Eesti Maaülikool
Estonian University of Life Sciences

IMPACT OF FARMING SYSTEM, PRE-CROP AND WEATHER CONDITIONS ON YIELD AND QUALITY OF SPRING WHEAT

VILJELUSSÜSTEEMI, EELVILJA JA ILMASTIKUTINGIMUSTE MÕJU SUVINISU SAAGILE JA KVALITEEDILE

ANNE INGVER

A Thesis
for applying for the degree of Doctor of Philosophy in Agriculture

Väitekiri
filosoofiadoktori kraadi taotlemiseks põllumajanduse erialal

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II Tamm, I., Tamm, Ü., **Ingver, A.**, Koppel, R., Tupits, I., Bender, A., Tamm, S., Narits, L., Koppel, M. 2016. Different leguminous pre-crops increased yield of succeeding cereals in two consecutive years. Acta Agriculturae Scandinavica, Section B - Soil & Plant Science, 66 (7), 593–601.

III **Ingver, A.**, Tamm, I., Tamm, Ü. Kangor, T. Koppel, R. 2010. The characteristics of spring cereals in changing weather in Estonia. Agronomy Research, 8 (3), 553–562.

IV Tamm, I., Tamm, Ü., **Ingver, A.** 2009. Spring cereals performance in organic and conventional cultivation. Agronomy Research, 7, 522–527.

V **Ingver, A.**, Tamm, I., Tamm, Ü. 2008. Effect of organic and conventional production on yield and quality of spring cereals. Agronomijas Vestis, Latvian Journal of Agronomy, 11, 61–67.

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The contributions from the authors to the papers were following:

	I	**II**	**III**	**IV**	**V**
Idea and design	All	All	**AI**, IT, ÜT	**AI**, IT, ÜT	**AI**, IT, ÜT
Field experiment	**AI**, ST; AB	**AI**, ST; AB	**AI**	**AI**	**AI**
Data collection	**AI**, ST; AB	**AI**, ST; AB	**AI**	**AI**	**AI**
Data analysis	**AI**, IT, ST	**AI**, IT, ST	**AI**, IT	**AI**, IT	**AI**, IT
Preparation of manuscript	All	All	All	All	All

AI - Anne Ingver, IT - Ilmar Tamm, ÜT - Ülle Tamm, AB - Ants Bender, ST - Sirje Tamm

ABBREVIATIONS

C	carbon
C:N	carbon nitrogen ratio
CV	coefficient of variation
DMY	dry matter yield
g	gram
ha	hectare
hl	hectolitre
K	potassium
kg	kilogram
N	nitrogen
P	phosphorus
TKW	thousand kernel weight

1. INTRODUCTION

World wheat production has increased steadily since the 1960s. Wheat (*Triticum aestivum* L.) is the most cultivated and traded commodity globally (Braun et al., 2016) and the most versatile grain among the cereals for the preparation of diverse foods (Peña-Bautista et al.,2017).

The worldwide success of wheat can be explained by gluten's unique properties that give bread and other products their derived structure and therefore wheat flour is attractive for many different industries. These unique physico-chemical attributes were first described by I.B. Beccari in 1726 (Beach, 1961). Grain quality consists of the physical parameters of the grain, such as volume weight and thousand kernel weight (TKW), and protein content. All these characteristics depend on agronomic practices, weather conditions, disease infection, kernel shape and density. Estonia is capable to produce wheat of high baking quality and also export it. During last five years (2015–2019) wheat was grown already on 150–170 thousand hectares (52–80 thousand of spring wheat) (Statistics Estonia, 2019).

