tubers in the tuber size fraction 35–55 mm ($r = 0.67$; $p < 0.001$) and in fractions over 55 mm and below 35 mm it is respectively $r = 0.47$; $p < 0.05$ and $r = 0.30$; $p < 0.05$.

Intensive growth of tubers begins when the above-ground parts of the plant have fully developed (LAI is at least 4). But different cultivars have significant variations (Putz, 1986). Tuber formation in early cultivars usually takes place earlier and their growth is much quicker than in late cultivars. Also the plants from physiologically older tubers of late cultivars begin their tuber formation slightly earlier (Van der Zaag, 1992b). T_S treatment increases the number of tubers if compared to P_S treatment (Table 2 in **III**), therefore, T_S treatment could be suggested for usage in seed-growing enterprises, as their main purpose is to obtain the maximum number of tubers from one plant. Similar findings were reported by Van der Zaag and Van Loon (1987) and Moll (1985).

4.2.4. Tuber weight

As the average of the three cultivars, P_S increased the formation of mean tuber weight during the vegetation period – LSD_{05} 4.9 (Table 3 in **III**).

T_S significantly decreased the mean tuber weight from 115 DAP to 120 DAP to the harvest, the interval of tubers weights were from 5.2 g to 6.1 g, respectively. The weight of the tubers, during the vegetation period, of the P_S treatment exceeded those of the T_0 treatment by 5.8 g to 11.6 g, ($LSD_{0.5}$ 4.9) and those of the T_S treatment by 4.4 g to 12.7 g, ($LSD_{0.5}$ 4.3).

The increment of the weight of tubers (as the average of 2000–2002) in P_S treatment exceeded the T_0 treatment by 0.21 g day^{-1} (Figure 1 in **III**). The single tuber average mass formation is significant from the 50 DAP. The single tuber average mass formation increase by P_S treatment exceeded the increase by T_0 treatment by 0.21 g day^{-1} on 55 DAP. The T_S treatment exceeds the T_0 treatment by 0.31 g day^{-1} from 50 DAP. The increment of single tuber average mass, in the case of T_S treatment, during the 50–120 DAP interval, exceeded the T_0 treatment by 0.10–0.19 g day^{-1}. The smallest rate of increment during the 50–100 DAP interval was observed in tubers that were treated by T_S.

The weight of tubers depends on the weather conditions and the available nutrients during tuber formation (Panelo and Caldiz, 1989; O'Brein *et al*., 1983). It also depends on the growth and development of leaves and branches, formation of assimilation products and their distribution between different parts of the plant, the rate of tuber formation and the time of perishing of haulms (Panelo and Caldiz, 1989). According to data presented by Burke (1997), the PA of tubers increases the average weight of tubers. In our experiment this effect was seen only in the P_S variant (Table 3 in **III**), while in the T_S variant the increase in the average weight of tubers could be seen until 75 DAP. The T_0 and T_S vatiants developed more slowly at the start, resulting in a longer vegetation period and the tubers did not reach their maximum weight by the time of harvest.

Based on the pre-planting treatments of seed tubers, only the P_S variant reached the maximum average tuber weight (77.6 g) by 120 DAP (Figure 3 in **I**).

By the time for harvest (**I**) the average tuber weight reached the maximum in variant P_S in 'Ants' by 116 DAP (69.6 g), in 'Piret' variant T_S by 117 DAP and variant T_0 by 120 DAP, with, respectively, 67.1 g and 71.1 g, in 'Agrie Dzeltenie' variant T_S by 114 DAP and variant P_S by 119 DAP (respectively, 66.3 g and 86.3 g).

According to Putz (1986), after the death of the haulms the growth of tubers ceases, the skin hardens and starts to suberizate. Decisions taken while planning the harvesting period should not be based on the data of years with optimum weather conditions but the average years. At the end of vegetation period the increase of the average weight of the tuber occurred mainly at the expense of the average size tuber (35–55 mm) and large tubers (over 55 mm).

4.2.5. Tuber yield

Tuber formation is a complex process including the emergence and growth of stolons and the development, growth and ripening of tubers at their top as a result of the accumulation of nutrients (Ewing and Wareing, 1978; Jackson, 1999). Stolons are horizontal sprouts that emerge from the basal bud of the stem in the ground. The buds that develop stolons emerge at the second stage of organogenesis. There are two morphostructure types at this stage during the realisation of morphogenetic information: sprouts specialising in vegetative reproduction (stolons) and duplicate structures (shoots above the ground) (Markov and Maslova, 1998). Due to the influence of the mother tuber, the potato plant is relatively autonomous for some time after emergence and depends on external conditions less than many other crops (Kadaja and Tooming, 2004).

PA is very important for the development of the tuber yield (Ewing and Struik, 1992; Struik and Wiersema, 1999). A physiologically older seed accelerates the growth rhythm of potatoes, due to which the yield develops earlier, while the yield formation ability decreases (Caldiz *et al*., 1996). The results also show that the earlier the cultivar, the greater the effect of treatment and that the yield develops evenly during the vegetation period in cultivars with longer growth period. Thus, both P_S and T_S increase the PA of tubers to some extent.

The dynamics of tuber yield depening on the year
The dynamics of potato yield formation is significantly influenced by weather conditions. The first experimental year (2000) was chillier than the other two. The air temperature sum during the vegetation period was 1715.5°C (which is more than 200°C lower than in the following experimental years). The sum of active temperatures was 555.6°C. This sum varied greatly in the three experimental years. Thus, in the vegeta-

tion period of 2001 it was 186.7°C higher and in 2002 it was 295.2°C higher than in 2000. While the air temperature sums in 2001 and 2002 were practically equal, the sum of active temperatures was 108.5°C higher in 2002. Tamm (1982) believes that potato needs 230.5 mm of rainfall during the vegetation period. This figure was exceeded in 2000 and 2002 (116.6 mm and 84.8 mm respectively). However, during the vegetation period of 2001 there only was 162.4 mm of rainfall. The time distribution of rainfall was different in all the three years. Only 66.9 mm of rain fell during tuber formation and in the active growth period (July–September) in 2002 and a significant part (65.7%) of the rain in 2001 fell during the same respective period. In 2000 most of the rain (68.5%) fell in the period from the last ten days of June to the first ten days of August, i.e., from tuber formation to the beginning of the active growth of the tubers.

To sum up the weather conditions, the most favourable year for the growth of potatoes was 2001. It was relatively warm and the plants received enough water during tuber formation and intensive growth, whereas the efficient blight control ensured an actively working leaf surface until harvesting.

The above findings are also shown in Table 2 in **V** comparing the yields in different years. During the early tuber formation period the yield was highest in 2002 (50–65 DAP) since the weather was then most favourable for potato growth. From 80 DAP to harvesting, the yield was highest in 2001. The active growth of the tubers was caused by the above-mentioned weather factors. In 2000 the yield was apparently largely influenced by the relatively chilly vegetation period.

PA is very important for the development of the tuber yield (Caldiz and Gaspari, 1997; Caldiz *et al*., 2001; O'Brein *et al*., 1998; Christiansen *et al*., 2006). A physiologically older seed accelerates the growth rhythm of potatoes, due to which the yield develops earlier, while the yield formation ability decreases (Wurr, 1979; Jõudu, 2002). The results also show that the earlier the cultivar, the greater the effect of treatment and that the yield develops evenly during the vegetation period in cultivars with a longer growth period. Obviously, any thermal treatment of seed tubers increases their PA (Perennec and Madec, 1980; Van Ittersum, 1992; Johansen *et al*., 2002). Thus, both P_S and T_S to some extent increase the PA of tubers.

The dynamics of tuber yield depending on the seed tuber treatment

The main purpose of P_S is obtaining an earlier yield (Struik and Wieserma, 1999). In order the yield to be as early as possible, the P_S should also start earlier, and sprouting would still take four or five weeks (Jõudu, 2002; Jõudu *et al*., 2004). If it is too late for P_S, the tubers can be stimulated using T_S which makes them develop faster (Eremeev *et al*., 2003; Eremeev *et al*., 2005b).

The yield formation of P_S treatment tubers had already started by 45 DAP (0.7 t ha^{-1}), followed by T_S treatment 50 DAP (4.9 t ha^{-1}) and the T_0 treatment 55 DAP (6.0 t ha^{-1}) (Table 4 in **III**, Table 3 in **V**). Both the pre-planting treatments of seed tubers accelerated the start and increase of tuber formation during the initial growth period, T_S treatment until 60 DAP, P_S treatment until 110 DAP (Table 4 in **III**, Figure 5 in **I**). This does not mean that the pre-planting T_S of seed tubers had no positive effect at all. The seed tubers that received T_S were physiologically older than the variant T_0, which enabled the tuber yield to develop faster. As a result, a harvest-ripe tuber yield was formed earlier. A gradually maturing tuber yield enables the harvest time to be extended even if only one cultivar is grown (Eremeev *et al*., 2005b).

In our studies, the PA of potato plants was increased by two treatments: pre-sprouting of seed tubers and pre-planting thermal shock treatment of seed tubers. In variants with physiologically older seed tubers, the higher growth rate of leaf (assimilate) area and developing tubers was observed.

The sprouts of tubers treated with T_S were smaller (2–5 mm) and therefore more resistant to damage than the sprouts (20–25 mm) in P_S variants.

The duration of yield formation could be shortened according to (Möller *et al.,* 2001) by 8–14 days with the pre-growing of seed tubers. The more unfavourable are the conditions during planting, the higher is the efficiency of pre-growing. This applies especially for temperature, since with the help of pre-growing the formation of maximum yield is shifted about couple of weeks earlier and consequently yield losses due to potato late blight are reduced. The current research experiment established that T_S had a positive effect until mid-August; so if harvesting is planned in September, there is no need to thermally treat the tubers and bear the extra costs involved, especially if cultivation occurs early in the growing season with medium to early cultivars. The experiment has proven that physiologically older tubers have a higher yield potential, particularly during the early period of tuber formation and growth. Also most authors agree that the yield of physiologically older seed is markedly higher than that of younger seed, if harvested prematurely (Van der Zaag and Van Loon, 1987; Mustonen, 2006). When P_S was used, the tubers received more heat than during T_S, therefore P_S tubers can be considered as physiologically older. The yield difference of the physiologically older tubers, T_S and P_S variants decreases more slowly than compared to the T_0 variants. Tubers that were treated with T_S were physiologically older compared to the T_0 variants, enabling higher growth rate of tubers resulting in earlier yield formation. Gradual maturation of the potato yield helps to lengthen the harvesting period even when growing just one cultivar. Depending on the radiation, agronomic measures and variety's potential under favourable conditions the potential yield in Estonia could reach 67–78 t ha^{-1}. In real farm practice the Estonian average 10–18 t ha^{-1} (Statistics Estonia, 2007). In our experiment the yield level was about 50 t ha^{-1}.

Dynamics of tuber yield depending on the cultivar

If we compare the cultivars, we can conclude that 'Piret' and 'Agrie Dzeltenie' start developing tubers early and are ahead of 'Ants' up to day 60 after planting (Table 3 in **V**). 'Ants' achieved its maximum yield by day 114: 47.0 t ha^{-1}.

As a result of P_S, a statistically reliable additional tuber yield was obtained in 'Ants' until 90 DAP, in 'Piret' until 70 DAP and in 'Agrie Dzeltenie' until 60 DAP. The reliably positive effect of T_S on tuber yield could be seen in 'Piret' until 60 DAP, in 'Agrie Dzeltenie' until the end of the vegetation period, and in 'Ants' until 85 DAP.

The increment of the average weight of a T_S tuber during the period of 50–120 DAP, exceeded the T_0 treatment by 0.10–0.19 g day^{-1} and during the period of 50–100 DAP it was lower than that of the P_S treatment by 0.02–0.31 g day^{-1}. While both T_S and P_S treatments started to form tubers earlier, the growth rate of tuber weight in the T_0 treatment was higher, exceeding the T_S treatment by 0.15 t day^{-1} and the P_S treatment by 0.08 t day^{-1} at 55 DAP (Figure 2 in **III**). The growth rate of the different variants were even at 95 DAP. While both, the T_S and P_S variants started to form tubers earlier, the growth rate of tuber weight in the T_0 treatment was higher, exceeding the T_S treatment by 0.15 and the P_S treatment by 0.08 t day^{-1} at 55 DAP (Figure 2 in **III**).

The tuber yield is in correlation with the weight of the haulms (r =0.57; $p < 0.001$), the number of stems (r = 0.29), the number of tubers per plant (r = 0.79; $p < 0.001$) and the average tuber weight (r = 0.97; $p < 0.001$). Thus, the tuber yield depended on the development of all plant parts. From different tuber fractions, the number of medium-sized and large tubers (r respectively 0.64; $p < 0.001$ and 0.95; $p < 0.001$) and tuber weight (r respectively 0.70; $p < 0.001$ and 0.95; $p < 0.001$) had highest positive influence on tuber yield.

The pre-planting treatment of seed tubers (variants T_S and P_S) did not significantly change the correlation between the tuber yield and the weight of the haulms (r respectively 0.52; $p < 0.001$ and 0.51; $p < 0.001$), the number of tubers per plant (r = 0.71–0.79; $p < 0.001$) and the average weight of a tuber (r = 0.92–0.97; $p < 0.001$). The negative effect of small tubers (less than 35 mm) on the formation of the tuber yield was established.

A physiologically young seed tuber is preconditioned to develop better and stronger roots as well as all parts of the plant that are above the ground and the largest assimilation surface possible. These advantages are preconditions for the formation of a high tuber yield (Struik and Wiersema, 1999). The draw-back is that the late sprouting and covering of furrows with leaves decreases the competitiveness of potato plants. The delayed development of the assimilation surface puts much of the assimilation potential past the time of maximum PAR (Boyd *et al.*, 2002).

Although there is an increasing corpus of literature on the PA of seed tubers, the application for potato management is currently imprecise. In general, advancing seed-potato age affects crop yield, but the actual effect depends not only on the cultivar (Van der Zaag and Van Loon, 1987), but also on the field conditions (Knowles and Botar, 1991; Caldiz *et al.*, 1998), cropping systems (Karalus and Rauber, 1997), and managerial skills.

Enhancing physiological aging of seed potatoes has the potential to substantially affect production, especially for short-season growing areas (Asiedu *et al.*, 2003). Achieving a relatively early potato yield is important not only for early but also for late potato cultivars. The growing of late cultivars is necessary due to their higher tuber yield potential and the fact that they can be preserved better.

5. CONCLUSIONS

The results of the experiment to a large extent depend on weather conditions in a particular year. The most favourable year for potato growth in terms of weather conditions was 2001. The weather during the period of tuber formation and intensive growth was reasonably warm and the plants' needs for water were satisfied, while efficient blight control ensured actively working leaf area until harvesting.

The primary conclusion that can be drawn from the results of this three year experiment are that the pre-sprouting treatment must be used to achieve a very early potato yield while thermal shock a very useful tool for mid to early yield formation. Photosynthetically active leaf area develops earlier under pre-sprouting, which results in larger tubers than other the other treatments and consequently a larger yield. Although pre-sprouting consumes a great deal of time and energy a potato variety's full yield potential is realized with the very early yield. Thermal shock, by contrast, is efficient in seed production but while it produces more tubers their average weight is smaller than pre-sprouted tubers.

A secondary conclusion is that the weight of the haulms of the plants developed from physiologically older seed tubers formed faster and remained smaller. Pre-planting treatment of seed tubers (*i.e.* increasing the physiological age) provided quicker field emergence. The slower the potato plants attained the maximum weight of the haulms, the bigger they formed. On physiologically older plants, obvious signs of senescence started to appear earlier (partial wilting and yellowing of the lower leaves). The value and timing of maximum LAI were, cultivar specific, 4.0 units at 72 DAP of the early cultivar 'Agrie Dzeltenie', 3.7 units at 74 DAP of the middle-maturing cultivar 'Piret' and 3.9 units at 75 DAP of the late cultivar 'Ants'.

The average results for the three years show that the potato did not have enough time to realise its full potential and did not reach its maximum yield. Pre-sprouting and thermal shock had a positive effect during the entire vegetation period. This effect was initially stronger but then gradually decreased. Thermal treatment of the tubers before planting has a different effect on cultivars with different growth times. A comparison between the cultivars showed that 'Piret' and 'Agrie Dzeltenie' started to form tubers early on and exceeded the cultivar 'Ants' until the 60th day of growth. 'Ants' reached its maximum yield, 47.0 t ha^{-1}, already by the 114th day, followed by the early cultivar 'Agrie Dzeltenie' and the mid-maturing cultivar 'Piret'. Thermal treatment did not give any advantage in terms of total yield formation compared to untreated seed, except in the pre-sprouted variant of the cultivar 'Agrie Dzeltenie', the total yield of which exceeded that of its untreated variant by 7.08 t ha^{-1}.

Thermal shock treatment was not as effective as pre-sprouting in the development of the leaf area and tuber yield formation. Nevertheless treated seed tubers were physiologically older than non-treated samples, enabling quicker leaf area and tuber growth and development.

By pre-sprouting seed tubers before planting, the development of plants was faster during the entire vegetation period, but with thermal shock treatment only the first stages of vegetation was affected. The pre-sprouted variant gave a significant tuber yield increase during the whole vegetation season.

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SUMMARY IN ESTONIAN

Stabiilse, majanduslikult tasuva kartulisaagi saamiseks on üheks põhikomponendiks terve, bioloogiliselt aktiivne ja suure saagipotentsiaaliga seeme, mis vastavalt kasutusotstarbele ka mahapanekuks ette valmistatakse. Seemne kvaliteedist sõltub kartuli tärkamine, pealsete moodustumine ning põllupinna kattumise kiirus. Kartuli kõrge saagipotentsiaali säilitamiseks tuleb kartuliseemne mahapanekuks valmistumise käigus jälgida, et kõik olulisemad saagikust suurendavad meetmed oleksid rakendatud. Seemnemugulate mahapanekueelne eelidandamine on laialdaselt kasutusel Hollandis, seda mitte üksnes varajase, vaid ka hilise kartuli puhul.

Füsioloogiliselt noorel seemnemugulal on eeldused välja arendada täiuslikumad ja tugevamad juured ning kõik taime maapealsed osad, mis tagavad võimalikult suure assimilatsioonipinna. Nimetatud eeldused on aluseks suure mugulasaagi kujunemisele. Puuduseks on see, et mõningane tärkamise ja lehestikuga vaovahede kattuvuse hilinemine vähendab kartulitaimede konkurentsivõimet umbrohtudega. Hilisem assimilatsioonipinna 'tööaeg' langeb ajale, kui väheneb fotosünteetiliselt aktiivse kiirguse hulk. Kõige selle tagajärjel hilineb ka mugulasaagi koristusküpseks muutumine.

Suhteliselt varajasema kartulisaagi saamine on oluline mitte ainult varajastel, vaid ka hilistel kartulisortidel. Hiliste sortide kasvatamine on vajalik nende suure saagipotentsiaali tõttu ja nad säilivad paremini. Varajasema kartulisaagi saamiseks on kasutusel mitmeid meetodeid, sealhulgas ka seemnemugulate termiline töötlemine, millega saab kartulimugulatele lisada füsioloogilist vanust ja muuta lühemaks see kronoloogiline aeg, mis on vajalik mugulasaagi koristusküpseks kujunemisel. Sellise meetodi kasutamine soodustab ensüümide aktiivsust mugulates, stimuleerib idude kiiremat arenemist silmadest, lühendab tärkamisperioodi pikkust, kiirendab taime arengut ja saagi moodustumist. Kui seemnemugulaid kevadel hoida mõnda aega kõrgemal temperatuuril, saame füsioloogiliselt vanemad mugulad. See on asjakohane nii varajase kui ka hilise kartuli kasvatamisel, sest pealsete massi ja lehepinna maksimum saavutatakse kiiremini ning majanduslikult optimaalset mugulasaaki on võimalik koristada varem. Samas aga füsioloogiliselt nooremad taimed võivad olla elujõulisemad ja moodustada isegi suurema mugulasaagi, kuid seda mõnevõrra hiljem.