There are multiple paths to improve the production, food security and environmental performance of agriculture, whether it be conventional agriculture, organic farming or other path (Pimentel et al., 2005; Van Stappen et al., 2015). Organic agriculture combines traditional conservation-minded farming methods with modern farming technologies. It emphasizes rotating crops, diversifying crops and livestock, and improving the soil with compost additions and green manures (Reganold & Wachter, 2016; Seufert & Ramankutty, 2017). Over the past 50 years, organic farms have provided conventional agriculture with examples of new ways to farm and acted as a testing ground for a different set of management practices. While crop rotations in conventional farming have been dramatically simplified over the last 50 years, then organic farming stands as an alternative production system that promotes crop diversification. Organic rotations use more nitrogen-fixing crops that provide up 2.6 times more nitrogen to soils farmed organically than they do in conventional ones (Barbieri et al., 2017). Organic rotations have been reported to be longer and more capable of buffering the effect of climate stresses such as increased temperature and rainfall variability (Barbieri et al., 2017).

Consumers often value quality over cost and organic farming is one of the fastest growing segments of agriculture (Crowder & Reganold, 2015; Van Stappen et al., 2015; Reganold & Wachter, 2016; Wilbois & Schmidt, 2019). Today, in Estonia, the organic land area has expanded more than 2.5 times over the last ten years, reaching 207 thousand ha in 2018, covering ca. 21% of the total agricultural area. This percentage makes Estonia one of the three leading countries in the EU by share of organic area together with Austria and Sweden (EUROSTAT, 2018). The organic cereal production covered ca. 20% of total organic area in Estonia in 2018 and organic wheat in turn comprised ca. 20% of the organic cereal production area in Estonia (Organic Farming in Estonia, 2018).

However, it was in 2004, when the first organic farmers in Estonia started to look for scientifically sound data to build up their sustainable farming systems. There was no information available about the fertilizers and pre-crops and their impact on yield and quality. Their questions were the starting point for the research that is now collected into this thesis. Small-scale testing and breeding of spring wheat varieties for organic conditions started in 2005 when the first breeding line (now the variety 'Mooni') was included in the organic trial. It is important in any breeding process to find the suitable balance between good yield and acceptable kernel quality (Gupta et al., 1991). New varieties should possess plasticity to respond to future changes in climate and in agricultural practices. Therefore adaptation to environmental stresses is important (Ingver et al., 2016).

A major task in the future will be the selection of legume species and varieties which could be effectively introduced across different farming systems. An important point concerns balancing yield, which gives economic return, with the environmental and agronomic benefits. It is also crucial to take into account local cultivation conditions and challenges as well as finding solutions for local issues. Nitrogen-fixing legumes in crop rotations fix atmospheric nitrogen into the soil through root nodules. This nitrogen is then available for subsequent crops. Some deep rooted pre-crops can also draw up nutrients such as potassium and phosphorus from deep in the soil profile, making these nutrients available for subsequent shallow rooted crops (Angus et al., 2015).

In the past, legumes were commonly used as a natural source of N for farming systems. Using legumes in rotation began to decline when synthetic nitrogen was introduced in the 1940s. Nowadays, N-fixing legumes have been recovering as viable crops because of the increased cost of N fertilizer and the need to develop more sustainable farming systems. This is especially important in organic agriculture when the system does not include livestock able to supply natural nitrogen fertiliser.

Leguminous species are adapted to grow in north-eastern European climatic conditions. As the climate changes, the growing season prolongs and creates the need to test the potential of common and novel leguminous species for crop rotations in the region. There is a wide selection of leguminous species with different traits that can be tested. If the growing period prolongs in the case of climate warming, new opportunities would open up to cultivate other types of legumes in order to supply subsequent crops with major plant nutrients. The results of this research are valuable not only for organic cultivation but every type of farming. Farmers have to switch from ecologically harmful measures to more sustainable ones (Stagnari et al., 2017).

Weather risks are a major source of uncertainty in agriculture, having the most obvious impact on yield and quality of crops. Climate change is causing increased temperatures and changed precipitation patterns. Plant species need to be adapted to new agro-climatic conditions. Climate change may also lead to need for farming system changes. Some crops may expand to new areas and new crop species may become introduced to maintain the competitiveness and sustainability of farming in the region (Borrelli et al., 2014; Ingver et al., 2016; Demone et al., 2018; Taugtes et al., 2018). The rise of the mean annual air temperature in Estonia has been faster than it has been globally, especially in recent periods, reaching even a rate of 0.5 °C per ten years. The air temperature has risen especially in winter and early spring. The changes in the 20th century (together with the beginning of the 21st century) are considerable compared to those of the 19th century (Eensaar, 2016).