Käesoleva uurimuse hüpoteesiks oli, et kartuli erineva kasvuajaga sortide seemnemugulate lühiajaline mõjutamine kõrgema temperatuuriga mõjutab kartuli lehepinda, pealsete massi, mugulate arvukust ja mugulate massi arengut ning suurust.

Käesoleva väitekirja eesmärgiks oli uurida:

(1) kuidas termošokk ja eelidandamine mõjutavad kartulitaime erinevate osade (lehepinna, pealsete massi, ühe taime mugulate arvu, ühe mugula massi ja mugulasaagi) kujunemist vegetatsiooniperioodil, tagamaks kvaliteetse ja võimalikult varajase saagi moodustumise.

(2) kas termošokiga on võimalik asendada pikaajalist ja energia-mahukat eelidandamist.

Tulemused ja järeldused

Katsete tulemused sõltusid olulisel määral konkreetse aasta ilmastikutingimustest. Ilmastikuliselt osutus kartulikasvuks kõige soodsamaks 2001. a, mis oli suhteliselt soe ning mugulate moodustumise ja intensiivse kasvu perioodil oli rahuldatud taimede veevajadus. Ja efektiivne lehemädanikutõrje tagas aktiivselt töötava lehepinna koristamiseni.

Kolmeaastase uurimuse tulemustest saadud peamiseks järelduseks on, et väga varajase kartulisaagi saamiseks tuleb kasutada eelidandamist, sama ajal kui termošokk on eriti kasulik keskmise kuni varajase saagi moodustumiseks. Eelidandamise mõjul moodustub fotosünteetiliselt aktiivse lehepind, mis tagab suuremad mugulad ja sellest tulenevalt ka suurema saagi kui teiste töötlusvõtete puhul. Kuigi eelidandamisele kulub märkimisväärselt aega ja energiat, saadakse väga varajase saagiga kartulisordi täielik saagipotentsiaal. Termošokk seevastu on kasulik seemnemugulate tootmiseks, aga kuna see annab taime kohta rohkem mugulaid, siis nende keskmine mass on väiksem kui eelidandatud mugulatel.

Teiseks leiti, et füsioloogiliselt vanematest seemnemugulatest moodustunud taimede pealsete mass moodustus kiiremini ning jäi väiksemaks. Seemnemugulate mahapanekueelne töötlemine (s.o füsioloogilise vanuse suurendamine) tagas põllul kiirema tärkamise. Mida aeglasemalt kartulitaimed oma pealsete maksimaalse kaalu saavutasid, seda suuremaks see kujunes. Füsioloogiliselt vanematel mugulatel ilmnesid selged vananemise märgid (alumiste lehtede osaline närbumine ja kolletumine) varem. Maksimaalse LAI väärtus ja selle moodustumise aeg olid sordispetsiifilised, varajasel sordil 'Agrie Dzeltenie' 4,0 ühikut 72. päevaks, keskvalmival sordil 'Piret' 3,7 ühikut 74. päevaks ja hilisel sordil 'Ants' 3,9 ühikut 75. päevaks.

Kartul ei jõudnud realiseerida oma potentsiaali maksimaalselt, ta ei jõudnud saavutada oma saagi maksimumi. Eelidandamine ja termošokk avaldasid positiivset mõju terve vegetatsiooni perioodi jooksul, algul tugevamalt ning seejärel sujuvalt kahanedes. Seemnemugulate termiline töötlemine enne mahapanekut avaldab erineva kasvuajaga sortidele ka erinevat mõju. Kui võrrelda sorte omavahel, võib järeldata, et 'Piret' ja 'Agrie Dzeltenie' hakkavad varakult mugulaid moodustama ning ületasid sorti 'Ants' kuni 60. kasvupäevani pärast kartulipanekut. Sort 'Ants' saavutas oma maksimumsaagi juba 114. päevaks 47,0 t ha^{-1}, millele järgnesid 'Agrie Dzeltenie' ja 'Piret'. Termiline töötlemine ei andnud lõppsaagi moodustumises eelist, võrreldes töötlemata seemnega, välja arvatud sort 'Agrie Dzeltenie' eelidandatud variant, mis andis lõppsaagis 7,08 t ha^{-1} enamsaaki võrrelduna töötlemata variandiga.

Termošokk ei olnud lehepinna ja mugulasaagi moodustumisel nii efektiivne kui eelidandamine. Sellele vaatamata olid töödeldud seemnemugulad füsioloogiliselt vanemad kui mitte-töödeldud proovid, võimaldades kiiremat lehepinna ja mugula kasvu ning arengut.

Seemnemugulate mahapanekueelsel eelidandamisel oli taimede areng kogu kasvuperioodi jooksul kiirem, kuid termošokiga mõjutati vaid kasvutsükli esimesi etappe. Eelidandatud variant andis kogu vegetatsiooniperioodi jooksul märkimisväärselt suurema mugulasaagi.

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I

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ORIGINAL ARTICLE

The influence of thermal shock and pre-sprouting of seed potatoes on formation of some yield structure elements

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Abstract

For earlier potato yield formation we used pre-sprouting and thermal treatment which both add to the physiological age of potato. At the same time, pre-sprouting is a very time- and energy-consuming procedure. We investigated if thermal treatment could replace pre-sprouting and how it affects the growth and development of potato haulms and tubers. For that purpose an experiment was conducted in 2000–2002 to examine the opportunities for growing potatoes by using different methods of pre-planting treatment of seed tubers.

Early, middle and late maturing potato varieties (two Estonian varieties and one Latvian) were used, each being subdivided into three variant categories: untreated, thermal shock and pre-sprouting.

The experiment indicated that one or the other of thermal shock or pre-sprouting shortened the time to emergence by up to 10 days. With pre-sprouting, the formation of tubers started as soon as 45 days after planting and with thermal shock 50 days after planting, i.e., 5–10 days earlier than in the untreated variant.

Thermal shock of seed tubers had the greatest effect on the number of tubers per plant, while pre-sprouting increased the average weight of tubers.

Both pre-sprouting and thermal shock had a strong effect on the weight of the haulms in varieties with a longer growth period.

Keywords: *Haulms, leaf area index, physiological age, potato, tuber weight, tuber yield.*

Introduction

In order to ensure the full maturation of varieties with various growing times, especially for late varieties, the sum of active temperatures in Estonia often remains low. At the same time it is vitally important for farmers to market early potatoes as early as possible. With late potato varieties the yield increase is usually negatively affected by wide infestation by diseases before full maturity. Therefore, measures to shorten the growth period of the potato should be implemented, especially for seed potato cultivation.

Different methods are used to achieve an earlier potato yield, including the thermal treatment of seed tubers, which adds physiological age to the tubers and shortens the chronological time that is necessary for the tubers to become harvest-ripe (Allen et al., 1992; Struik & Wiersema, 1999). This method boosts enzyme activity in tubers, stimulates faster development of sprouts from the eyes, reduces the sprouting period and accelerates plant development and tuber formation. The leaf area and tuber yield of potatoes may vary. After the breaking of dormancy, the seed tuber goes through different phases: apical dominance, normal sprouting, production of branched sprouts, senility and incubation (little tuber formation). Crops grown from seed tubers in different phases differ in canopy structure, tuber number, yield, tuber size distribution and quality (Ewing & Struik, 1992; Struik & Wiersema, 1999). If seed tubers are kept at a higher temperature for some time in spring, then the result is physiologically older tubers. This can be used in the growing of both

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early and late potatoes as the maximum weight of the haulms (leaves and stems) and maximum leaf area are achieved faster. An economically optimal tuber yield can also be harvested earlier. However, physiologically younger plants can be more viable and even form a higher tuber yield, although slightly later. The physiological age of the tuber affects the numbers of sprouts and sprout behaviour, but also the growth pattern of the plant that originates from it and thus sometimes the tuber yield of the crop produced (van der Zaag & van Loon, 1987).

In the Estonian University of Life Sciences (EMU) Institute of Agricultural and Environmental Sciences (IAES), at the Department of Field Crop Husbandry we have focused on the effects of seed tubers of different age on the different parts of a potato plant. If the seed tubers are kept for a certain time at higher temperatures before planting, physiologically older tubers are obtained (Eremeev et al., 2003). This is important when growing early or late potato varieties, because maximum weight of the haulms and the leaf area index are attained faster and it is possible to harvest also the economically optimal tuber yield much earlier (Eremeev et al., 2005). Current research analyses the development of potatoes throughout their growth as well as tuber yield, whereas seed tubers are treated by different methods to wake them from the dormancy period. The aims of the present research were: 1) to discover what pre-planting treatment methods (thermal shock and pre-sprouting) are best for our weather conditions to ensure the formation of a large high-quality tuber yield as early as possible; 2) to answer the following questions – can thermal shock replace the long and energy-consuming pre-sprouting period and how can thermal shock affect the growth and development of potato haulms and tubers? 3) to discover correlations between the different parts of a potato plant (leaves, haulms and tubers) depending on the pre-planting treatment of seed tubers.

Material and methods

The experiment was carried out during the 2000–2002 growing seasons at the Department of Field Crop Husbandry, Plant Biology Experimental Station (58°23′N, 26°44′E) in EMU IAES. Random block placement in four replications was used (Hills & Little, 1972). The size of a test plot was 21 m^2. The distance between seed tubers was 25 cm and distance between furrows 70 cm. Seed tubers with a diameter of 35–55 mm were used in the experiment.

Different methods of growing potato were analysed, using various pre-planting treatments. Seed tubers were treated before planting as follows:

1. Untreated variant (0); no thermal treatment was conducted.
2. Thermal shock (TS); a week before planting the seed tubers were kept for two days at 30°C, then 5 days at 12–15°C in a lighted room (Lõhmus et al., 1999).
3. Pre-sprouting (PS); the tubers were kept for 35–38 days before planting in a sufficiently humid (85–90% RH) and lighted room at 12–15°C. Seed tubers were pre-sprouted in wooden boxes (in one or two layers).

The late variety 'Ants' and the mid-maturing variety 'Piret', both bred at the Jõgeva Plant Breeding Institute in Estonia, and the early variety 'Agrie Dzeltenie', bred at the Latvian Priekuli State Plant Breeding Station, were used in the experiments.

The soil of the experimental field was Stagnic Luvisol according to WRB classification (Deckers et al., 1998) with a texture of sandy loam and a humus layer of 20–30 cm. Soil analyses were carried out at the laboratories of the Department of Soil Science and Agrochemistry, EMU. Air-dried soil samples were sieved through a 2-mm sieve. The following characteristics were determined: pH (in 1 M KCl and in 0.01 M $CaCl_2$ 1: 2.5; organic carbon by Tjurin, Ca and Mg in NH_4OAc at pH 7 (Soil Survey Laboratory Staff 1996), P and K after the Mehlich-3 method (Handbook on Reference Methods for Soil Analysis, 1992), The Kjeldahl method was used to determine the content of total N of the soil (Procedures for Soil Analysis, 1995).

The soil data of the humus layer of the experimental field were as follows: pH $\approx$6.2; C, 1.4%; Ca, 674 mg kg^{-1}; Mg, 101 mg kg^{-1}; P, 183 mg kg^{-1}; K, 164 mg kg^{-1}; N, 0.11%; 56% sand; 35% silt and 9% clay.

The Estonian climate is a transitional climate from maritime to continental. It is mainly influenced by the Baltic Sea and the north-eastern part of the Atlantic Ocean. Year-round intensive cyclonic activity causes moist and continuously changing weather conditions. Summer is relatively short and cool, autumn is long, and winter mild. The vegetation period (average diurnal temperature continuously above 5°C) begins usually in the second half of April, lasts 170–180 days and ends in September or October. The period of active plant growth (average diurnal temperature continuously above 10°C) ranges usually from 115 to 135 days (Tarand, 2003). The experimental area belongs to the south Estonia upland agroclimatic region, where the sum of active air temperatures of the year is on average 1750–1800°C and total precipitation is 550–650 mm.

Table I. Average monthly temperatures (°C) and precipitation (mm) average during the vegetation period in 2000–2002 (according to the Erika meteostation) and the average of 1966–1998 in Estonia (Jaagus, 1999).

	Temperatures, °C		Precipitation, mm	
Month	Average of 2000–2002	Average of 1966–1998	Average of 2000–2002	Average of 1966–1998
May	12.0	11.6	42.7	55
June	15.2	15.1	75.7	66
July	19.8	16.7	101.2	72
August	17.1	15.6	75.6	79
September	10.8	10.4	22.2	66

During the trial years, in the vegetation period (from May to September) the amount of precipitation was greater than average in June and July, less than average in May, August and September (Table I). Air temperature remained similar to the average of 32 years (1966–1998); only July was significantly warmer.

Agronomic measures were typical for potato experiments. Composted manure (60 t ha^{-1}) before autumn ploughing was used as organic fertilizer. Mineral fertilizers were applied locally at the same time as planting of potatoes in the spring. In 2000–2002, compound mineral fertilizer (78 kg N, 72 kg P, 117 kg K ha^{-1}) was applied at planting. For plant protection, the insecticide Fastac and fungicides Ridomil Gold, Acrobat Plus and Shirlan were used. All active ingredients for plant protection were used with 400 litres of water per ha.

The dynamics of tuber yield, the weight of the haulms, leaf area, the number of tubers per plant and the average weight of each tuber were determined with an interval of 3–5 days and each sample consisted of four plants from the test plot.

Statistical data analysis by regression methods was performed (Mead et al., 1993; Lauk, 1995, 1996; Lauk et al., 1996).

The following formula was used:

$y = a + bx + cx^2$, where y is the argument function, the index that is calculated on the basis of the equation: tuber yield, the weight of the haulms, leaf area index (LAI), the number of tubers per plant and the average weight of a tuber, a is the constant term of the equation, b and c the regression coefficients, x the argument, number of days after planting (DAP).

For every variant, separate regression formulas were found, and based on their differentials it was possible to calculate the average formulas for multiple years. Standard errors (SE) and confidence limits (CL_{05} – level of statistical significance $p = 0.05$) were calculated by using the relevant methodology (Lauk & Lauk, 2000). The calculation of confidence limits was based on the Student's theoretical criterion (Mead et al., 1993).

All the data in the figures were calculated according to the formulas of regression analysis. To assess the probability of differences between test variants the least significant differences (LSD_{05}) were calculated according to the corresponding methodology (Lauk et al., 2004).

Correlation analysis was used to study the correlation between different parts of the potato plants and pre-planting treatment of seed tubers. Linear correlation coefficients between variables were calculated, the significance of coefficients being $p < 0.001$, $p < 0.01$, $p < 0.05$, NS = non-significant ($p > 0.05$).

In this paper all the experimental data are presented on the average of 2000–2002 years.

Results and discussion

Weight of the haulms

Physiological ageing advanced sprout growth, crop emergence, crop establishment and usually improved tuber yield (Burke & O'Donovan, 1998). Transition of developmental stages and their duration is often quite different. It depends on the biological characteristics of a variety, quality of seed potato, climatic and soil conditions and also agronomic measures used (Christiansen et al., 2006).

Earlier studies at the Department of Field Crop Husbandry indicated that PS and TS increased the physiological age of seed tubers and initiated earlier emergence (Lõhmus et al., 1999; Eremeev et al., 2001). Plants from seed tubers treated before planting emerged 1–4 days (late varieties) and 1–7 days (early varieties) earlier (Lõhmus et al., 1999; Eremeev et al., 2001). In present study, the pre-planting treatment of seed tubers ensured earlier field sprouting in the TS variant by 4, and in the PS variant by 10, days earlier than in variant 0, as a three-year average. The faster growth of the haulms of the plants that developed from thermally treated seed tubers provided furrow coverage nearly a week earlier, as a result of which the last inter-row tillage could be omitted at just the critical time when there were very favourable conditions for the growth of weeds.

The pre-planting treatment of seed tubers (PS and TS) accelerated the development of the haulms, and the weight of the latter was higher than in variant 0 up to 50 DAP (Figure 1). The weight of the haulms reached its maximum in variant PS by 76 DAP, in TS by 77 DAP and in 0 by 81 DAP (Figure 1). The later the maximum weight of the haulms was achieved, the higher it was because the visible signs of ageing appeared earlier in physiologically older plants. Thus, the maximum weight of the haulms in variant 0 was 31.9 t ha^{-1}, exceeding PS and TS, respectively, by 4.2 and 2.9 t ha^{-1} (Figure 1). Therefore, the weight of the haulms in plants formed from physiologically older seed tubers developed faster and was lower.

Both PS and TS had a stronger effect on the development of the weight of the haulms in varieties with a longer growth period. 'Ants' achieved the maximum weight of the haulms in thermally treated variants (PS and TS) 7–8 days earlier than in variant 0. It occurred in 'Piret' five days earlier and practically at the same time as 'Agrie Dzeltenie' in all variants.

Thus, the weight of the plant haulms developed from physiologically older seed tubers, formed more quickly and remained lower. Pre-planting treatment of seed tubers (i.e., increasing the physiological age) gave earlier field emergence. The later the potato plants attained the maximum weight of the haulms, the higher it was. In physiologically older plants obvious signs of senescence started to appear earlier (partial wilting and yellowing of the lower leaves). According to Putz (1986), after the death of the haulms, growth of tubers ceases, the skin hardens and starts to suberizate.

There were positive correlations between the weight of the haulms and the LAI and the number of stems, both as the average for all experimental variants ($r = 0.95$; $p < 0.001$ and $r = 0.53$; $p < 0.001$) and at the level of varieties and the pre-planting treatment of seed tubers. The number of tubers per plant ($r = 0.79$; $p < 0.001$) and the average tuber weight ($r = 0.45$; $p < 0.05$) increased with the development of the weight of the haulms.

Leaf area index

Leaf area index indicates the ratio of assimilative area of the leaf and the surface area (Watson, 1947). For optimal photosynthetic rate it is necessary that LAI should be over 4 for as long a period as possible, otherwise the use of photosynthetically active radiation (PAR) and thus the production of organic matter, decreases (Scott & Wilcockson, 1978; Allen & Scott, 1980; Khurana & McLaren, 1982). The pre-planting treatment of seed tubers (TS and PS) accelerated the growth and development of leaves and leaf area from the beginning of sprouting until 60 DAP (statistically significant until 45 DAP). Later, the increase of the leaf area in different variants became similar. From earlier experiments with late varieties it is known that the LAI reaches a maximum (average 3.7 units) by 72 DAP and then starts to decrease (Eremeev et al., 2001). In the present research (Figure 2) the maximum LAI (3.9 units) was reached 74 DAP and on 50 days after emergence (DAE). According to the 30-years study by the Norwegian scientist Eltun (1996), it took 45 DAE to form maximum LAI. In the present experiment the highest LAI was reached between 68 and 81 DAP. The maximum LAI in variant PS was achieved by 72 DAP (3.7 units), in TS (3.8 units) and 0 (4.1 units), respectively, by 73 and 76 DAP. In varieties with a shorter growth period the leaf area reaches its maximum earlier.

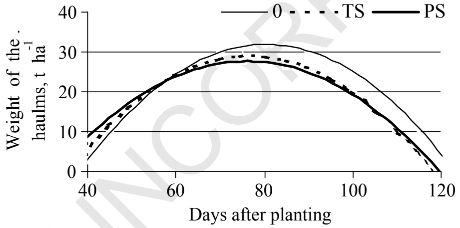

Figure 1. The effect of thermal treatment on the weight of the haulms (average of 2000–2002, t ha^{-1}). 0 = Untreated variant: $y = -82.8 + 2.849x - 0.01769x^2$, $n = 117$, $R^2 = 0.985$, SE = 0.45, $CL_{05} = 1.02$; TS = Thermal shock: $y = -72.3 + 2.63x - 0.01715x^2$, $n = 117$, $R^2 = 0.946$, SE = 0.55, $CL_{05} = 1.24$; PS = pre-sprouting: $y = -57.1 + 2.227x - 0.01462x^2$, $n = 117$, $R^2 = 0.946$, SE = 0.46, $CL_{05} = 1.04$.

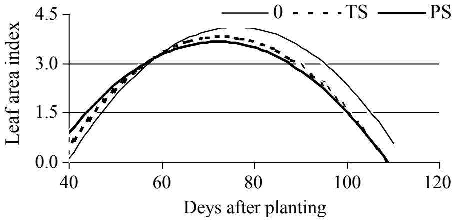

Figure 2. The effect of thermal treatment on the leaf area index (the average of 2000–2002). 0 = Untreated variant: $y = -13.7 + 0.468x - 0.00307x^2$, $n = 123$, $R^2 = 0.953$, SE = 0.09, $CL_{05} = 0.20$; TS = Thermal shock: $y = -12.5 + 0.446x - 0.00306x^2$, $n = 123$, $R^2 = 0.917$, SE = 0.11, $CL_{05} = 0.24$; PS = Pre-sprouting: $y = -10.3 + 0.389x - 0.00271x^2$, $n = 123$, $R^2 = 0.911$, SE = 0.10, $CL_{05} = 0.22$.

Tuber weight

The weight of tubers depends on the weather conditions and the available nutrients during tuber formation (Panelo & Caldiz, 1989). It also depends on the growth and development of leaves and branches, formation of assimilation products and their distribution between different parts of the plant, rate of tuber formation and the time of perishing of haulms (Caldiz et al., 2001).

Pre-sprouting provided a stably reliable (LSD_{05} 4.9) average tuber weight throughout the vegetation period (Figure 3). According to data presented by Burke (1997), the physiological age of the tubers increases the average weight of tubers. In our experiment this effect was seen only in the PS variant, while in the TS variant the increase in the average weight of tubers could be seen until 75 DAP. The 0 and TS variants developed more slowly at the start, resulting in a longer vegetation period and the tubers did not reach their maximum weight by the time of harvest.

Based on the pre-planting treatment of the seed tubers, only the PS variant reached the maximum average tuber weight (77.6 g) by 121 DAP (Figure 3).

By the time of harvest the average tuber weight reached the maximum in variant PS in 'Ants' by 116 DAP (69.6 g), in 'Piret' variant TS by 117 DAP and variant 0 by 120 DAP, with, respectively, 67.1 g and 71.1 g, in 'Agrie Dzeltenie' variant TS by 114 DAP and variant PS by 119 DAP (respectively, 66.3 g and 86.3 g).

The number of tubers per plant

PS and TS increased the formation of tubers per plant, particularly at the beginning of tuber formation (until 60 DAP, LSD_{05} 1.3), whereas the maximum number of tubers was formed at 93–94 DAP (12.6 and 14.0 tubers, respectively). In variant 0, the respective value was 13.2 and it formed at 95 DAP. Throughout the entire vegetation period the positive effect of TS treatment on the number of tubers per plant was observed (Figure 4).

Pre-sprouting increased the number of tubers with the variety 'Piret' and only at the beginning of tuber initiation. Throughout the entire vegetation period the number of tubers of the variety 'Ants' was higher due to the TS treatment than in other variants, in the varieties 'Piret' and 'Agrie Dzeltenie', until 50 DAP and 60 DAP, respectively.

The varieties 'Piret' and 'Agrie Dzeltenie' started to form tubers early but had a lower average number of tubers per plant compared to 'Ants'. In 'Agrie Dzeltenie' the maximum number of tubers was formed at 92 DAP (12.8 tubers), in 'Ants' (14.6 tubers) and 'Piret' (12.1 tubers), respectively, at 93 and 97 DAP.

Tuber yield

The main purpose of PS is obtaining an earlier yield (Struik & Wieserma, 1999). In order to obtain the yield as early as possible, the PS should also start earlier, and sprouting would still take four or five weeks (Jõudu, 2002). If it is too late for PS, the tubers can be stimulated using TS, which makes them develop faster (Eremeev et al., 2003; Eremeev et al., 2005). The pre-planting TS accelerated the beginning of tuber yield formation and ensured its increase during the initial growth period (until 60 DAP) (Figure 5). The positive effect of PS on tuber yield was longer (until 110 DAP). This does not mean that the pre-planting TS of seed tubers had no positive effect at all. The seed tubers that received TS were physiologically older than the variant 0, which enabled the tuber yield to develop faster. As a result, a harvest-ripe tuber yield was formed earlier.

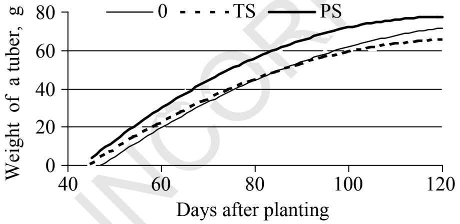

Figure 3. The effect of thermal treatment on the average weight of a tuber (the average of 2000–2002, g). 0 = Untreated variant: $y = -99.4 + 2.545x - 0.00932x^2$, $n = 126$, $R^2 = 0.969$, SE = 1.11, $CL_{05} = 2.43$; TS = Thermal shock: $y = -91.7 + 2.505x - 0.00995x^2$, $n = 130$, $R^2 = 0.974$, SE = 0.88, $CL_{05} = 1.92$; PS = Pre-sprouting: $y = -110.2 + 3.108x - 0.0128x^2$, $n = 137$, $R^2 = 0.971$, SE = 1.13, $CL_{05} = 2.46$.

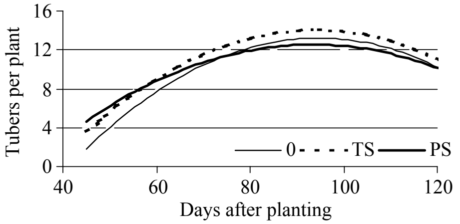

Figure 4. The effect of thermal treatment on the number of tubers per plant (the average of 2000–2002). 0 = Untreated variant: $y = -28.2 + 0.876x - 0.00463x^2$, $n = 126$, $R^2 = 0.896$, SE = 0.29, $CL_{05} = 0.63$; TS = Thermal shock: $y = -24.6 + 0.822x - 0.00437x^2$, $n = 130$, $R^2 = 0.796$, SE = 0.32, $CL_{05} = 0.68$; PS = Pre-sprouting: $y = -16.8 + 0.63x - 0.00338x^2$, $n = 137$, $R^2 = 0.796$, SE = 0.31, $CL_{05} = 0.67$.

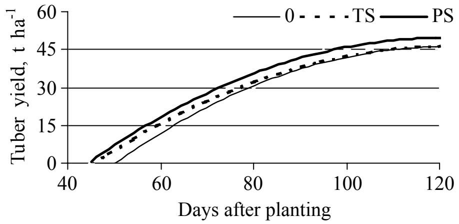

Figure 5. The effect of thermal treatment on the tuber yield (the average of 2000–2002, t ha^{-1}). 0 = Untreated variant: $y = -88.2 + 2.216x - 0.00914x^2$, $n = 126$, $R^2 = 0.960$, SE = 0.88, $CL_{05} = 1.93$; TS = Thermal shock: $y = -71.4 + 1.915x - 0.00778x^2$, $n = 130$, $R^2 = 0.965$, SE = 0.79, $CL_{05} = 1.72$; PS = Pre-sprouting: $y = -75.2 + 2.073x - 0.00861x^2$, $n = 137$, $R^2 = 0.968$, SE = 0.80, $CL_{05} = 1.73$.

Gradually maturing tuber yield enables the harvest time to be extended even if only one variety is grown (Eremeev et al., 2003; Eremeev et al., 2005).

As a result of PS, a statistically reliable additional tuber yield was obtained in 'Ants' until 90 DAP, in 'Piret' until 70 DAP and in 'Agrie Dzeltenie' until 60 DAP. The reliably positive effect of TS on tuber yield could be seen in 'Piret' until 60 DAP, in 'Agrie Dzeltenie' until the end of the vegetation period, and in 'Ants' until 85 DAP.

Depending on the radiation, agronomic measures and a variety's potential under favourable conditions, the potential yield in Estonia could reach 67–78 t ha^{-1}. In real farm practice the Estonian average potato yield has been 10–18 t ha^{-1} (ESA, 2004). In our experiment the yield level was about 50 t ha^{-1}.

The maximum yield was attained in variants 0 by 121 DAP (46.1 t ha^{-1}) and in PS variants by 120 DAP (49.6 t ha^{-1}). The TS variant could not attain maximum yield by harvest time.

The tuber yield correlates with the weight of the haulms ($r = 0.57$; $p < 0.001$), the number of stems ($r = 0.29$), the number of tubers per plant ($r = 0.79$; $p < 0.001$) and the average tuber weight ($r = 0.97$; $p < 0.001$). Thus, the tuber yield depends on the development of all plant parts. From different tuber fractions, the number of medium-sized and large tubers (r, respectively, 0.64; $p < 0.001$ and 0.95; $p < 0.001$) and tuber weight (r, respectively, 0.70; $p < 0.001$ and 0.95; $p < 0.001$) had the highest positive influence on tuber yield.

The pre-planting treatment of seed tubers (variants TS and PS) did not significantly change the correlation between tuber yield and the weight of the haulms (r, respectively, 0.52; $p < 0.001$ and 0.51; $p < 0.001$), the number of tubers per plant ($r = 0.71$–0.79; $p < 0.001$) and the average weight of a tuber ($r = 0.92$–0.97; $p < 0.001$). The negative effect of small tubers (less than 35 mm) on the formation of the tuber yield was established. Within one variety there were no significant correlative differences between the yield structure elements and yield formation. However, the negative effect of small tubers (less than 35 mm) on the tuber yield was established in 'Ants' and 'Piret'.

Thermal treatment of the seed tubers before planting had a different effect on varieties with different growing periods. A physiologically young seed tuber is preconditioned to develop better and stronger roots as well as all parts of the plant that are above the ground and the largest assimilation surface possible. These advantages are preconditions for the formation of a high tuber yield. The drawback is that the late sprouting and covering of furrows with leaves decreases the competitiveness of potato plants. The later 'working time' of the assimilation surface is the time when the quantity of physiologically active radiation decreases.

Although there is a growing literature on the physiological age of seed tubers, the application for potato management is currently imprecise. In general, advancing seed-potato age affects crop yield, but the actual effect depends not only on the variety (van der Zaag & van Loon, 1987), but also on the field conditions (Knowles & Botar, 1991; Caldiz et al., 1998), cropping systems (Karalus & Rauber, 1997), and managerial skills.

Enhancing physiological ageing of seed potatoes has the potential to substantially affect production, especially for short-season growing areas (Asiedu et al., 2003). Obtaining a relatively early potato yield is important not only for early but also for late potato varieties. Growing of late varieties is necessary due to their higher tuber yield potential and the fact that they can be preserved better.

As a conclusion it must be noted that especially for early potato yield formation pre-sprouting should be used. Photosynthetically active leaf area develops earlier which results in a bigger yield, and also the tubers are larger than in other variants. Thermal shock is an effective tool in seed production, while it increases the number of tubers compared to using the pre-sprouted seed tubers. Also the average weight of the tubers is lower. When grown as maincrop potato it is useful for mid-early yield formation.

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ORIGINAL ARTICLE

Consequences of pre-planting treatments of potato seed tubers on leaf area index formation

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Abstract
In field trials conducted in 2000–2002, we examined the influence of pre-planting treatments of seed tubers on the formation of leaf area index. The potato varieties used were Agrie Dzeltenie (early), Piret (middle-maturing) and Ants (late). The following treatments were used: untreated control, thermal shock and pre-sprouting. Pre-sprouting treatments of all varieties and thermal shock treatment of the variety Agrie Dzeltenie had a significant effect on the leaf area index. The value and timing of maximum leaf area index were: variety specific, 4.0 units of the early variety Agrie Dzeltenie, 3.7 units of the middle-maturing variety Piret and 3.9 units of the late variety Ants. The weight of the haulms of the plants developed from physiologically older seed tubers formed faster and remained smaller. Pre-planting treatment of seed tubers provided quicker field emergence. The slower the potato plants developed the haulms, the greater the maximum weight achieved. Pre-planting treatments influence the leaf area index. The importance of this influence lies in potato varieties with different maturity times since increases in quality and yield depend on the size of the photosynthetic area.

Keywords: *Dynamics, leaf area index, pre-sprouting, thermal shock, variety.*

Introduction

Potato yield is strongly affected by the size of the leaf area and the duration of photosynthesis. The duration of photosynthesis is influenced by agro-climatic conditions and agrotechnics, e.g., night frosts can shorten the duration of photosynthesis. Rapid emergence (i.e., the formation of optimum-sized leaf area) and maintaining the plant's productivity for as long as possible are vital for obtaining high potato yields. However, early development is also associated with the earlier senescence of the leaves (Allen et al., 1979; O'Brien et al., 1983). Plants that have emerged earlier have the benefit of using more sunlight. It is known that the rate of photosynthesis decreases with senescence because the respiration rate in young leaves is higher than in older leaves. The rate of photosynthesis is highest in leaves that have just reached their maximum leaf area but this rate declines in leaves older than 50 days (van der Zaag, 1992) and the ageing process progresses more rapidly at higher temperatures. Plants from pre-sprouted tubers develop faster and reach their maximum leaf area earlier but their leaves also age more rapidly.

The rate of photosynthesis depends on the leaf area, which itself depends on the growing conditions and variety. These conditions and varieties may vary widely, and consequently the leaf areas of potato varieties differ by a magnitude of three. However, a larger mass of top leaves (canopy) may be an indicator of a larger leaf area, a higher rate of photosynthesis or a higher yield only when the leaves are not overshadowed and all the necessary components are provided. Unilateral nitrogen fertilization significantly increases the weight of the haulms of the potato plant as well as the leaf area (Grindlay, 1997) and also reduces the effects of

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diseases and weeds (Jornsgard et al., 1996; Möller et al., 1998). The vigorous growth of haulms or the density of the plants after canopy closure will cause overshadowing of many of the leaves, especially those on the lower section of the plant. Under sufficient light intensity, 320 μmol m^{-2} s^{-1} (Struik & Wiersema, 1999), the processes of photosynthesis and respiration in a plant are in balance. As light intensity decreases, a greater number of the lower leaves switch from net producers to net consumers of photosynthetic products. The production of organic matter from the whole plant therefore decreases and the tuber yield may be negatively affected.

Leaf area index (LAI) indicates the ratio of the assimilative area of the leaf and the surface area (Watson, 1947). LAI needs a value higher than 4 for as long a period as possible to achieve an optimum photosynthetic rate; otherwise, photosynthetically active radiation causes the production of organic matter to decrease (Scott & Wilcockson, 1978; Allen & Scott, 1980; Khurana & McLaren, 1982).

Certain pre-planting treatments of seed tubers can result in significantly higher potato yields through a combination of faster emergence, the formation of optimum-sized leaf area and the maintenance of productivity for as long a period as possible. Seed tubers that are stored at higher temperatures for a week before planting become physiologically older (Eremeev et al., 2003). Haulms of physiologically older seed reach their maximum weight and the LAI reaches maximum value faster than plants of younger seeds and thus an economically optimum tuber yield can be harvested much earlier (Eremeev et al., 2005). Research using seed tubers that were exposed to different temperatures at various time intervals before planting was undertaken to examine the effects of physiological age on LAI, the growth and development of potato haulms.

Materials and methods

Experimental site and design

The experiment was carried out during the growing seasons of 2000, 2001 and 2002 at the Department of Field Crop Husbandry at the Plant Biology experimental station (58°23′N, 26°44′E) of the Estonian University of Life Sciences (EMU). A randomized complete block with four replications was used (Hills & Little, 1972). The size of the test plot was 21 m^2. Within-row spacing was 25 cm and the rows were 70 cm apart. Seed tubers with a diameter of 35–55 mm were used in the experiment.

Meteorological conditions

The Estonian climate is a transitional climate from maritime to continental. It is mainly influenced by the Baltic Sea and the north-eastern part of the Atlantic Ocean. Year-round intensive cyclonic action causes moist and continuously changing weather conditions. Summer is relatively short and cool, while autumn is long and winter is mild. The vegetation period (average diurnal temperature continuously above 5°C) usually begins in the second half of April, lasts 170–180 days and ends in September or October. The period of active plant growth, in which the average diurnal temperature is continuously above 10°C, usually ranges from 115 to 135 days (Tarand, 2003). The experimental area belongs to the south Estonian upland agroclimatic region where the annual sum of active temperatures greater than 10°C averages 1750–1800 degree-days and the total annual precipitation is 550–650 mm. The mean amounts of precipitation were, during the May–September vegetation period of the experimental years, greater than average in June and July, and less than average in May, August and September (Table I). The air temperature (the mean of three years) was similar to that of the 32-year average (1966–1998); only July was significantly warmer.

Table I. Average monthly temperatures (°C) and precipitation (mm) in Estonia during the vegetation period.

	Temperatures, °C		Precipitation, mm	
Month	Average of 2000–2002*	Average of 1966–1998**	Average of 2000–2002*	Average of 1966–1998**
May	12.0	11.6	42.7	55.0
June	15.2	15.1	75.7	66.0
July	19.8	16.7	101.2	72.0
August	17.1	15.6	75.6	79.0
September	10.8	10.4	22.2	66.0

*according to the Eerika weather station.
**(Jaagus, 1999).

Plant material

The late maturing variety Ants and the middle-maturing variety Piret, both bred at the Jõgeva Plant Breeding Institute in Estonia, and the early maturing variety Agrie Dzeltenie, bred at Latvia's Priekuli State Plant Breeding Station, were used in the experiments. These cultivars were chosen because local varieties are better adapted to Estonian climatic conditions and are, therefore, able to give reasonably high yields of good quality tubers. Also, the use and effect of fertilizers and plant protection products on these cultivars have been studied on EMÜ research fields since 1951.

Soil conditions and analysis

The soil of the experimental field was Stagnic Luvisol according to WRB classification (Deckers et al., 2002) with a texture of sandy loam and a humus layer of 20–30 cm (Reintam & Köster, 2006). Soil analyses were carried out at the laboratories of the Department of Soil Science and Agrochemistry, EMU. Air-dried soil samples were passed through a 2-mm sieve. The following characteristics were determined: pH (in 1 *M* KCl and in 0.01 *M* $CaCl_2$ 1:2.5), organic carbon by Tjurin, Ca and Mg in NH_4OAc at pH 7 (Soil Survey Laboratory, 1996), P and K after the Mehlich-3 method (Handbook on Reference Methods for Soil Analysis, 1992). The Kjeldahl method was used to determine the content of total N of the soil (Procedures for Soil Analysis, 1995).