This thesis presents the current state of knowledge about the effect of farming system, pre-crop and weather conditions to cultivation of spring wheat in Estonia.

More specifically, this study intended to determine whether different leguminous pre-crops can provide sufficient amounts of N and other nutrients to subsequent spring wheat in order to produce high grain yield with good kernel quality in an organic farming system. There is a need to re-introduce more legumes in crop rotations (Preissel et al., 2015) but there is a lack of information in the region available how different annual, biennial and perennial leguminous species influence yield and kernel quality of subsequent cereals like spring wheat and thereby diversify farmers' choices.

Novelty of this research:

1) Complexity of comparison of five spring and winter cereals cultivated after six leguminous pre-crops.

2) The series of trials comparing the influence of farming system on yield and quality of spring cereals was carried out during the period when organic cultivation in Estonia started to expand in response to farmers' questions.

3) Twenty-nine year long study of weather impact on yield and quality characteristics of three main spring cereals.

The novelty of this research lies specifically in the participatory approach itself. The scope of the paper, indeed, was to assess the state of the art of current research on several topics to shed light on both the practical and scientifically relevant issues.

2. REVIEW OF LITERATURE

2.1. Wheat cultivation in the world

Wheat is a crop that is fundamental to human civilization (Shiferaw et al., 2013). The first cultivation of wheat occurred about 10 000 years ago, as a threshold in the evolution of human societies transitioning from hunting and gathering to settled agriculture (Dubcovsky & Dvorak, 2007; Shewry, 2009). The reasons why this cereal became so widely adopted by man include its high environmental adaptability and its excellent food qualities, not only regarding carbohydrates, proteins and vitamin content, but also for the unique elastic property of its gluten, which allows for diverse uses of its flour (Dubcovsky & Dvorak, 2007; Shewry, 2009). Today, approximately 95% of wheat cultivated is hexaploid and is grown under wide ranges of climatic conditions and in many geographic regions (Dubcovsky & Dvorak, 2007; Shewry, 2009). Wheat is now the most widely cultivated cereal in the world with more than 220 million ha planted annually and depending on agro-climatic conditions, about 670 million tons produced annually (FAOSTAT, 2019). The largest wheat producing countries in the world are the European Union, China, India, Russian Federation, the United States, Australia, Canada, Pakistan, Ukraine and Kazakhstan (FAOSTAT, 2019).

Wheat is perhaps the most political commodity in the world because it is the main ingredient in the most basic food, which is bread. The demand for wheat in the world is expected to increase by 60 percent by the middle of the 21st century, as per the Food and Agriculture Organization (FAO) (Alexandratos & Bruinsma, 2012).

Wheat is divided into spring and winter wheat. In areas of severe winters spring wheat varieties are grown. Spring wheat does not need vernalization for heading. Mean daily temperature for optimum growth and tillering is between 15 and 20 °C.

Intensification and specialization of agriculture in Europe has raised concerns about the sustainability of farming systems (Voisin et al., 2014; Scherer et al., 2018; Reckling et al., 2020). For researchers, this reflection leads to reconsidering questions about legumes, for a transition towards more diversified production systems, which will therefore be more flexible and more resilient (Voisin et al., 2014). Although organic agriculture covers only 1.4% of global agricultural land and only contributes about 1 to 8% of total food sales in most European and North American countries, it is the fastest-growing food sector in those areas (Willer & Lernoud, 2019).

2.2. A brief overview of wheat cultivation and breeding in Estonia

Cultivation and consumption of cereals in Estonia has undergone significant changes during the last 100 years. At the beginning of the 20th century winter rye was the most important crop. This changed to barley being the main cereal during the Soviet period (1939–1991). Wheat production increased from five thousand hectares before the First World War to 85 thousand hectares before the Second World War. During the Soviet period wheat production in Estonia decreased as high-quality bread wheat was imported from the southernmost republics. Wheat (spring and winter) acreage only surpassed that of barley in 2010 (Ingver et al., 2016; Ingver & Koppel, 2020).

Wheat breeding in Estonia started on manors in the 1850s and has continued at the Estonian Crop Research Institute (formerly the Jõgeva Plant Breeding Institute) since the 1920s. Dr. Mihkel Pill, who was also called "Father of white bread", was an outstanding person as a promoter of wheat cultivation in Estonia. M. Pill concluded in the 1920s that the reason for low and variable spring wheat yields and quality, was the cultivation of varieties unsuited for the Estonian climate. As a result of his breeding work, varieties better adapted to Estonian conditions were bred and spring wheat cultivation expanded significantly. On his initiative, the systematic weather observations began at Jõgeva in 1922, later followed by systematic agro-meteorological observations starting in 1964 (Ingver et al., 2016).

Spring wheat breeding was stopped in the Soviet period in the 1970s and only restarted in 1991 after Estonia regained its independence. Cereal breeder, academician Hans Küüts and wheat breeders Reine Koppel and Anne Ingver made efforts to restart spring wheat breeding in Estonia to produce high quality bread wheat for local market and secure self-sufficiency in white bread. A series of new varieties suitable for Estonian conditions have been bred and released since 1991. The most recent of these spring wheat varieties are 'Voore' and 'Hiie', which are suitable for bread baking (Ingver, 2020).

A series of organic farming trials, which include spring wheat, were initiated at the Jõgeva Plant Breeding Institute in 2005 (Ingver et al., 2016; Ingver & Koppel, 2020).

2.3. Impact of factors on yield and quality

Additional N supply for crop uptake could become more important in the future. To combat the negative effects of increasing temperature, breeding for a higher rate of grain filling could improve both grain yield and protein concentration (Asseng et al., 2018).

Grain yield and quality are influenced by genetic factors, agronomic practices and especially weather conditions (Nuttall et al., 2017; Pinto et al., 2019). The negative relationship existing between grain yield and protein content (Fowler, 2003; Lollato et al., 2019), suggest that factors affecting grain yield could be expected to have an effect on protein content in all farming systems. It is possible to produce comparable grain yields and protein levels, without significant losses, also in organic farming systems (Mason et al., 2007; Cavigelli et al., 2013). Protein content has a large impact on price when wheat is sold, since it plays critical role in gluten strength in baking (Borrelli et al., 2014). Schrama et al. (2018) found that comparisons between organic and conventional agriculture have been based on relatively short-term experiments and a period longer than 10 years would provide a better understanding of the processes. The yield gap between organic and conventional agriculture declines and may eventually close over a significant amount of time (Schrama et al., 2018).

Protein content. The proportion of protein in organic grain maybe reduced because of organic systems have often limited availability of soluble N (Krejčířová et al., 2006; Bilsborrow et al., 2013). Several studies have shown considerably lower protein concentration in organic conditions compared to conventional (Talgre et al., 2009; Tamm et al., 2009; Bilsborrow et al., 2013; Cox et al., 2019). During grain filling, the amount of solar radiation directly affects biomass accumulation, and thus may also affect grain protein content and grain weight (Singh & Jenner, 1984). Climate change adaptations that benefit grain yield are not always positive for grain quality, putting additional pressure on global wheat production (Asseng et al., 2019).

Volume weight testing is one of the simplest and most widely used criteria of cereal quality. It mostly depends on weather conditions, variety, amount of available nutrients in the soil and grain cleaning. In the process of marketing minimum requirements for every cereal crop are imposed (Tamm et al., 2008). The trial results from 10 years of study (1998–2007) concluded that the main factor influencing the value of volume weight was weather. The amount of precipitation had a greater influence on volume weight than the sum of effective temperatures. The effect of a variety on volume weight was smaller than the effect of weather conditions (Tamm et al., 2008). Casebow et al. (2016) found that volume weight is also influenced by grain shape and shrivelling factors. The volume weight is also influenced by sunlight and precipitation. Duration of sunlight is connected with activity of photosynthesis which results in sufficient carbohydrates to ensure proper grain filling. Thus, well-filled grains usually have a higher volume weight and TKW. A strong positive correlation ($r=0.89$; $p<0.05$) between 1000 grain and volume weight of spring wheat was found (Tamm et al., 2008). Increasing N applications in organic cultivation resulted in significantly lower grain volume weight compared with the control treatment (Bicego et al., 2019).