The humus layer of the experimental field had the following analysis: pH_{KCl} ≈6.2; C 1.4%; Ca_{avb} 674 mg kg^{-1}; Mg_{avb} 101 mg kg^{-1}; P_{avb} 183 mg kg^{-1}; K_{avb} 164 mg kg^{-1}; N_{tot} 0.11%; 56% sand; 35% silt and 9% clay.

Pre-planting treatments

All the dates of the particular stages of the pre-planting treatments were the same each year during the experiment. The seed tubers were kept in a storehouse, until 30 March, under equal storage conditions and at 4°C. All the potato tubers, irrespective of pre-planting treatment, were planted on the same day, 7 May. The sum of the temperatures above 0°C differed according to the treatment. The treatments were applied between 30 March and 6 May.

The effects of various pre-planting treatments of seed tubers on potato growing were analysed. The treatments were as follows:

1. Untreated (0) treatment – 37 days. The seed tubers were kept from 1 April to 6 May, i.e., 37 days at 4°C. The total accumulated temperature was 148°C.
2. Thermal shock (TS) treatment – 37 days. The seed tubers were initially removed from storage and kept for 30 days, from 1 April to 30 April, at 4°C (accumulated temperature of 120°C); then for two days, from 31 April to 1 May, at 30°C (accumulated temperature 60°C) and lastly for five days, from 2 May to 6 May, at 12°C (accumulated temperature 60°C). These seed tubers received during the thermal shock treatment an accumulated total of 240°C, which is 92°C more than in 0 treatment.
3. Pre-sprouted (PS) treatment – 37 days. The seed tubers were removed from storage and kept for 37 days, from 1 April to 6 May, at 12°C. These seed tubers received during the pre-sprouting treatment an accumulated total of 444°C, which is 204°C more than TS and 296°C more than in 0 treatment.

Experimental field agrotechnics

The agrotechnic inputs included composted manure (60 t ha^{-1}) used as an organic fertilizer before the autumn ploughing and a compound mineral fertilizer (78 kg N: 72 kg P: 117 kg K ha^{-1}) was applied at planting. For plant protection, the insecticide Fastac and fungicides Ridomil Gold, Acrobat Plus and Shirlan were used. All active ingredients for plant protection were used with 400 litres of water per ha.

Measurements

LAI was determined at five-day intervals. Each sample consisted of four plants from the test plot. The time of sample collection and the number of samples collected varied among treatments and years due to differences in emergence dates and durations of the vegetative period (e.g., in 2001 the vegetation period was long, lasting 118 days).

Leaf area can be measured in various ways including portable devices (Gordon et al., 1994; Lusk, 2002; Veteli et al., 2002) or manual methods (Haverkort et al., 1991; Burstall & Harris, 1983; Khurana & McLaren, 1982). The so-called 'copy method' was selected for determining the leaf area in this research experiment. The haulm and leaves of the sample plants were weighed together. Randomly selected leaf segments were then scanned at 100 dpi resolution and saved as black-and-white Windows Bitmap images (*.bmp). A special PC program written by Department of Botany EMU was used to calculate the areas of the scanned leaves.

Statistical analysis

Regression analysis was conducted on the compiled data (see Mead et al., 1993; Lauk, 1995, 1996; Lauk et al., 1996) using the following formula: $y = a + bx + cx^2$; where y is the argument function – LAI, a is the constant term of the equation, b and c are regression coefficients and x is the argument, the number of days after planting (DAP).

Standard errors (SE) were calculated using Lauk and Lauk's method (2000) and Student's theoretical criterion (see Mead et al., 1993) to determine confidence (CL) limits (CL_{05}–statistical significance at $p = 0.05$).

To assess the probability of differences between the three treatments, the three potato varieties and the three-year average, the least significant differences (LSD_{05}) were calculated according to the corresponding methodology (Lauk et al., 2004).

The results are expressed as not only a three-year average but also for separate seasons to indicate the effect of different years.

Results and discussion

The dynamics of LAI depending on the year

At the start of the growing cycle of the potato plant, the increase in LAI was highest in 2002 when the increase was statistically significant (LSD_{05} 0.3) until 55 DAP. Evidently, the weather of this period of the growing season was most favourable for haulm growth. The LAI started to decrease slowly, after 55 DAP, because the soil water supply decreased and nearly reached wilting point. The haulms turned yellow and dried up. The LAI was lower (LSD_{05} 0.4) during the 2000 vegetation period, in the periods 45–50 DAP and 80–100 DAP, than the average LAI of the three experiment years. This was due to the relatively cool weather conditions during the vegetation period. The good weather in 2001 was a significant factor in the highest LAI of the experiment's years, from the period of 65 DAP (LSD_{05} 0.3) until the harvest. Moisture evaporation through the plant foliage in the field is somewhat lower (41%) than from the soil (59%). The value of LAI should be at least 3.0, in order to considerably reduce the evaporation from the soil surface, and this level of shading also reduces the amount of radiation into the soil by 95–98% (MacKerron & Waister, 1985).

Earlier experiments (Eremeev et al., 2001) with late potato varieties have shown that LAI reaches the maximum value (average 3.7 units) by 72 DAP, and then starts to decrease. The Norwegian scientist Eltun (1996) concluded that the maximum LAI was formed at 68 DAP. Our experiment records that the highest LAIs were reached at 68–81 DAP; in 2002 the maximum LAI (3.7 units) was attained at 68 DAP, in 2000 at 73 DAP (3.6 units) and in 2001 at 81 DAP (4.5 units). The weather conditions were most favourable for the growth of potato plants and development of the leaf area in 2001. The water supplies were sufficient in the period of intensive growth and tuber formation, and were also efficient protection against late blight, providing effective photosynthesizing foliage until the harvest.

The dynamics of LAI depending on the seed tuber treatment

The pre-planting treatment of the seed tubers had a different effect on the leaf area formation of the different potato varieties. The initial slower development of the 0 variant caused the prolongation of its growing period. The LAI in untreated variants could be determined until 110 DAP, while the assimilative leaf area of treated variants was destroyed by 105 DAP (Table II). Jõudu et al. (2002) indicated that plants developed from pre-sprouted tubers have a better ability to assimilate nutrients from the mother tuber. The pre-planting treatment of seed tubers (PS and TS) stimulated the development of the haulms and their weight exceeded the same characteristic of 0 variants until 60 DAP. Later, the weight of the haulms of the plants developed from the 0 variant exceeded both TS and PS until the leaves perished. In the current experiment both of the pre-planting treatments of potato seed resulted in larger LAI.

The LAI maximum was reached, in all variants, at 72–76 DAP. The maximum LAI in the PS variants (3.7 units) was reached at 72 DAP, in TS variants (3.8 units) at 73 DAP and in the 0 variant (4.1 units) at 76 DAP. The LAI of the PS variant plants, starting from 75 DAP, was significantly (LSD_{05} 0.4) lower than in the 0 variants and from 80 DAP in TS variants (LSD_{05} 0.4).

Dynamics of LAI depending on the variety

Comparison of different potato varieties indicated that from the start of the haulm development until 90 DAP, the LAI was quite stable in all variants (see Table III). The earliest leaf development was observed in the early variety Agrie Dzeltenie: its LAI exceeded the middle-maturing variety Piret until 85 DAP (0.2–0.4 units) and the late variety Ants until 70 DAP (0.1–0.2 units). The LAIs of Piret, from 95 DAP, and of Agrie Dzeltenie, from 85 DAP, were, compared with Ants, statistically lower (LSD_{05} 0.4) (see Table III).

Table II. The effect of seed tuber pre-planting treatment on leaf area index (average of 2000–2002).

Days after planting	Untreated (0)	Thermal shock (TS)	Pre-sprouting (PS)
40	0.11a*	0.49ab	0.91b
45	1.14a	1.42ab	1.70b
50	2.02a	2.20a	2.36a
55	2.74a	2.83a	2.89a
60	3.32a	3.30a	3.28a
65	3.73a	3.62a	3.53a
70	4.00a	3.79a	3.65a
75	4.11a	3.80ab	3.64b
80	4.07a	3.66ab	3.48b
85	3.87a	3.37b	3.20b
90	3.52a	2.93b	2.78b
95	3.01a	2.33b	2.22b
100	2.36a	1.58b	1.53b
105	1.55a	0.68b	0.70b
110	0.58		
n[1]	122	123	123
SE[2]	0.09	0.11	0.10
CL_{05}[3]	0.20	0.24	0.22

* = Means followed by the same letter in the same row are not significantly different ($p < 0.05$).

[1] n = number of samples.

[2] SE = standard error.

[3] CL_{05} = confidence limits at $p = 0.05$.

Maximum LAI was attained by all varieties at 72–75 DAP. Agrie Dzeltenie reached its maximum LAI (4.0 units) at 72 DAP, followed by the middle-maturing variety Piret (3.7 units) and the late variety Ants (3.9 units), at 74 DAP and 75 DAP, respectively. Thus, the difference between varieties in attaining the maximum LAI was 1–3 days and 0.1–0.3 units.

Dynamics of the LAI in Ants

According to Putz (1986), rapid development and growth of assimilative leaf area occurs from emergence to the start of tuber formation. The

Table III. The effect of potato variety on leaf area index (average of 2000–2002).

Days after planting	Ants late-maturing	Piret middle-maturing	Agrie Dzeltenie early-maturing
40	0.55a*	0.32a	0.67a
45	1.44a	1.23a	1.61a
50	2.19a	1.99a	2.39a
55	2.81a	2.61a	3.01a
60	3.29a	3.08a	3.48a
65	3.63a	3.42a	3.79a
70	3.84a	3.61a	3.94a
75	3.91a	3.66a	3.93a
80	3.84a	3.57a	3.77a
85	3.64a	3.33a	3.45a
90	3.30a	2.95a	2.97a
95	2.83a	2.43ab	2.34b
100	2.22a	1.77b	1.55b
105	1.47a	0.96b	0.60b
110	0.59a	0.02b	
n[1]	122	123	123
SE[2]	0.08	0.10	0.10
CL_{05}[3]	0.18	0.24	0.22

* = Means followed by the same letter in the same row are not significantly different ($p < 0.05$).

[1] n = number of samples.

[2] SE = standard error.

[3] CL_{05} = confidence limits at $p = 0.05$.

pre-planting treatments of Ants seed tubers had a different effect on the leaf area development. The 0 variant of Ants had a slow initial development which meant that the vegetation period was longer. The LAI at 40 DAP, of the 0 variant and the TS variant, was 0.5–0.6 units lower than that of the PS variant (Table IV).

The LAI of all the 0 variants could be determined at 115 DAP, whereas in those for TS and PS variants the assimilative area had perished by 105 DAP. Plants developed from tubers treated with TS had a smaller leaf area during the vegetation period compared with the 0 variant. The PS variant of Ants had a higher LAI (LSD$_{05}$ 0.4) until 45 DAP and then, from 70 DAP until the end of vegetation, its LAI was lower than for the 0 variant.

All the variants of Ants reached their maximum LAI, 72–79 DAP. The PS variant reached maximum LAI (3.7 units) at 72 DAP, followed by the TS variant (3.9 units) and the untreated variant (4.3 units), at 74 DAP and 79 DAP, respectively. Consequently, the optimum leaf area needed for the photosynthesis of Ants in the TS variant perished two days later than in the PS variant and five days earlier than in the 0 variant.

Dynamics of LAI in Piret

The LAI of TS (0.3 units) and PS (0.7 units) in Piret exceeded the 0 variant at 40 DAP (Table V). Due to the fast initial development, the LAI of treated variants exceeded that of untreated variants, from the beginning of the vegetation until 60 DAP for TS treatment and until 55 DAP for PS.

All the variants of Piret reached their maximum LAI value, 72–77 DAP. The PS variant reached 3.5 units at 72 DAP, followed by the TS variant's 3.7 units at 73 DAP, and the 0 variant's 4.0 units at 77 DAP. The LAI subsequently decreased gradually on a daily basis due to the loss of leaves. This decrease was clearly observed in the TS and PS variants since they reached their maximum LAI earlier, by four and five days, respectively, than the 0 variants. The LAI of the TS variant started to decrease from 85 DAP (LSD$_{05}$ 0.6) and that of the PS variant from 65 DAP (LSD$_{05}$ 0.5) until the end of the vegetation period.

Dynamics of LAI in Agrie Dzeltenie

As with other varieties, the TS and PS variants of Agrie Dzeltenie emerged earlier. The LAI of these two variants proved higher than the 0 variant at the start of the vegetation period. The LAI of the TS variant increased until 40 DAP (LSD$_{05}$ 0.5) and the PS variant until 45 DAP (LSD$_{05}$ 0.6) (see Table VI). Moreover, PS variant plants reached their LAI maximum (3.7 units) at 72 DAP, followed by the TS variant (3.8 units) at 73 DAP and the 0 variant (4.1 units) at 76 DAP. The LAI of the thermally treated variants was subsequently lower than in the untreated variants from 60 DAP in the TS variants and from 65 DAP in the PS variants. The lower LAI in the thermally treated variants could be explained by the fact that a plant uses a larger amount of energy for better development of its underground organs. The LAI, in all varieties, was fairly stable from the start of haulm development until 90 DAP. As a three-years' average, maximum LAI (3.9 units) formed at 74 DAP and on the 50th day after emergence. In all variants of Agrie Dzeltenie, the LAI formed relatively steadily during the whole vegetation period, reaching its maximum at 72–73 DAP. The maximum LAI of TS variant (3.9 units) and PS variant (4.0 units) were attained by 72 DAP and in the 0 variant (4.1 units) by 73 DAP.

Table IV. The effect of seed tuber pre-planting treatment on leaf area index of variety Ants (the average of 2000–2002).

Days after planting	Untreated (0)	Thermal shock (TS)	Pre-sprouting (PS)
40	0.37a*	0.35a	0.89b
45	1.32a	1.32a	1.68a
50	2.15a	2.14a	2.35a
55	2.84a	2.80a	2.88a
60	3.39a	3.31a	3.27a
65	3.82a	3.67a	3.53a
70	4.11a	3.87ab	3.66b
75	4.27a	3.92ab	3.66b
80	4.30a	3.82b	3.52b
85	4.20a	3.57b	3.25b
90	3.96a	3.16b	2.84b
95	3.59a	2.60b	2.30b
100	3.09a	1.88b	1.63b
105	2.45a	1.01b	0.83b
110	1.69		
n[1]	40	41	41
SE[2]	0.08	0.12	0.09
CL$_{05}$[3]	0.19	0.26	0.21

* =Means followed by the same letter in the same row are not significantly different ($p < 0.05$).

[1] n =number of samples.

[2] SE =standard error.

[3] CL$_{05}$ =confidence limits at $p = 0.05$.

Table V. The effect of seed tuber pre-planting treatment on leaf area index of variety Piret (average of 2000–2002).

Days after planting	Untreated (0)	Thermal shock (TS)	Pre-sprouting (PS)
40		0.32a	0.74a
45	0.89a*	1.25ab	1.53b
50	1.79a	2.03a	2.18a
55	2.53a	2.66a	2.69a
60	3.13a	3.14a	3.08a
65	3.57a	3.46a	3.33a
70	3.86a	3.63a	3.44a
75	4.01a	3.65ab	3.43b
80	4.00a	3.51ab	3.27b
85	3.84a	3.23b	2.99b
90	3.54a	2.79b	2.57b
95	3.08a	2.20b	2.02b
100	2.47a	1.46b	1.34b
105	1.71a	0.56b	0.52b
110	0.81		
n[1]	41	41	41
SE[2]	0.13	0.13	0.11
CL$_{05}$[3]	0.29	0.30	0.25

* =Means followed by the same letter in the same row are not significantly different ($p < 0.05$).

[1] n =number of samples.

[2] SE =standard error.

[3] CL$_{05}$ =confidence limits at $p = 0.05$.

Conclusions

It should be noted that the weight of the haulms of plants developed from physiologically older seed tubers formed faster and remained smaller.

Table VI. The effect of seed tuber pre-planting treatment on leaf area index of variety Agrie Dzeltenie (average of 2000–2002).

Days after planting	Untreated (0)	Thermal shock (TS)	Pre-sprouting (PS)
40	0.10a*	0.80b	1.06b
45	1.21a	1.69ab	1.91b
50	2.14a	2.43a	2.61a
55	2.89a	3.01a	3.17a
60	3.46a	3.45a	3.58a
65	3.84a	3.73a	3.84a
70	4.05a	3.85a	3.96a
75	4.08a	3.83a	3.93a
80	3.93a	3.65a	3.76a
85	3.59a	3.32a	3.44a
90	3.08a	2.83a	2.97a
95	2.38a	2.19a	2.36a
100	1.51a	1.40a	1.60a
105	0.45a	0.45a	0.69a
n[1]	41	41	41
SE[2]	0.13	0.11	0.12
CL$_{05}$[3]	0.30	0.24	0.28

* =Means followed by the same letter in the same row are not significantly different ($p < 0.05$).

[1] n =number of samples.

[2] SE =standard error.

[3] CL$_{05}$ =confidence limits at $p = 0.05$.

Pre-planting treatment of seed tubers (i.e., increasing the physiological age) provided quicker field emergence. The slower the potato plants attained the maximum weight of the haulms, the bigger they formed. On physiologically older plants, obvious signs of senescence started to appear earlier (partial wilting and yellowing of the lower leaves). The value and timing of maximum LAI were, variety specific, 4.0 units at 72 DAP of the early variety Agrie Dzeltenie, 3.7 units at 74 DAP of the middle-maturing variety Piret and 3.9 units at 75 DAP of the late variety Ants.

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III

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THE INFLUENCE OF THERMAL SHOCK AND PRE-SPROUTING OF
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The influence of thermal shock and pre-sprouting of seed potatoes on formation of tuber yield

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Short title: Pre-treatment influence to potato yield
Topic: Plant production
This article has 5 tables and 2 figures.

Abstract

Thermal shock and pre-sprouting increase the initial development of potato plant which enables an earlier harvest. Growing the early potato without pre-sprouting is not economically viable in Nordic climate conditions. The aim of this research was to discover how pre-planting treatments of seed tubers (untreated variant, thermal shock and pre-sprouting) influence the time to emergence, the average weight of the tuber, the number of tubers per plant and the formation of yield including the yield formation dynamics. The main findings from this research experiment were that the thermal shock of seed tubers shortened the time to emergence by 2-5 days and pre sprouting by 7-12 days. Moreover, thermal shock was effective on seed production while increasing the number of tubers but the average weight of the tubers remained smaller in comparison with pre-sprouted variants. A very early yield is possible with pre-sprouted tubers consisting of large tubers; the harvest period of tubers treated with thermal shock is a little later followed by the tubers from untreated variant.

Additional key words: day after planting, emergence, growth rate, *Solanum tuberosum*, tuber formation.

Introduction

Potato (*Solanum tuberosum* L.) consumption trends in the world are that consumers prefer locally grown tubers because of their fresh and delicious taste. In order to satisfy the demand for locally grown potato, scientists are investigating the best agrotechnical measures to obtain high quality yield and to maintain the marketability and nutritional quality of potato throughout the storage and consumption period. Potato varieties which are able to provide high quality yields as early as possible in order to be market competitive are vital. Accumulated temperature, precipitation and radiation during the vegetation period favour the growth of early varieties rather than late varieties. Biologically active and potentially high-yielding seed must be prepared for planting according to the end usage. The pre-sprouting of seed tubers of early as well as late potato varieties is, among the yield-increasing pre-planting measures, widely used in the Netherlands (Struik and Wiersema, 1999). Late-maturing varieties are beneficial because of their higher yield potential and also their ability to maintain nutritional quality during storage. Another technique also used for obtaining earlier yield, besides pre-sprouting, is thermal treatment (otherwise known as thermal shock), which increases the physiological age of seed tubers and shortens the chronological time needed for the formation of harvestable tubers (Allen *et al.,* 1992; Van der Zaag, 1992a).