2.3.1. Impact of leguminous pre-crops

N production from legumes is a key benefit of growing green manures. The amount of N available from legumes depends on the species of legume, the total biomass produced, and the percentage of N in the plant tissue. Cultural and environmental conditions that limit legume growth, such as a delayed planting date, poor stand establishment, and drought will reduce the amount of N produced (Hirel et al., 2011). Legumes are often preferred as pre-crops because of their ability to supply a renewable source of nitrogen by fixing atmospheric N. Biological N fixation is one of the primary sources of N in organic farming providing an option to deliver N to non-leguminous crops. Well-designed crop rotations are fundamental to organic farming systems as soil productivity is an important concern for organic cultivation. Legume-based systems also improve other aspects of soil fertility, such as soil organic carbon, humus content and availability of nutrients (Stagnari et al., 2017). Nowadays, legumes also add biodiversity to both organic cropping and conventional systems where cereals and oilseeds predominate (Rice et al., 1993).

Traditional field experiments about the pre-crops are resource intensive, therefore Peltonen-Sainio et al. (2019) developed a satellite-based method to evaluate the effect of different pre-crops on several subsequent crops in rotation. Legumes were found to be very beneficial pre-crops for spring wheat and other spring cereals.

Annual, biennial and perennial legumes can fit in several niches as part of diverse crop rotations. Use of annual green manure species can be advantageous in crop rotations where continuation of legume species for more than one year is undesirable (Ross et al., 2009). By the results of Rice et al. (1993) was concluded that annual legumes have a good potential as green manure crops in place of the conventional practice of summer fallowing on different soils in Canada.

A major task in the future will be the selection of legume species and cultivars which could be effectively introduced across multiple cropping systems. It is important to balance yield increase, which gives economic return, with the environmental and agronomic benefits (Stagnari et al., 2017).

2.3.2. Impact of farming system

Conventional agriculture is defined as mainstream agriculture, as dominantly practised today (Seufert & Ramankutty, 2017). Sustainable agricultural development aims at increasing the productivity and quality of crop production, while decreasing its harmful environmental impacts (Tilman et al., 2002). These objectives can be partially achieved by using organic farming practices which prohibit the use of synthetic fertilizers and pesticides. In an organic farming system, grain yields are generally low compared to conventional farming systems (Mäder et al., 2002; Mason et al., 2007; Reid et al., 2009; Nelson et al., 2011; de Ponti et al., 2012; Seufert et al., 2012), but it provides better environmental and socio-economic benefits compared with conventional agriculture (Smith et al., 2019). Organic farming needs crops and varieties that grow well without synthetic inputs (Lammerts van Bueren et al., 2011) and are adapted to local climatic conditions. Despite increasing interest in organic cereal production, adequate information on expected grain yields and production challenges is still lacking for many areas in the world (Cavigelli et al., 2008; Peltonen-Sainio et al., 2019).

Organic agriculture is an important tool in sustainable crop production but there is the need for a better understanding of the factors limiting organic yields and quality, as well as the positive aspects of organic farming on social factors, environment and economy (Seufert et al., 2012).

The series of organic trials at the Estonian Crop Research Institute were started almost at the same time as organic cultivation started to increase in Estonia at the beginning of this century and the farmers started to ask the scientists for help in answering questions about organic practices. We all started to expand our activities and develop our knowledge of organic production of cereals in Estonia (Tamm et al., 2016). Since then, the development of organic cultivation, processing and marketing has shown good growth (Organic farming in Estonia, 2018).