If the seed tubers are kept at higher temperatures for certain durations in spring, physiologically older tubers are obtained (Van Loon, 1987). This is vital when growing the early as well as late potato varieties because the maximum weight of haulms and leaf area index (LAI) are obtained earlier, so it is also possible to harvest the economically optimum tuber yield earlier. But physiologically younger plants can be more vigorous and may produce higher yields which will form somewhat later in the growing period (Wurr, 1979).

Temperatures higher than 30-35°C are rarely used in thermal shock, even for a short time, as the albumins curdle at 40°C (Kulaeva, 1997). While thermal shock is recognised as a good alternative to pre-sprouting there is scant in-depth information regarding the treatment in the literature.

Previous research with potato discovered the influential effect pre-treatments of seed tubers have on plant development and yield structure elements (Eremeev *et al.,* 2007). The hypothesis, for this research experiment is that a high temperature treatment for a short period has a positive influence on the seed tuber formation as well as contributing to earlier yield formation. The aims of this experiment were to analyse the influence of different pre-planting treatments (thermal shock and pre sprouting) on time to emergence; the average weight of tuber; the number of tubers per plant and yield formation.

Materials and Methods

Experimental site and design

The experiment was carried out during the growing seasons of 2000, 2001 and 2002 at the Department of Field Crop Husbandry at the Plant Biology experimental station (58°23´N, 26°44´E) of the Estonian University of Life Sciences (EMU), Kreutzwaldi. A randomized complete block in four replications was used (Hills and Little, 1972). The size of the test plot was 21 m^2. The distance between seed tubers was 25 cm and the distance between rows was 70 cm. Seed tubers with a diameter of 35-55 mm were used in the experiment. The dynamics of the tuber yield, the number of tubers per plant and mean tuber weight was determined with an interval of 3-5 days and each sample consisted of four plants from the test plot.

Thermal shock treatments

Until the 30th of March all seed tubers were kept in same conditions in a storage room where the temperature was kept at 4°C. Seed tubers were treated before planting as follows:

1. Untreated variant (T_o) – the seed tubers were stored in darkness at a temperature of 4°C. An additional 148°C (the average accumulation of the three experimental years) was applied to this variant from March 30th until planting.

2. Thermal shock (T_S) – the seed tubers were stored in darkness at a temperature of 4°C. A week before planting the tubers were kept in a brightly lit room for two days at 30°C and then dimly lit room for a further five days at 12°C. An additional 240°C (the average accumulation of the three experimental years) was applied to this variant from March 30th until planting. Thermal treatment of seed tubers means that they are exposed to higher temperatures for a short time. Compared to the tubers from a cellar, strong (3–4 mm) sprouts appear on the tubers treated with T_S. Under certain conditions the T_S treatment may be less labour and energy-consuming than pre-sprouting, for example by using thermo-regulated storehouses (Jõudu *et al.,* 2002).

3. Pre-sprouting (P_S) – the seed tubers were stored in darkness at a temperature of 4°C, then 37 days before planting were kept in a sufficiently humid (85-90%) and in a dimly lit room at 12°C. An additional 444°C (the average accumulation of the three experimental years) was applied to this variant from March 30th until planting.

Plant material

The late maturing variety 'Ants' and the middle-maturing variety 'Piret', both bred at the Jõgeva Plant Breeding Institute in Estonia, and the early maturing variety 'Agrie Dzeltenie', bred at the Latvian Priekuli State Plant Breeding Station, were used in the experiments. Here the results will be presented as averages of the three varieties. 'Bintje', a middle maturing variety of potato, of Dutch origin and widely grown in Europe (Wolf and Van Oijen, 2003) was, during the years of this research experiment, a standard variety at the Jõgeva Plant Breeding Institute for varieties' comparison trials in Estonian climatical conditions. 'Bintje' was, therefore, an ideal choice of variety to use in the comparisons of total yields. The key elements in the decision to choose which potato varieties for the experiment were twofold. First were the adaptability of local Estonian varieties to Estonian climatic conditions and the resultant high level of yields of good quality tubers (compared to non-local varieties). Secondly the Department of Field Crop Husbandry has for a long time studied the use and effect of fertilizers and plant protection products.

Soil conditions and analyses

The soil of the experimental field was *Stagnic Luvisol* by World Reference Base for Soil Resources 1998 classification, the texture of which is sandy loam with a humus layer of 20-30 cm (Reintam and Köster, 2006).

Soil analyses were carried out at the laboratories of the Department of Soil Science and Agrochemistry, EMU. Air-dried soil samples were passed through a 2 mm sieve. The following characteristics were determined: pH (in 1M KCl and in 0.01M $CaCl_2$, 1:2.5 w:v); organic carbon by standard Tjurin method; Ca and Mg in NH_4OAc at pH 7 (Soil Survey Laboratory Staff, 1996). Available P and K were analysed according to the Mehlich-3 method (Soil and Plant Analysis Council, 1992). The Kjeldahl method was used to determine the content of total-N of soil.

These various analyses produced the following data for: the humus layer of the experimental field - $pH_{KCl} \approx 6.2$; C 1.4%; the plant available elements in the soil - 674 mg Ca kg^{-1}, 101 mg Mg kg^{-1}; 183 mg P kg^{-1} and 164 mg K kg^{-1}; the content of total-N of soil – 0.11%; soil loam - 56% sand; 35% silt and 9% clay.

Meteorological conditions

The amount of precipitation was, during the vegetation period, from May to September, of the experimental years, greater than average in June and July, and less than average in May, August and September (Table 1). The air temperature remained similar to the average of 32 preceding years (1966-1998) except that July was significantly warmer.

Experimental field techniques

The agro-technical measures employed were typical for potato experiments. Composted manure (60 Mg ha^{-1}) before autumn ploughing was used as organic fertilizer. The tubers from all treatments were planted on 7 May each year and inorganic fertilizer (78 kg N, 72 kg P, 117 kg K per hectare) was applied locally at the same time.

The insecticide Fastac and the fungicides Ridomil Gold, Acrobat Plus and Shirlan were used for plant protection. The insecticide Fastac 50 (BASF Ag, Germany) had the active ingredient alpha-cypermethrin 100 g l^{-1}. The fungicide Ridomil Gold MZ 68 WG (Syngenta, Poland) contained Mankozeb (64%) and metalaksyl-M (4%) as active ingredients. Acrobat Plus (BASF Ag, Germany) contained di ethomorph 90 g kg^{-1} and Mankozeb 600 g kg^{-1} for active ingredients. Shirlan 500 SC (ISK Bioscience Europe S.A, Belgium) contained the active ingredient fluazinam 500 g l^{-1}.

The water usage for all the active ingredients for plant protection was set at 400 L ha^{-1}.

The dynamics of the tuber yield, the number of tubers per plant and the mean tuber weight were determined at intervals of 3-5 days. Each sample consisted of four plants harvested by hand from the test plot. The experiment was terminated at 120 DAP.

Statistical analysis

A statistical data analysis by regression methods was carried out (Mead *et al*., 1993, Lauk *et al*., 1996), using the following formula: $y = a + bx + cx^2$; where 'y' is the argument function – tuber yield, number of tubers per plant or mean tuber weight, 'a' is the constant term of the equation, 'b' and 'c' are regression coefficients and 'x' is the argument, the number of days after planting (DAP). The derivative of the given function (b-2c) indicates the increase of value calculated according to the formula for each following day.

Separate regression formulas were found for every variant and based on their differentials the average formulas for multiple years were calculated. Standard errors (SE) and confidence limits (CL_{05} – level of statistical significance P = 0.05) were calculated by using the relevant methodology (Lauk and Lauk, 2000). The calculation of confidence limits was based on Student's theoretical criterion (Mead *et al.* 1993).

All the data in the tables were calculated according to the regression formulas of regression analysis. To assess the probability of differences between treatments, the least significant differences (LSD_{05}) were calculated according to Lauk *et al.* (2004). Statistica 7 (Statsoft Inc, 2005) was used for the statistical analysis. Vertical bars denote 0.95 confidence intervals.

In this paper all the experimental data were presented on the average of the three years 2000-2002.

Results

Influence of treatments on the number of tubers

The number of T_S treated tubers significantly exceeded the number of tubers of the untreated variants (T_o), until 60 DAP (Table 2). At the same time the number of P_S treated tubers exceeded the 50-60 DAP numbers of tubers for the untreated plants (T_o). The significant differences between the P_S and T_o treatments occurred on 50 DAP (LSD_{05} 2.2) to 55 DAP (LSD_{05} 1.6). In the period of 85-105 DAP fewer tubers in the case of T_S treatment were observed, LSD_{05} 1.4, than for P_S treatment. Based on the average results of the three year experiment, T_S increased the number of tubers per plant from the start of tuber formation until the harvest (statistically significantly until 60 DAP). P_S increased the average number of tubers per plant until 55 DAP (statistically significantly until 55 DAP). The greatest number of tubers per plant occurred on average at 94 DAP; in P_S treatment the greatest numbers occurred at 93 DAP (12.6 tubers), followed by T_S (14.0 tubers) and T_o treatment (13.2 tubers), at 94 and 95 DAP, respectively.

Influence of treatments on the weight and growth rate of tubers

As the average of the three varieties, P_S increased the formation of mean tuber weight during the vegetation period – LSD_{05} 4.9 (Table 3). T_S significantly decreased the mean tuber weight from 115 DAP to 120 DAP to the harvest, the interval of tubers weights were from 5.2 g to 6.1 g, respectively. The weight of the tubers, during the vegetation period, of the P_S treatment exceeded those of the T_o treatment by 5.8 g to 11.6 g, ($LSD_{0.5}$ 4.9) and those of the T_S treatment by 4.4 g to 12.7 g, ($LSD_{0.5}$ 4.3).

The increment of the weight of tubers (as the average of 2000-2002) in P_S treatment exceeded the T_o treatment by 0.21 g day^{-1} (Fig. 1). The single tuber average mass formation is significant from the 50 DAP. The single tuber average mass formation increase by P_S treatment exceeded the increase by T_o treatment by 0.21 g day^{-1} on 55 DAP. The T_S treatment exceeded the T_o treatment by 0.31 g day^{-1} from 50 DAP. The increment of single tuber average mass, in the case of T_S treatment, during the 50-120 DAP interval, exceeded the T_o-treatment by 0.10-0.19 g day^{-1}. The smallest rate of increment during the 50-100 DAP interval was observed in tubers that were treated by T_S.

Influence of treatments on the yield

The yield formation of P_S treatment tubers had already started by 45 DAP (0.7 Mg ha^{-1}), followed by T_S treatment 50 DAP (4.9 Mg ha^{-1}) and the T_o treatment 55 DAP (6.0 Mg ha^{-1}) (Table 4). Both the pre-planting treatments of seed tubers accelerated the start and increase of tuber formation during the initial growth period, T_S treatment until 60 DAP, P_S treatment until 110 DAP.

The increment of the average weight of a T_S tuber during the period of 50-120 DAP, exceeded the T_o treatment by 0.10-0.19 g day^{-1} and during the period of 50-100 DAP it was lower than that of the P_S treatment by 0.02-0.31 g day^{-1}. While both T_S and P_S treatments started to form tubers earlier, the growth rate of tuber weight in the T_o treatment was higher, exceeding the T_S treatment by 0.15 Mg day^{-1} and the P_S treatment by 0.08 Mg day^{-1} at 55 DAP (Fig. 2). The growth rate of the different variants were even at 95 DAP. While both, the T_S and P_S variants started to form tubers earlier, the growth rate of tuber weight in the T_o treatment was higher, exceeding the T_S treatment by 0.15 and the P_S treatment by 0.08 Mg day $^{-1}$ at 55 DAP (Fig. 2).

The varieties

The comparison of experimental varieties showed that 'Piret' and 'Agrie Dzelteni' were, by the number of tubers, quite similar with 9.9 and 10.5 units respectively, and that 'Ants' and 'Bintje' were also similar with 12.2 and 12.3 units respectively (Table 5). 'Bintje' provided the highest tuber mass with a yield of 762.9 g, which was significantly higher than either 'Piret' (515.7 g) and 'Agrie Dzeltenie' (550.1 g) but not when compared to 'Ants' (574.7 g). No significant differences were observed in the yield range, 24.4-32.8 Mg ha^{-1}, of the experimental varieties.

Discussion

The pre-planting treatment influence to the potato emergence and number of tubers

Physiological ageing advances sprout growth, crop emergence, crop establishment and usually improved tuber yields (Burke and O'Donovan, 1998). The onset of developmental stages and their duration is often quite different. They depend on the biological characteristics of a potato variety, the quality of seed potato, climatic and soil conditions and also the agrotechnical measures used. Some authors have found that physiologically older seed has a faster emergence than younger seed (Iritani, 1968, O'Brien *et al.,* 1983), others have found no difference (Bus and Schepers, 1978). The experiments of Van Loon (1987) showed that the physiologically older seed emerged more slowly in all years.

A potato plant usually takes 20-35 days for to emerge in Estonian climatic conditions. The time from planting to emergence depends on the treatment of seed tubers, i.e. their physiological age (Jõudu *et al.,* 2002). In this study, T_S accelerated the emergence of plants by 2-5 days and P_S by 7-12 days. T_S had a positive effect on a potato plant during its early developmental phases. The length of periods from planting to emergence depended on the physiological age of seed tubers (Struik and Wiersema, 1999).

Intensive growth of tubers begins when the above-ground parts of the plant have fully developed (LAI is at least 4). But different varieties have significant variations (Putz, 1986). Tuber formation in early varieties usually takes place earlier and their growth is much quicker than in late varieties. Also the plants from physiologically older tubers of late varieties begin their tuber formation slightly earlier (Van der Zaag 1992b). T_S treatment increases the number of tubers if compared to P_S treatment (see Table 2), therefore, T_S treatment could be suggested for usage in seed-growing enterprises, as their main purpose is to obtain the maximum number of tubers from one plant. Similar findings were reported by Van der Zaag and Van Loon (1987) and Moll (1985).

The pre-planting treatment influence on the weight of tubers

The weight of tubers depends on the weather conditions and the available nutrients during the tuber formation. The weight also depends on the growth and development of leaves and branches, formation of assimilation products and their distribution between different parts of the plant, the rate of tuber formation and the perishing time of the haulms (Panelo and Caldiz, 1989). According to data presented by Burke (1997), the physiological age of tubers increases their average weight; in our experiment this effect was seen only in P_S treatment (Table 3). Among pre-planting treatments of seed tubers, P_S had the strongest influence on tuber weight; in this variant the highest value (77.6 g) formed at 120 DAP. According to Putz (1986), after the death of the haulms the growth of tubers ceases, the skin hardens and starts to suberizate. Decisions taken while planning the harvesting period should not be based on the data of years with optimum weather conditions but the average years. At the end of vegetation period the increase of the average weight of the tuber occurred mainly at the expense of the average size tuber (35-55 mm) and large tubers (over 55 mm).

The pre-planting treatment and variety influence to the yield

The duration of yield formation could be shortened according to Möller *et al.* (2001) by 8-14 days with the pre-growing of seed tubers. The more unfavourable the conditions are during planting, the higher is the efficiency of pre-growing. This applies especially for temperature, since with the help of pre-sprouting the formation of maximum yield is shifted about couple of weeks earlier and consequently yield losses due to potato late blight are reduced. This research experiment established that T_S had a positive effect until mid-August; so if harvesting is planned in September, there is no need to thermally treat the tubers and bear the extra costs involved, especially if cultivation occurs early in the growing season with medium to early varieties. The experiment has proven that physiologically older tubers have a higher yield potential, particularly during the early period of tuber formation and growth. When P_S was used, the tubers received more heat than during T_S, therefore P_S tubers can be considered as physiologically older. The yield difference of the physiologically older tubers, of the T_S and P_S treatments, decreases more slowly than compared to the T_o treatment. Tubers that were treated with T_S were physiologically older compared to the T_o treatment, enabling a higher growth rate of tubers resulting in earlier yield formation. Gradual maturation of the potato yield helps to lengthen the harvesting period even when growing just one variety. The average Estonian potato yield has recently been as low as 10–18 Mg ha^{-1} (ESA, 2004). All T_S and P_S treatments in the current experiment reached maximum yield by 120 DAP and the yield levels were about 50 Mg ha^{-1}. Yields per hectare ultimately depend on radiation levels, the agro-technical measures afforded by the grower and the potato variety's potential; given favourable conditions and affordable measures the estimation is that the potential yields in Estonia could reach as high as 67-78 Mg ha^{-1}.

According to the results of the three year experiment the conclusion can be made that for very early potato yield the pre-sprouting treatment must be used. Thermal shock is efficient in seed production for while it produces more tubers their average weight is smaller than P_S tubers. If the purpose is the growing of potato for consumption then T_S is a useful tool for mid to early yield formation. At the same time, P_S consumes a lot of time and energy but with pre-sprouting a very early yield is achieved using the variety's full yield potential.

The different pre-planting treatments of seed tubers enable variations in harvest times for any given potato variety. A very early yield is possible with P_S treated tubers while the harvest period for T_S treated tubers is in the second half of July or the start of August.

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VAN LOON C.D., 1987. Effect of physiological age on growth vigour of seed potatoes of two cultivars. 4. Influence of storage period and storage temperature on growth and yield in the field. Potato Res 30, 441-450.

Table 1. Average monthly temperatures (ºC) and precipitation (mm) in Estonia during the vegetation period.

Month	Temperatures, ºC		Precipitation, mm	
	Average of 2000-2002*	Average of 1966-1998**	Average of 2000-2002*	Average of 1966-1998**
May	12.0	11.6	42.7	55
June	15.2	15.1	75.7	66
July	19.8	16.7	101.2	72
August	17.1	15.6	75.6	79
September	10.8	10.4	22.2	66

* according to the Eerika weather station

** (Jaagus 1999)

Table 2. The effect of pre-planting treatment on the number of tubers per plant (the average of 2000-2002 results).

Days after planting	Untreated (T_o)	Thermal shock T_S	Difference	Pre-sprouting (P_S)	Difference	
			T_S-T_o		P_S-T_o	P_S-T_S
45		3.5		4.7		1.2
50	4.0	5.6	1.6*	6.2	2.2*	0.6
55	6.0	7.4	1.4*	7.6	1.6*	0.2
60	7.7	9.0	1.3*	8.8	1.1	-0.2
65	9.2	10.4	1.2	9.8	0.6	-0.6
70	10.4	11.5	1.1	10.7	0.3	-0.8
75	11.5	12.5	1.0	11.4	-0.1	-1.1
80	12.2	13.2	1.0	12.0	-0.2	-1.2
85	12.8	13.7	0.9	12.3	-0.5	-1.4*
90	13.1	14.0	0.9	12.5	-0.6	-1.5*
95	13.2	14.0	0.8	12.5	-0.7	-1.5*
100	13.1	13.9	0.8	12.4	-0.7	-1.5*
105	12.7	13.5	0.8	12.1	-0.6	-1.4*
110	12.1	12.9	0.8	11.6	-0.5	-1.3
115	11.3	12.1	0.8	11.0	-0.3	-1.1
120	10.2	11.1	0.9	10.1	-0.1	-1.0
N[1]	126	130		137		
SE[2]	0.3	0.3		0.3		
CL$_{05}$[3]	0.6	0.7		0.7		
LSD$_{05}$[4]			1.3		1.3	1.4

* = Significant differences ($P < 0.05$) between treatments

[1] N = number of samples

[2] SE = Standard error

[3] CL$_{05}$ = Confidence limits at $P = 0.05$

[4] LSD$_{05}$ = Least significant differences at $P = 0.05$

Table 3. The effect of pre-planting treatment on the average weight (g) of a tuber, (the average of 2000-2002 results).

Days after planting	Untreated (T_o)	Thermal shock (T_S)	Difference	Pre-sprouting (P_S)	Difference	
			T_S-T_o		P_S-T_o	P_S-T_S
45		0.9		3.6		2.7
50	4.6	8.7	4.1	13.1	8.5*	4.4*
55	12.4	16.0	3.6	21.9	9.5*	5.9*
60	19.8	22.8	3.0	30.0	10.2*	7.2*
65	26.7	29.1	2.4	37.5	10.8*	8.4*
70	33.1	34.9	1.8	44.4	11.3*	9.5*
75	39.1	40.2	1.1	50.6	11.5*	10.4*
80	44.6	45.0	0.4	56.2	11.6*	11.2*
85	49.6	49.4	-0.2	61.1	11.5*	11.7*
90	54.2	53.2	-1.0	65.4	11.2*	12.2*
95	58.2	56.5	-1.7	69.0	10.8*	12.5*
100	61.9	59.3	-2.6	72.0	10.1*	12.7*
105	65.0	61.7	-3.3	74.4	9.4*	12.7*
110	67.8	63.5	-4.3	76.1	8.3*	12.6*
115	70.0	64.8	-5.2*	77.2	7.2*	12.4*
120	71.8	65.7	-6.1*	77.6	5.8*	11.9*
N[1]	126	130		137		
SE[2]	1.1	0.9		1.1		
CL$_{05}$[3]	2.5	1.9		2.4		
LSD$_{05}$[4]			4.4		4.9	4.3

* = Significant differences ($P < 0.05$) between treatments

[1] N = number of samples

[2] SE = Standard error

[3] CL$_{05}$ = Confidence limits at $P = 0.05$

[4] LSD$_{05}$ = Least significant differences at $P = 0.05$

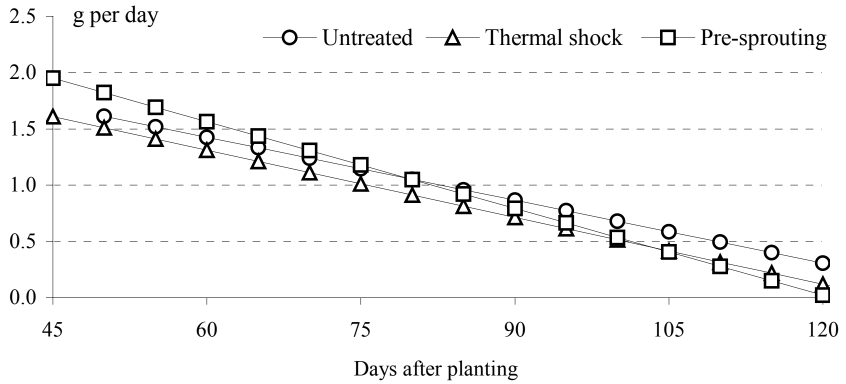

Figure 1. The effect of pre-planting treatment on the growth rate of the average weight of tubers (the average of 2000-2002 results). The data points values predicted on the basis of the regression.

Table 4. The effect of pre-planting treatment on potato yield (Mg ha^{-1}) (the average of 2000-2002 results).

Days after planting	Untreated (0)	Thermal shock (T_S)	Difference	Pre-sprouting (P_S)	Difference	
			T_S-0		P_S-0	P_S-T_S
45				0.7		
50		4.9		6.9		2.0
55	6.0	10.4	4.4*	12.8	6.8*	2.4
60	11.9	15.5	3.6*	18.2	6.3*	2.7
65	17.2	20.2	3.0	23.2	6.0*	3.0
70	22.1	24.5	2.4	27.7	5.6*	3.2
75	26.6	28.5	1.9	31.9	5.3*	3.4
80	30.6	32.0	1.4	35.5	4.9*	3.5*
85	34.1	35.2	1.1	38.8	4.7*	3.6*
90	37.2	37.9	0.7	41.6	4.4*	3.7*
95	39.8	40.3	0.5	44.0	4.2*	3.7*
100	42.0	42.3	0.3	46.0	4.0*	3.7*
105	43.7	43.9	0.2	47.5	3.8*	3.6*
110	45.0	45.1	0.1	48.7	3.7*	3.6*
115	45.8	45.9	0.1	49.3	3.5	3.4
120	46.1	46.4	0.3	49.6	3.5	3.2
N[1]	126	130		137		
SE[2]	0.9	0.8		0.8		
CL_{05}[3]	1.9	1.7		1.8		
LSD_{05}[4]			3.6		3.7	3.5

* = Significant differences ($P < 0.05$) between treatments

[1]N = number of samples

[2]SE = Standard error

[3]CL_{05} = Confidence limits at $P = 0.05$

[4]LSD_{05} = Least significant differences at $P = 0.05$

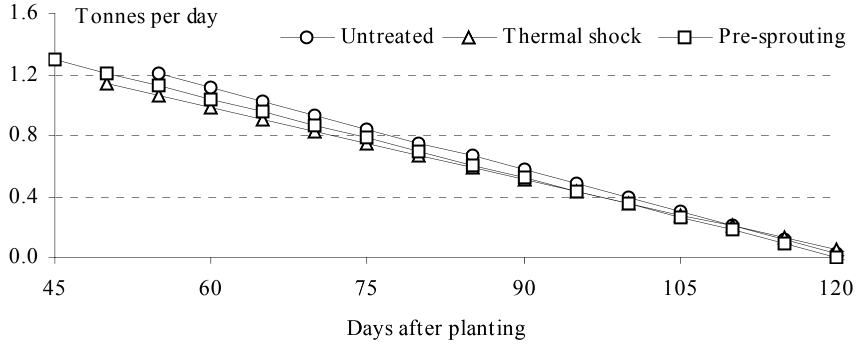

Figure 2. The effect of pre-planting treatment on potato yield increase (the average of 2000-2002 results). The data points values predicted on the basis of the regression.

Table 5. The number of tubers (pieces per plant), mass (g) and yield (Mg ha^{-1}) of potato varieties in the average of three years. Different letters within each column indicate significant difference of the mean values at $P < 0.05$.

Variety	Number of tubers, pieces per plant	Mass, g per plant	Yield, Mg ha^{-1}
Piret*	9.9^{a}	515.7^{a}	24.4^{a}
Agrie Dzeltenie*	10.5^{ab}	550.1^{a}	29.5^{a}
Ants*	12.2^{c}	574.7^{ab}	31.4^{a}
Bintje**	12.3^{bc}	762.9^{b}	32.8^{a}

* The average of variety is given as 15 untreated plants

**The average of variety is given as 30 untreated plants

IV

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Effects of thermal shock and pre-sprouting on field performance of potato in Estonia

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Abstract. Pre-sprouting (PS), and to a lesser degree, pre-planting thermal shock (TS) had positive effects on tuber yield and other performance indicators. The experiment was carried out during the 2000, 2001 and 2002 growing seasons in the Department of Field Crop Husbandry of the Estonian University of Life Sciences. An untreated control (0) was compared with TS (2 days at 30°C, then 5 days at 12–15°C in a lighted room just prior to planting) and PS (35–38 days before planting in a humid (85–90%) and lighted room at 12–15°C). All treatments were applied to three varieties: 'Agrie Dzeltenie' (early), 'Piret' (medium early) and 'Ants' (medium late). In the present study, the TS accelerated the emergence of plants by 2–5 days and PS by 7–12 days. Averaged over 3 years and 3 varieties, maximum leaf area index (LAI, 3.9 units) was reached 74 days after planting (DAP) and on the 50th day after emergence. Maximum LAI was 3.7 at 72 DAP for PS, 3.8 at 73 DAP for TS, and 4.1 at 76 DAP for the control. TS accelerated the beginning of tuber formation by about 5 days compared to the control, but the tuber yield of the control equalled TS from 65 days onward. Tuber formation began even slightly earlier in the PS treatment, and tuber yield exceeded PS throughout the season. All treatments reached maximum yield by 120 DAP.

Key words: dynamics, growth analysis, haulms, LAI, leaf area index, tuber yield

INTRODUCTION

Potato plant (*Solanum tuberosum* L.) has an indeterminate growth pattern. Quantifying above-and below-ground plant phenology in relation to different environmental factors (Ojala et al., 1990) and cultivars (Van der Zaag et al., 1990) is an important step toward an adequate understanding of potato growth and development. This quantification has been done only in a few environments, especially in relation to pre-planting thermal shock (TS) and pre-sprouting treatments (Lõhmus et al., 1999).

A physiologically young seed tuber has preconditions to develop better and stronger roots as well as all above-ground parts of the plant, and the largest assimilation surface possible, leading to formation of a high tuber yield. The drawback is that the late sprouting and canopy closure decreases the ability of potato plants to compete with weeds. The delayed development of the assimilation surface puts much of the assimilation potential past the time of maximum physiologically active radiation.

Getting a relatively early potato yield is important not only for early varieties but also for late ones. Late varieties are grown for their higher tuber yield potential and easier preservation. Various methods are used to get an earlier potato yield, including the thermal treatment of seed tubers, which adds physiological age to potato tubers and shortens the chronological time that is necessary for the tuber yield to become harvest-ripe (Allen et al., 1992). This method boosts enzyme activity in tubers, stimulates faster development of sprouts from the eyes, reduces the sprouting period and accelerates plant development and tuber yield formation. The physiological age is defined as the physiological status of a tuber that influences its productivity. It could also be defined as the developmental level which has been modified by varying the chronological age (Caldiz et al., 2001). The physiological age of a tuber is its chronological age that has been affected by storage conditions (Struik & Wiersema 1999).

The physiological age of the seed tubers could be divided into the following stages: (1) single sprout stage; (2) multiple sprout stage; (3) branching stage; and (4) small tuber formation stage (Wurr 1982). If seed tubers are kept at a higher temperature for some time in spring, they will produce physiologically older tubers. This can be applied to the growing of both early and late potatoes, as the maximum weight of the haulms (leaves and stems) and maximum leaf area are achieved more quickly. An economically optimal tuber yield can also be harvested earlier. However, physiologically younger plants can be more viable and even form a greater tuber yield, although slightly later. The physiological age of the tuber affects the number of sprouts and the sprout behaviour, the growth pattern of the plant that originates from it and, sometimes, the tuber yield of the crop produced from it (Van der Zaag & Van Loon, 1987).

MATERIALS AND METHODS

The experiment was carried out for three years (2000, 2001 and 2002) using two pre-planting treatments on three potato plant varieties. The location was the Plant Biology experimental station of the Department of Field Crop Husbandry (58°23′N, 26°44′E) in EMU IAES. Random block-placement in 4 repetitions was used (Little & Hills, 1972). The size of a test plot was 21 m^2, the distance between furrows was 70 cm and the distance between seed tubers, 25 cm. Seed tubers with a diameter of 35–55 mm were used in the experiment.

Seed tuber treatments were as follows:

1. Untreated variant (0) – no thermal treatment was conducted;
2. Thermal shock (TS) – a week before planting the seed tubers were kept for 2 days at 30°C, then for 5 days at 12–15°C in a lighted room (Lõhmus et al., 1999). Thermal treatment of seed tubers means that they are exposed to higher temperatures for a short time. Compared to the tubers from the cellar, strong (3–4 mm) sprouts appear on the tubers treated with TS. Under certain conditions the TS treatment may be less labour- and energy-consuming than pre-sprouting, for example by using thermo-regulated storehouses (Jõudu et al., 2002);
3. Pre-sprouting (PS) – the tubers were kept for 35–38 days before planting in a sufficiently humid (85–90%) and lighted room at 12–15°C. Seed tubers were pre-sprouted in wooden boxes (in 1 or 2 layers).

The late variety ‘Ants’ and the middle-maturing variety ‘Piret’, both bred at the Jõgeva Plant Breeding Institute in Estonia, and the early variety ‘Agrie Dzeltenie’, bred at the Latvian Priekuli Plant Breeding Institute, were used in the experiments. Local varieties were used because they are better adapted to our climatic conditions and are therefore able to produce relatively high yields with good quality. Also, we have extensive experience with optimum fertilization and chemical plant protection for these varieties at our department fields in EMU.

The soil of the experimental field was *Stagnic Luvisol* by WRB classification (Deckers et al., 1998); the texture is sandy loam with a humus layer of 20–30 cm (Reintam & Köster, 2006). The soil data of the experimental field was as follows: pH ≈6.2; C 1.4%; Ca 674 mg kg^{-1}; Mg 101 mg kg^{-1}; P 183 mg kg^{-1}; K 164 mg kg^{-1}; N 0.11%.

The amount of precipitation during the vegetation period (from May to September) of the experimental years was above average in June and July, and less than average in May, August and September (Table 1). The air temperature remained similar to the average of 32 years (1966–1998); only July was significantly warmer.

Table 1. Average monthly temperatures (ºC) and precipitation (mm) in Estonia during the vegetation period.

Month	Temperatures, ºC		Precipitation, mm	
	Average of 2000–2002*	Average of 1966–1998**	Average of 2000–2002*	Average of 1966–1998**
May	12.0	11.6	42.7	55
June	15.2	15.1	75.7	66
July	19.8	16.7	101.2	72
August	17.1	15.6	75.6	79
September	10.8	10.4	22.2	66

* according to the Eerika weather station
** (Jaagus 1999)

Agrotechnics were typical for potato experiments (Table 2). Composted manure (60 t ha^{-1}) was used as organic fertilizer before autumn ploughing. Mineral fertilizers were applied locally, concurrently with planting of the potatoes in spring. In 2000–2002, compound mineral fertilizer (78 kg N, 72 kg P, 117 kg K ha^{-1}) was applied at planting. For plant protection, insecticide Fastac and fungicides Ridomil Gold, Acrobat Plus and Shirlane were used. All active ingredients for plant protection were used with 400 l of water per ha^{-1}.

The dynamics of the weight of the haulms (leaves and stems), leaf area index (LAI) and tuber yield were determined at a 3–5 day interval; each sample consisted of 4 plants from the test plot.

As various tuber thermal treatment methods were used, the first samples were taken at different times. The number of samplings also depended on the duration of the vegetation period.

Table 2. Agrotechnics of the experiment.

	Year		
	2000	2001	2002
Application of organic fertilizer	12th October	9th October	15th October
Ploughing of red clover Aftermath	13th October	10th October	19th October
Cultivation	20th, 25th April	8th May	7th May
Deep cultivation	2nd May	8th May	7th May
Furrowing	3rd May	9th May	8th May
Application of mineral fertilizers and planting of potatoes	4th May	10th May	9th May
Number of harrowing	1	1	1
Number of hilling	3	3	3
Spraying against late blight	2 times	5 times	5 times
Final harvest	5th September.	22nd September	4th September

Statistical data analysis by regression methods were carried out (Mead et al., 1993; Lauk, 1995; 1996; Lauk et al., 1996).

The following formula was used:

$$y = a + bx + cx^2,$$

wherein: y – argument function, the index that is calculated on the basis of the equation: LAI, haulm weight, or tuber yield, a – constant term of the equation, b and c – regression coefficients, x – argument; number of days after planting (DAP).

For every variant, separate regression formulas were found and based on their differentials it was possible to calculate the average formulas for multiple years. Standard errors (SE) and confidence limits (CL_{05} – level of statistical significance $P = 0.05$) were calculated by using the relevant methodology (Lauk & Lauk, 2000). The calculation of confidence limits was based on the Student's theoretical criterion (Mead et al., 1993).

All the data in the figures are calculated according to the regression formulas of regression analysis. To assess the probability of differences between test variants the least significant differences (LSD_{05}) were calculated according to the corresponding methodology (Lauk et al., 2004).

The derivative of this function (b–2c) indicates the estimated increase per day. In this paper all the experimental data presented are based on the average of 2000–2002.

RESULTS AND DISCUSSION

Physiological aging advanced sprout growth, crop emergence, crop establishment and usually improved tuber yield (Burke and O'Donovan 1998). The arrival of developmental stages and their duration is often quite varied, depending on the biological characteristics of a variety, the quality of seed potato, climatic and soil conditions and the agrotechnical measures used (Christiansen et al., 2006). It usually takes 20–35 days for a potato plant to emerge in Estonian climatic conditions (Jõudu et al., 2002), depending on the treatment of seed tubers.

Earlier studies at the Department of Field Crop Husbandry indicated that PS and TS increased the physiological age of seed tubers and initiated their earlier emergence. Plants from seed tubers treated before planting emerged 1–4 days (late varieties) and 1–7 days (early varieties) earlier than the untreated ones (Lõhmus et al., 1999, Eremeev et al., 2001). In the present study, the TS accelerated the emergence of plants by 2–5 days and PS by 7–12 days (Fig. 1). The TS had a positive effect on potato plant during its early developmental phases. The length of periods from planting to emergence depended on the physiological age of seed tubers (Struik & Wiersema, 1999). The faster growth of the haulm of the plants that developed from thermally treated seed tubers provided furrow coverage nearly a week earlier. As a result, the last intertillage could be eliminated at the critical time when there were very favourable conditions for the growth of weeds.

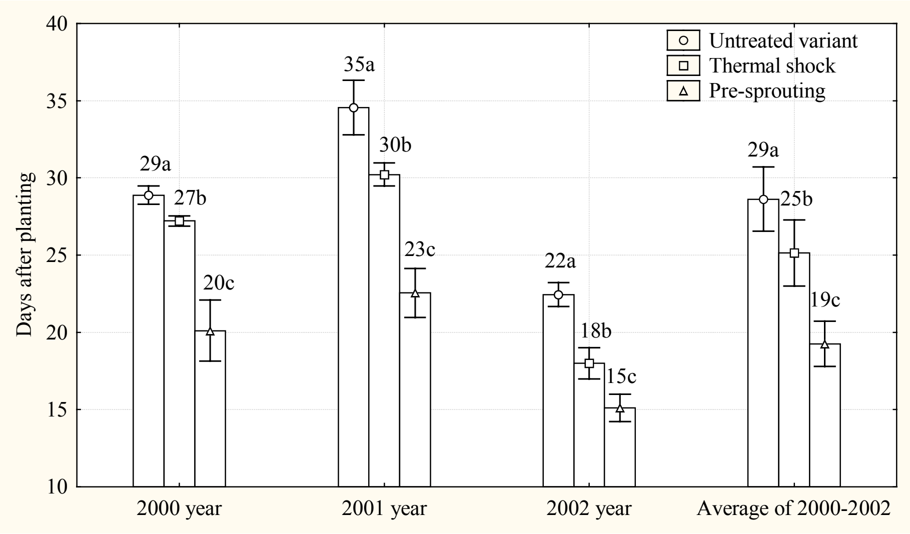

Fig. 1. The emergence of potato plants. Vertical bars denote 0.95 confidence intervals. Different letters indicate significant differences (P < 0.05) between planting dates.

Leaf area index indicates the ratio of assimilative area of the leaf and the surface area (Watson, 1947). For optimal photosynthetic rate it is necessary that the LAI would be over 4 for as long a period as possible, otherwise the use of photosynthetically active radiation and the resulting production of organic matter decreases (Scott & Wilcockson, 1978; Allen & Scott, 1980; Khurana & McLaren, 1982).

The pre-planting treatment of the seed tubers had different effects on the leaf area formation of the varieties. At first, the 0-variant developed more slowly, causing the prolongation of its growing period. The LAI in untreated variants could be determined until 110 DAP while the assimilative leaf area of treated variants was destroyed by 105 DAP (Fig. 1). According to Jõudu et al. (2002), plants developed from pre-sprouted tubers are better able to assimilate nutrients from the mother tuber. The pre-planting thermal treatment of seed tubers (TS and PS) accelerated the growth and development of the leaves and leaf area from the beginning of sprouting until 60 DAP (statistically significant until 45 DAP). Later, there was a similar increase of the leaf area in the different variants (Fig. 1). Earlier experiments with late varieties indicate that the maximum LAI (average 3.7 units) increased until 72 DAP and then started to decrease (Eremeev et al., 2001). In the present research the maximum LAI (3.9 units) was reached 74 DAP and on the 50th day after emergence. The maximum LAI in variant PS was achieved by 72 DAP (3.7 units), in TS (3.8 units) and 0 (4.1 units) respectively by 73 and 76 DAP. In varieties with a shorter growth period the leaf area reaches its maximum earlier.

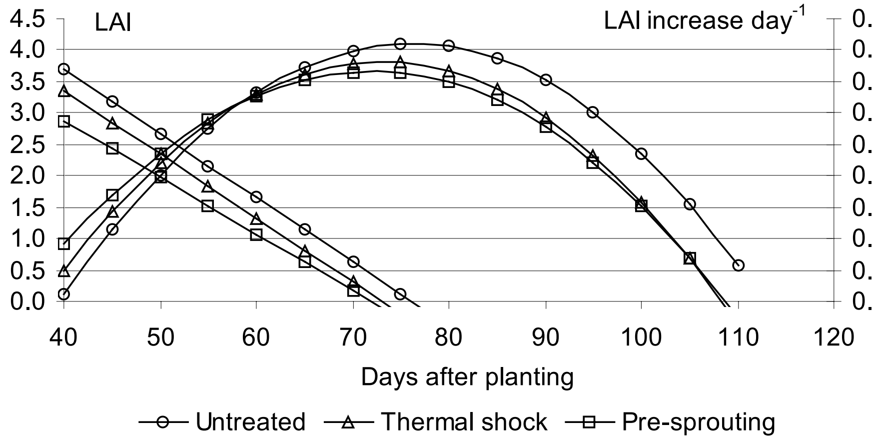

Fig. 1. Influence of the seed tuber pre-planting preparation method on the LAI (the average of 2000–2002, t ha^{-1}).

0 = Untreated variant: $y = -13.7+0.468x-0.00307x^2$, $n=123$, $R^2=0.953$, $SE=0.09$, $CL_{05}=0.20$;
TS = Thermal shock: $y=-12.5+0.446x-0.00306x^2$, $n=123$, $R^2=0.917$, $SE=0.11$, $CL_{05}=0.24$;
PS = Pre-sprouting: $y=-10.3+0.389x-0.00271x^2$, $n=123$, $R^2=0.911$, $SE=0.10$, $CL_{05}=0.22$.

Thus, the weight of the haulms of the plants that developed from physiologically older seed tubers formed more quickly and remained smaller. The pre-planting treatment of seed tubers (*i.e.* increasing the physiological age) provided earlier field emergence. The later the potato plants attained the maximum weight of the haulms, the bigger their size. On physiologically older plants obvious signs of senescence started to appear earlier (partial wilting and yellowing of the lower leaves). According to Putz (1986), after the death of the haulms, the growth of tubers ceases, the peel hardens and starts to suberizate.

The leaf areas increased most intensively in all variants at 40 DAP, whereas in the variants that sprouted later the increment of the LAI was bigger (in variant 0 – 0.22 units, in TS – 0.20 units, in PS – 0.17 units per day). After 40 DAP the increment of the LAI gradually decreased. All varieties that were used in the experiment demonstrated relatively even speed of the growth of the LAI throughout the vegetation period.

Weight of the haulms. The pre-planting thermal treatment of seed tubers (PS and TS) accelerated the development of the haulms, and the weight of the latter was higher than in variant 0–50 DAP (Fig. 2). The haulms reached its maximum weight in variant PS by 76 DAP, in TS by 77 DAP and in 0 by 81 DAP. The later the maximum weight of the haulms was achieved, the bigger it was, because the visible signs of aging appeared earlier in physiologically older plants. Thus, the maximum weight of the haulms in variant 0 was 31.9 t ha^{-1}, exceeding PS and TS respectively by 4.2 and 2.9 t ha^{-1}. Therefore the weight of the haulms in plants formed from physiologically older seed tubers developed faster and was smaller.

The growth of the weight of the haulms was the most intensive in all variants at 40 DAP (variant 0 – 1.43 t day^{-1}, TS – 1.26 and PS –1.06 t day^{-1}).

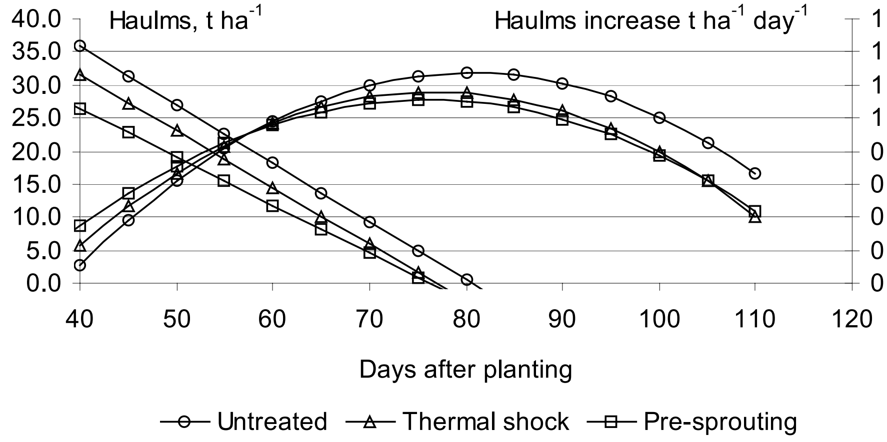

Fig. 2. Influence of the seed tuber pre-planting preparation method on the weight of the haulms (the average of 2000–2002, t ha^{-1}).

0 = Untreated variant: $y = -82.8+2.849x-0.01769x^2$, $n=117$, $R^2=0.985$, $SE=0.45$, $CL_{05}=1.02$;
TS = Thermal shock: $y=-72.3+2.63x-0.01715x^2$, $n=117$, $R^2=0.946$, $SE=0.55$, $CL_{05}=1.24$;
PS = Pre-sprouting: $y=-57.1+2.227x-0.01462x^2$, $n=117$, $R^2=0.946$, $SE=0.46$, $CL_{05}=1.04$.

Tuber yield. The pre-planting thermal treatment of seed tubers (TS) accelerated the beginning of tuber yield formation and ensured its increase during the initial growth period (until 60 DAP). The positive effect of pre-sprouting on the tuber yield was longer (until 110 DAP) (Fig. 3). All TS- and PS-variants reach maximum yield by 120 DAP.

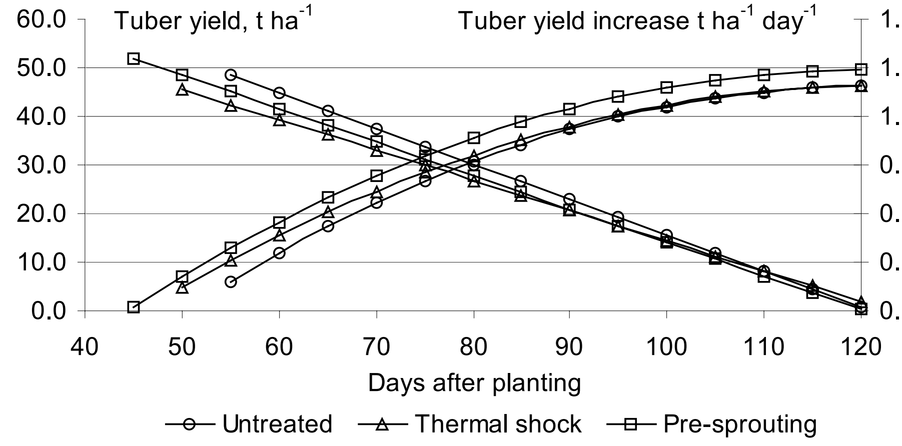

Fig. 3. Influence of the seed tuber pre-planting preparation method on the tuber yield (the average of 2000–2002, t ha^{-1}).

0 = Untreated variant: $y=-88.2+2.216x-0.00914x^2$, n=126, $R^2=0.960$, SE=0.88, $CL_{05}=1.93$;
TS = Thermal shock: $y=-71.4+1.915x-0.00778x^2$, n=130, $R^2=0.965$, SE=0.79, $CL_{05}=1.72$;
PS = Pre-sprouting: $y=-75.2+2.073x-0.00861x^2$, n=137, $R^2=0.968$, SE=0.80, $CL_{05}=1.73$.

In the variants that started forming tubers later, the tuber yield was growing faster. By 55 DAP the increment of the tuber yield was larger in variant 0 (1.2 t ha^{-1} per day), exceeding variants TS and PS respectively by 0.15 and 0.08 t day^{-1}. The growth increment speed of the tubers became unified in different variants by 95 DAP.

CONCLUSIONS

The physiological age of potato plants could be increased by either, 1. pre-sprouting of seed tubers, or 2. thermal shock to the deeply dormant seed tubers. In variants with physiologically older seed tubers, the higher growth rate of accumulation to the developing tubers is achieved.

In the development of the leaf area and tuber yield formation, the thermal shock treatment was not as effective as pre-sprouting. Nevertheless treated seed tubers were physiologically older than non-treated samples, enabling quicker leaf area and tuber growth and development.

By pre-sprouting seed tubers before planting, the development of plants was faster during the entire vegetation period, but with thermal shock treatment only the first stages of vegetation was affected. The pre-sprouted variant gave a significant tuber yield increase during the whole vegetation season.

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The effect of pre-planting treatment of seed tubers on potato yield formation

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Abstract. In the trials conducted in 2000–2002, we examined possibilities for growing potato using different methods of pre-planting treatment of seed tubers.

The varieties exploited were 'Varajane kollane' (early), 'Piret' (medium early) and 'Ants' (medium late). There were used the following ways of treatment for all varieties: PS – pre-sprouting, TT – thermal treatment and 0 – tubers not treated.

The dynamics of tuber yield formation during the vegetation period was significantly influenced by the weather. In terms of potato growth, weather conditions were the most favourable in 2001. The weather in 2000 and 2002 was not the most suitable for potato growth and development, and the yield in these years proved lower than the three-year average.

The average results from the three years show that potatoes could not realise their full potential to reach maximum yield. Pre-planting germination and thermal treatment had positive effects during the entire vegetation period, the effect being stronger at the beginning and then gradually decreasing.

Pre-planting treatment of seed tubers had a different effect on varieties with different growing times.

A comparison between the varieties showed that 'Piret' and 'Varajane kollane' started to form tubers early and thus exceeded the development of the variety 'Ants' until the 60th day of growth. 'Ants' reached its maximum yield, 47.0 t ha^{-1}, already by the 114th day, followed by the fast-ripening 'Varajane kollane' and the medium-ripening 'Piret'. Thermal treatment did not give any advantage in terms of total yield formation compared to untreated seeds, except for the pre-planting germination variant of the variety 'Varajane kollane', the total yield of which exceeded that of its untreated variant by 7.08 t ha^{-1}.

Key words: storage, variety, thermal treatment, pre-sprouting, dynamics, weather conditions

INTRODUCTION

One of the main components of producing a stable and economically viable yield of potatoes are healthy and biologically active seeds with a high yield potential. The emergence of the potato in the field, development of the leafy tops and speed of covering the field area depend on the quality of the seed (Kuill, 2002). In order to keep a high yield potential, we should take all essential measures to increase the yield while preparing for planting. One of these measures – the pre-planting thermal treatment of the tubers or pre-sprouting – is widely used, for example, in Holland (Struik & Wiersema, 1999), not only for the early potato but also for the late potato. Each seed batch has a storage period history consisting of the treatment, cooling, storing and preparation period. The parameters of all the aforementioned periods has a direct effect on the overall durability of the potato as well as on the yield potential of the tubers (Allen et al., 1992). The Department of Field Crop Husbandry has studied age differences of seed tubers. This article analyses the growth and yield of potatoes considering different techniques that have been applied to influence tubers when they wake up after the dormant period.

MATERIALS AND METHODS

The experiments that we performed in 2000–2002 established the possibilities for growing potatoes, using different ways of treating tubers before planting. The tubers were treated as follows: pre-sprouting (PS); thermal treatment (TT) and untreated tubers (0) (Lõhmus et al., 1999). The medium late variety 'Ants', the medium early variety 'Piret' of the Jõgeva SAI, and the early variety 'Varajane kollane' of the Latvian Priekuli SAJ were used in the experiments. The dynamics of the tuber yield formation was determined by taking samples of all options of each variety. The purpose was to find out which way of treatment was the best for growing potato varieties with different growth periods in Estonian climatic conditions in order to ensure a higher and better yield during the vegetation period. The experiments were conducted using methods developed by the Department of Field Crop Husbandry of the Estonian Agricultural University (Lauk, 1995, 1996; Lauk et al., 1996).

The experiments were performed in the Eerika experimental field of the Department of Field Crop Husbandry of the EAU Faculty of Agronomy, where the soil was LP pallescent (Kõlli & Lemetti, 1995). Agricultural techniques typical of potato experiments were used. The yield formation dynamics was determined in every 3 to 5 days.

As different tuber treatment methods were used, the first samples were taken at different times (Table 1). The sampling time and number of samples were different for different options. The number of samplings also depended on the duration of the vegetation period. The potato vegetation period was extremely long in 2001, ending on day 126. As varieties in different options started to develop tubers at different times, the number of samplings fluctuated each year +/- 3 samples.

Table 1. Yield formation dynamics and the number of tuber samples over the vegetation period.

Value	2000 year	2001 year	2002 year
Number of samples	11–14	14–16	15–17
Days from planting:			
a) to the first sampling	42–56	49–61	36–41
b) to the last sampling	118	126	111
Days from planting to emergence	18–30	23–39	16–27

The results have been processed using the regression analysis method with the following quadratic equation:

$y = a + bx + cx^2$, where
y – argument function, yield calculated on the basis of the equation, t ha^{-1}
a – constant term of the equation,
b and c – regression coefficients,
x – argument, number of days after planting.

RESULTS AND DISCUSSION

Tuber formation is a complex process including the emergence and growth of stolons and the development, growth and ripening of tubers at their top as a result of the accumulation of nutrients. Stolons are horizontal sprouts that emerge from the basal bud of the stem in the ground. The buds that develop stolons emerge at the second stage of organogenesis. There are two morphostructure types at this stage during the realisation of morphogenetic information: sprouts specialising in vegetative reproduction (stolons) and duplicate structures (shoots above the ground) (Markov & Maslova, 1998). Due to the influence of the mother tuber, the potato plant is relatively autonomous for some time after emergence and depends on external conditions less than many other crops.

The dynamics of potato yield formation is significantly influenced by weather conditions. The first experimental year (2000) was chillier than the other two. The sum of air temperatures during the vegetation period was 1715.5°C (which is more than 200°C lower than in the following experimental years). The sum of active temperatures was 555.6°C. This sum varied greatly during the three experimental years. Thus, in the vegetation period of 2001 it was 186.7°C and in 2002 295.2°C higher than in 2000. While the air temperature sums in 2001 and 2002 were almost equal, the sum of active temperatures was 108.5°C higher in 2002. V. Tamm (1982) believes that potato needs 230.5 mm of precipitation during the vegetation period. This figure was exceeded in 2000 and 2002 (by 116.6 mm and 84.8 mm, respectively). However, during the vegetation period of 2001 there was only 162.4 mm of precipitation. The time distribution of precipitation was different in all the three years. Only 66.9 mm of rain fell down during tuber formation and in the active growth period (July–September) in 2002. A significant part (65.7%) of rain fell down during the respective period in 2001. In 2000 most rain (68.5%) fell down in the period from the last ten days of June to the first ten days of August, i.e. from tuber formation to the beginning of the active growth of tubers.

To sum up the weather conditions, the most favourable year for the growth of potatoes was 2001. It was relatively warm and the plants got enough water during tuber formation and intensive growth, whereas the efficient blight control ensured an actively working leaf surface until harvesting.

The findings above have also been presented in Table 2 comparing the yields in different years. During the early tuber formation period the yield was highest in 2002 (day 50 to day 65 after planting) since the weather was then most favourable for potato growth. From day 80 to harvesting, the yield was highest in 2001. The active growth of the tubers was caused by the above-mentioned weather factors. In 2000 the yield was apparently largely influenced by the relatively chilly vegetation period.

Table 2. Formation of tuber yield depending on the trial year.

Day	3. years average	Difference		
		2000-average	2001-average	2002-average
50	4.94	0.00		5.67*
55	10.47	-0.25	-4.11*	4.36*
60	15.62	-0.53	-2.55	3.08*
65	20.39	-0.84	-0.99	1.84
70	24.79	-1.19	0.57	0.62
75	28.80	-1.57	2.14	-0.58
80	32.44	-1.98	3.71*	-1.74
85	35.70	-2.42	5.29*	-2.87*
90	38.59	-2.89	6.86*	-3.97*
95	41.09	-3.39	8.44*	-5.05*
100	43.22	-3.93	10.02*	-6.10*
105	44.97	-4.49*	11.61*	-7.11*
110	46.34	-5.09*	13.20*	-8.10*
115	47.33	-5.72*	14.79*	-9.06*
120	47.95	-6.39*	16.38*	-9.99*
LSD_{05}		4.20	3.27	2.74

Explanation: * – reliability

The accumulation of the average yield during the three years for all the varieties and options can be described by the formula:

$y = -71.1 + 1.899\,x - 0.00756\,x^2$, where $r = 0.983$ and $s_y = 3.05554$

where r = correlation coefficient,
s_y = regression standard deviation.

Physiological age is very important for the development of tuber yield. A physiologically older seed accelerates the growth rhythm of potatoes, due to which the yield develops earlier, while the yield formation ability decreases (Jõudu, 2002). The results also show that the earlier the variety, the greater the effect of treatment and that the yield develops evenly during the vegetation period in varieties with a longer growth period. Obviously, any thermal treatment of seed tubers increases their physiological age (Jõudu, 2002). Thus, both pre-sprouting and thermal treatment to some extent increase the physiological age of tubers.

The main purpose of pre-sprouting is to obtain an earlier yield. In order to gain the yield as early as possible, the pre-sprouting should also start earlier, and sprouting would still take 4 or 5 weeks (Jõudu, 2002). If it is too late for pre-sprouting, the tubers can be stimulated using thermal treatment making them develop faster.

Table 3 confirms that physiologically older tubers provide yield earlier. The average results of the three years show that the potato did not have enough time to realise its full potential. It did not achieve the maximum yield it could provide. Pre-sprouting and thermal treatment had a positive effect during the whole vegetation period.

Table 3. Effect of the seed tuber pre-planting preparation method and of the variety on the yield (the average of 2000–2002, t ha^{-1}).

Day	0	Difference		‘Ants’	Difference	
		TT-0	PS-0		‘Piret’-‘Ants’	‘V.koll.’-‘Ants’
50				1.44	4.30*	1.78
55	6.05	4.35*	6.74*	8.28	2.49	0.97
60	11.87	3.63	6.33*	14.56	0.93	0.28
65	17.24	2.97	5.94*	20.28	-0.39	-0.28
70	22.15	2.38	5.59*	25.45	-1.47	-0.73
75	26.60	1.87	5.25*	30.06	-2.31	-1.06
80	30.60	1.41	4.95*	34.12	-2.90	-1.26
85	34.14	1.03	4.67*	37.62	-3.24	-1.35
90	37.22	0.72	4.41*	40.56	-3.35*	-1.31
95	39.85	0.47	4.19*	42.95	-3.20	-1.15
100	42.02	0.29	3.99*	44.78	-2.82	-0.87
105	43.73	0.18	3.81*	46.05	-2.19	-0.48
110	44.99	0.13	3.66	46.77	-1.32	0.04
115	45.79	0.16	3.54	46.94	-0.20	0.68
120	46.13	0.25	3.45	46.55	1.16	1.44
LSD_{05}		3.65	3.67		3.25	3.54

Explanations *– reliability
0 = average of non-treated tubers of different varieties
TT = average of thermal treatment tubers of different varieties
PS = average pre-sprouting tubers of different varieties
‘Ants’ = average of different treatments variety ‘Ants’
‘Piret’ = average of different treatments variety ‘Piret’
‘V. koll.’ = average of different treatments variety ‘Varajane kollane’

The effect was first stronger and then gradually decreasing. The thermal treatment provided reliable extra yield (LSD_{05}) during the first samplings (55–65 days after planting), and pre-sprouting until day 110, accordingly. It was established that thermal treatment had a positive effect until mid-August. If harvesting is planned for September, there is no need to thermally treat tubers and bear extra costs, especially in cultivating early and medium early varieties. The experiments have proven that physiologically older tubers have a higher yield potential, particularly during the early period of tuber formation and growth. When pre-sprouting was used, the tubers received more heat than during thermal treatment, therefore pre-sprouted tubers can be considered as physiologically older. The yield difference compared to the untreated option decreased more slowly in the case of physiologically older tubers.

The tubers that were exposed to thermal treatment did not provide a yield higher than expected compared to pre-sprouting. The thermally treated tubers were physiologically older in relation to the untreated option, which enabled faster initial development resulting in the earlier formation of a harvest ripe yield. The tubers that gradually achieve full ripeness also enable the harvesting period to be extended if one variety is cultivated.

Table 4. Effect of the seed tuber pre-planting preparation method on the yields of different varieties (the average of 2000–2002, t ha^{-1}).

Day	'Ants'			'Piret'			'Varajane kollane'		
	0	Difference		0	Difference		0	Difference	
		TT-0	PS-0		TT-0	PS-0		TT-0	PS-0
55	2.84	1.73	8.63*	5.97	5.24*	7.02*	3.53	2.57	8.30*
60	10.04	1.45	7.94*	11.60	4.41*	6.02*	9.84	2.99	7.86*
65	16.60	1.18	7.27*	16.81	3.64	5.12*	15.62	3.31	7.47*
70	22.52	0.90	6.61*	21.60	2.94	4.33*	20.88	3.53	7.15*
75	27.80	0.62	5.97*	25.98	2.30	3.64	25.62	3.65	6.88*
80	32.44	0.35	5.34*	29.94	1.72	3.05	29.84	3.67	6.67*
85	36.44	0.08	4.73*	33.48	1.21	2.57	33.54	3.59	6.52*
90	39.80	-0.19	4.14*	36.61	0.76	2.19	36.71	3.41	6.43*
95	42.51	-0.46	3.56	39.32	0.38	1.90	39.36	3.13	6.39*
100	44.59	-0.73	3.00	41.62	0.06	1.73	41.49	2.75	6.41*
105	46.03	-1.00	2.45	43.49	-0.19	1.65	43.09	2.28	6.49*
110	46.82	-1.26	1.92	44.96	-0.38	1.67	44.17	1.70	6.63*
115	46.98	-1.53	1.40	46.00	-0.50	1.80	44.73	1.02	6.82*
120	46.49	-1.79	0.90	46.63	-0.56	2.03	44.77	0.24	7.08*
LSD$_{05}$		3.73	4.03		3.80	4.03		3.80	3.94

Explanation: * – reliability

If we compare the varieties, we can conclude that 'Piret' and 'Varajane kollane' start developing tubers early and are ahead of 'Ants' up to day 60 after planting (Table 3). 'Ants' achieved its maximum yield by day 114: 47.0 t ha^{-1}.

Thermal treatment of tubers before planting has a different effect on varieties with different growth periods. Pre-sprouting had the greatest effect on 'Varajane kollane'. During the early tuber growth period it was similar in the medium late variety 'Ants' (in the first three samplings the extra yield was respectively 8.30–7.47 and 8.63–7.27 t ha^{-1}(Table 4).

Thermal treatment had a positive effect on the yield of the early and medium early varieties during the entire assessment period and on the yield of the medium late variety Ants in the first three samplings. Thermal treatment affected most the tuber yield of 'Piret' in the first samplings where the statistically reliable extra yields were 4.41–5.24 t ha^{-1}. In the medium late variety, tubers develop similarly to the early and medium early varieties. Thermal treatment accelerates the accumulation of extra yield in the early period. The pre-sprouted option of 'Ants' provided reliable extra yield until day 90 of growth (+4.14 t ha^{-1}). The 'Piret' tubers that were thermally treated provided extra yield until day 60 of growth and the pre-sprouted option of the same variety provided extra yield until day 70 (+4.33 t ha^{-1}). The pre-sprouted option of the early variety provided reliable extra yield during the entire vegetation period.

Thermal treatment provided no benefit in terms of the final yield compared to the untreated seed, except for 'Varajane kollane'. The pre-sprouted option gave extra 7.08 t ha^{-1} in the final yield compared with the untreated option. The medium late variety 'Ants' achieved its maximum yield fastest of all options, followed by the early 'Varajane kollane' and medium early 'Piret'.

CONCLUSIONS

The yield formation dynamics during the vegetation period is significantly affected by weather conditions. In this respect, the most favourable year for potato growth was 2001. In 2000 and 2002 the weather was not so good for the growth and development of potatoes, and the yield was lower than the three- year average.

The average results for the three years show that the potato did not have enough time to realise its full potential and did not reach its maximum yield. Pre-sprouting and thermal treatment had a positive effect during the entire vegetation period. This effect was first stronger and then gradually decreased.

Thermal treatment of the tubers before planting has a different effect on varieties with different growth times.

A comparison between the varieties showed that 'Piret' and 'Varajane kollane' started to form tubers early and exceeded the variety 'Ants' until the 60th day of growth. 'Ants' reached its maximum yield, 47.0 t ha^{-1}, already by the 114th day, followed by the fast-ripening 'Varajane kollane' and the medium-ripening 'Piret'. Thermal treatment did not give any advantage in terms of total yield formation compared to untreated seed, except for the pre-planting germination variant of the variety 'Varajane kollane', the total yield of which exceeded that of its untreated variant by 7.08 t ha^{-1}.

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Training and special courses

13.09–12.10.2005. Course “Teaching in University”. Tartu, Estonia.

30.09–04.10.2002. Courses in advanced design and use of databases and development of components, Estonian Agricultural Advisory and Training Centre, Jäneda, Estonia.

Current research program

Biosciences and Environment, Agricultural Sciences (The physiological age of seed potatoes)

Grant funding and projects

Target-financed project No. 0172616s03: “Investigation of different systems of plant and land cultivation (including environment friendly methods) as well as of the theoretical basis of their elements for finding optimal practical solutions”. 2003–2007; (Participant)

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Euroopa kartuliteadlaste ühingu (EAPR) – liige alates 2002
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Erialane enesetäiendus
13.09–12.10. 2005. Kursus "Õpetamine kõrgkoolis". Tartu, Eesti.
30.09–04.10. 2002. Courses in advanced design and use of databases and development of components, Estonian Agricultural Advisory and Training Centre, Jäneda, Eesti.

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SF teema 0172616s03 "Erinevate taimekasvatus– ja maaviljelussüsteemide (s.h. loodussäästlike viljelusviiside) ning nende elementide teoreetiliste aluste uurimine optimaalsete praktiliste lahendite leidmiseks", 2003–2007, Osalus abijõuna.

LIST OF PUBLICATIONS

1.1. Articles indexed by ISI Web of Science

Eremeev, V., Jõudu, J., Lääniste, P., Mäeorg, E., Selge, A., Tsahkna, A., Noormets, M. 2007. The influence of thermal shock and pre-sprouting of seed potatoes on formation of tuber yield. Spanish Journal of Agricultural Research (in press).

Eremeev, V., Lõhmus, A., Lääniste, P., Jõudu, J., Talgre, L., Lauringson, E. 2007. The influence of thermal shock and pre-sprouting of seed potatoes on formation of some yield structure elements. Acta Agriculturae Scandinavica, Section - Plant Soil Science (in press).

Eremeev, V., Jõudu, J., Lääniste, P., Mäeorg, E., Makke, A., Talgre, L., Lauringson, E., Raave, H., Noormets, M. 2007. Consequences of pre-planting treatments of potato seed tubers on leaf area index formation. Acta Agriculturae Scandinavica, Section B - Plant Soil Science (in press).

Lääniste, P., Jõudu, J., **Eremeev, V.**, Mäeorg, E. 2007. Effect of sowing date and increasing sowing rates on plant density and yield of winter oilseed rape (*Brassica napus* L.) under Nordic climate condition. Acta Agriculturae Scandinavica, Section B - Plant Soil Science (in press).

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1.2. Peer-reviewed articles in other international research journals with an ISSN code and international editorial board, which are circulated internationally and open to international contributions

Eremeev, V., Lõhmus, A., Jõudu, J. 2007. Effects to thermal shock and pre-sprouting of field performance of potato in Estonia. Agronomy Research 5(1): 21–30.

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Eremeev, V., Jõudu, J., Lõhmus, A., Lääniste, P., Makke, A. 2003. The effect of preplanting treatment of seed tubers on potato yield formation. Agronomy Research 2(1): 115–122.

Lääniste, P., Jõudu, J., **Eremeev, V**. 2004. Spring oilseed rape seeds oil content according to fertilisation. Agronomy Research 2(1): 83–86.

1.3. Articles in Estonian and other peer-reviewed research journals with a local editorial board

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Jeremejev, V., Jõudu, J., Lõhmus, A. 1998. Mugulasaagi formeerumine ja kvaliteet sõltuvalt seemnemugulate töötlemisest. Põllumajanduskultuuride produktiivsus ja kvaliteet, Teadustööde kogumik 199: 88–93.

Jõudu, J., **Eremeev, V.**, Lõhmus, A., Roostalu, H. 2004. Formation of potato yield and its quality according tos eed tuber pre-planting preparation and agrotechnology. Proceedings of EAPR agronomy section meeting. Mamaia, Romania. 2004, pp. 265–268.

Lõhmus, A., Jõudu, J., Lääniste, P., **Jeremejev, V**. 1999. Potato quality improvement with pre-planting treatment of seed tubers. Agroecological optimization of husbandry technologies, Proceedings of the international scientific conference, Jelgava, Latvia. pp. 66–74.

Lääniste, P., Jõudu, J., Lõhmus, P., **Jeremejev, V**. 1999. Mehhaaniliste ja keemiliste umbrohutõrje võtete mõju kartuli umbrohtumusele, saagile ning kvaliteedile. Agronoomia, Teadustööde kogumik 203: 106–110.

3.2. Articles/chapters in books published by the publishers not listed in Annex

Eremeev, V., Jõudu, J., Lääniste, P., Lõhmus, A., Makke, A 2001. Tärkliserikkamate kartulisortide tärklisesaagist ja selle kvaliteedist. Akadeemilise Põllumajanduse Seltsi Toimetised 14: 27–31.

Eremeev, V., Makke, A., Lõhmus, A., Jõudu, J. 2005. Kartuli tärkamine sõltuvalt seemnemugulate mahapanekueelsest ettevalmistusviisist. Agronoomia 2005, Teadustööde kogumik 220: 78–80.

Makke, A., Jõudu, J., Lõhmus, A., **Eremeev, V.**, Lääniste, P. 2004. Kartuli väetamine Silmeti lämmastikulahusega. Agronoomia 2004, Teadustööde kogumik 219: 76–78.

Lääniste, P., Jõudu, J., **Eremeev, V.** 2004. Rapsiseemnete õlisisaldus sõltuvalt väetamisest. Agronoomia 2004, Teadustööde kogumik 219: 82–84.

Jõudu, J., Makke, A., Lääniste, P., **Eremeev, V.**; Lõhmus, A. 2001. Eestis aretatud kartulisortide ja aretiste sobivus mahe ja tavaviljeluseks. Agronoomia: EPMÜ teadustööde kogumik 213: 60–66.

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Lõhmus, A., **Eremeev, V.**, Makke, A., Jõudu, J. 2005. Soojalöögi ja eelidandamise mõju varajase kartuli kasvule. Agronoomia 2005, Tartu, pp. 75–77.

Makke, A., **Eremeev, V.**, Jõudu, J. 2006. Silmeti vedelväetise mõju kartul 'Anti' saagile ja tärklisesisaldusele. Agronoomia 2006, Jõgeva, pp. 120–123.

3.4. Articles/presentations published in conference proceedings not listed in Section 3.1

Eremeev, V.; Jõudu, J., Lõhmus, A., Lääniste, P. 2001. Effect of thermal treatment on late potato varieties. Sustainable Agriculture in Baltic States, Proceedings of the International Conference, Tartu, pp. 34–38.

Eremeev, V., Jõudu, J., Lõhmus, A. 2000. Seemnekartuli mahapanekueelse termilise töötlemise mõju mugulasaagi kujunemisele. Kartul aias, põllul ja toidulaual. Eesti - Soome ühisseminar, Saku–Võru, pp. 31–33.

Lõhmus, A., **Eremeev, V.**, Jõudu, J. 2006. The Timing of the Potato Late Blight Control Implemented by use of a Program NegFry. Theoretic and practice achievements of young agrarian scientists, Works of International scientific-practice conference of young scientists, Dnepropetrovsk, Ukraina, pp. 74–76.

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Lääniste, P., Jõudu, J., **Eremeev, V.**, Lõhmus, A. 2001. The effect of tillage techniques on the tubers chemical composition of the potato variety 'LASUNAK' in 1997–1999. Sustainable Agriculture in Baltic States, Proceedings of the International Conference, Tartu, pp. 134–142.

3.5. Articles/presentations published in local conference proceedings

Eremeev, V., Jõudu, J., Lõhmus, A., Lääniste, P., Makke, A. 2004. Kartulisordi "Varajane kollane" seemnemugulate mahapanekueelse ettevalmistusviisi mõju kasvudünaamikale. Agronoomia 2004, Teadustööde kogumik 219: 70–72.

Lõhmus, A., Jõudu, J., Koppel, M., **Eremeev, V.**, Makke, A. 2004. Kartuli lehemädaniku tõrje ajastamine. Agronoomia 2004, Teadustööde kogumik 219: 175–177.

5.2. Conference abstracts that do not belong to section 5.1

Eremeev, V., Lõhmus, A., Jõudu, J. 2005. A field study of early potato with different physiological age. Optimizing agricultural output production: theory and praxis. The International Scientific Conference. Book of abstracts, Jelgava, Latvia, p. 23.

Jõudu, J., **Eremeev, V.**, Lõhmus, A., Lääniste, P. 2002. Thermal treatment of seed potato tubers. 15th Triennial Conference of the European Association for Potato Research, Abstracts of Papers and Posters, Hamburg, Germany, p. 254.

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Jõudu, J., Makke, A., Lõhmus, A., **Eremeev, V.**, Lääniste, P. 2002. Silmeti lämmastikulahuse mõju kartulile. Säästev põllumajandus Eestis –kogemused, võimalused, suundumused. Tartu, 28. novembril 2002. a., teesid, p. 35.

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Lääniste, P., Jõudu, J., Makke, A., **Eremeev, V.**, Lõhmus, A. 2002. The properties of Estonian potato varieties and breedes in organic and conventional farming. International scientific and practical conference, Scientific aspects of organic farming. Programme Book of Abstracts, March 21–22, 2002, Jelgava, Latvia, p. 47.

6.3. Popular science articles

Jeremejev, V., Jõudu, J., Lääniste, P., Lõhmus, A. 1998. Seemnemugulate mahapanekueelse termilise töötlemise mõju mugulasaagi kujunemisele ja selle kvaliteedile. Teaduselt põllule ja aeda, Jäneda, pp. 123–127.

Lõhmus, A., Jõudu, J., Lääniste, P., **Jeremejev, V**. 1999. Kartuli kvaliteedi parandamine seemnemugulate mahapanekueelse töötlemisega. Teaduselt põllule ja aeda, Jäneda, pp.151–158.

Lääniste, P., Jõudu, J., **Jeremejev, V.**, Lõhmus, A. 1998. Harimisvõtete mõju kartuli umbrohtumusele, saagile ja kvaliteedile. Teaduselt põllule ja aeda, Jäneda, pp. 128–129.

Submitted articles indexed by ISI Web of Science

Eremeev, V., Jõudu, J., Makke, A., Lääniste, P., Lõhmus, A., Mäeorg, E., Alaru, M. 2006. Influence of seed potato pre-planting treatments on leaf area and tuber yield formation. (Submitted to Agricultural and Food Science).

Alaru, M., **Eremeev, V.**, Laur, Ü., Selge, A., Reintam, E. 2006. Influence of divided N fertilizer application on winter triticale grain yield and quality. (Submitted to Agricultural and Food Science).

Talgre, L., Lauringson, E., Roostalu, H., Astover, A., **Eremeev, V.**, Selge, A. 2007. The effects of pure and undersowing green manures on yields of succeeding spring cereals. (Submitted to Acta Agriculturae Scandinavica, Section B - Plant Soil Science).

APPROBATION

International and regional conferences and workshops

Oral presentations

Conference: Theoretic and practice achievements of young agrarian scientists. June, 11–12, 2006, Dnepropetrovsk, Ukraina. Oral presentation. – The Timing of the Potato Late Blight Control Implemented by use of a Program NegFry.

Conference: Optimizing agricultural output production: theory and praxis. July, 7–9, 2005, Jelgava, Latvia. **Eremeev, V.**, Lõhmus, A., Jõudu, J. Oral presentation – A field study of early potato with different physiological age.

Poster presentations

The 16th trienial conference: EAPR-2005. July, 17–22, 2005, Bilbao, Spain. **Eremeev, V.**, Lõhmus, A., Jõudu, J. Poster: A field study of early potato with different physiological age in Estonia.

EAPR Agronomy section meeting: Scientific aspects of organic farming. June 23–27, 2004, Mamaia, Romania. Jõudu, J., **Eremeev, V.**, Lõhmus, A., Roostalu, H. Poster: Formation of potato yield and its quality according to seed tuber pre-planting preparation and agrotehnology.

The 15th triennial conference: Potatoes today and tomorrow. July, 14–19, 2002, Hamburg, Germany. Jõudu, J., **Eremeev, V.**, Lõhmus, A., Lääniste, P. Poster: Thermal treatment of seed potato tubers.

Conference: Scientific aspects of organic farming. March 21–22, 2002, Jelgava, Latvia. Lääniste, P., Jõudu, J., Makke, A., **Eremeev, V.**, Lõhmus, A. Poster: The properties of Estonian potato varieties and breedes in organic and conventional farming.