Nelson et al. (2011) concluded that the quality of the organic production varies from one location to other and should not be universalized. A number of studies suggest organic production to be superior and high in their quality values (Reid et al. 2009; Nelson et al., 2011), however, there are studies reporting significant loss in grain protein content under organic conditions (Talgre et al., 2009; Tamm et al., 2009; Bilsborrow et al., 2013; Wiebe et al., 2017; Cox et al., 2019). Mäder et al. (2007) reported non-significant differences in nutritional value and baking quality in European germplasm studied over 21 years. The influence of the cropping techniques in France was analysed by Casagrande et al. (2009) and the results showed that organic wheat grain protein content could be increased by using N-fixing legume crops as the preceding crop. Schrama et al. (2018) found that increased organic matter levels in the soil make organic systems also less susceptible to extreme drought.

Adoption of organic management on more fertile lands and more beneficial production climates could potentially increase the productivity of organic farming (Seufert & Ramankutty, 2017). Many conventional farms have, in recent years, increased the use of organic practices such as cover cropping, or composts. A further expansion of organic agriculture and integrating successful organic management practices into conventional farming are important next steps (Seufert & Ramankutty, 2017).

Grain protein content, which is derived from grain nitrogen concentration (N%), is a major determinant of grain quality of wheat. Grain protein content has a major impact on the end-use quality of products made from wheat. Therefore, this trait is typically a high priority in wheat improvement programs aimed at improving bread-making qualities. Grain N% is strongly affected by soil N availability.

Volume weight is a good overall quality characteristic for spring wheat. Wheat grain with high volume weight will usually contain kernels that reduce milling costs and increase flour yields relative to wheat grain with low volume weight.

2.3.3. Impact of weather

The actual final yield and quality of a crop is determined by many factors: weather, variety, fertiliser supply, soil conditions, occurrence of pests and diseases. When the crop is sufficiently supplied with nutrients, yield and quality variation depends mostly on weather conditions.

Changes in the climate will affect agriculture in several ways. Some can be positive such as increased growing season or increased CO_2 stimulating photosynthesis, while others, such as drought and floods will have a negative effect (Harkness et al., 2020).

As in the whole of northern Europe, air temperature has increased in Estonia during the period of instrumental meteorological observations (Jaagus, 1998; Jaagus et al., 2017). The highest warming was detected during the second half of the 20th century, when statistically significant trends were detected for annual and spring mean temperature (Jaagus, 2006). At the majority of the studied weather stations, annual and winter precipitation also increased significantly in Estonia (Jaagus, 2006). Precipitation extremes are projected to intensify in all seasons and regions of Europe, most distinct in the north (Rajczak & Schär, 2017).

Future climate warming will likely negatively affect crop production in low latitudes, while in northern latitudes, including all the Baltic Sea area, the initial effect is projected to increase crop yields. This would be mostly due to the lengthening of the, presently too short, growing period (Tarand et al., 2013). Until now, northern regions under current climate conditions normally have a narrow window for spring crop sowing and greater future challenges could be expected, which may alter attainable yield (Saue et al., 2016; Kolberg et al., 2019). Over the last 50-years the vegetation period in Estonia has prolonged on average by 3 weeks by trend and the start of climatic season in the spring has tended to shift as average ca 2 weeks earlier (Tarand et al., 2013; Saue et al., 2016). From the other side, an increase in temperature would speed up crop development, which may have an adverse effect on the productivity of cereals (Saue et al., 2016). The effect of elevated temperatures on spring cereal yields depends on the timing of the event. Cereals suffer significantly from periods with high temperatures that occur around heading (Saue et al., 2016).

As a consequence, growing crops under intense spring and summer daylight combined with elevated temperatures from one side and scarcity of light towards autumn and winter despite of elevated temperatures, poses additional challenges for crop breeding (Saue et al., 2016).

Climate change is expected to have large effects on wheat production: for every 1 °C increase in temperature, global wheat yields become more variable over space and time and is predicted to decline between 4.1–6.4% (Alexandratos & Bruinsma 2012; Asseng et al., 2015; Liu et al., 2016). In warmer regions wheat yields are expected to decrease compared to higher latitudes where extension of growing period is likely to lead to higher yields of spring wheat (Sommer et al., 2013). Gradual warming extends the wheat growing season and new varieties need to match this to utilize their environmental potential. Late spring drought is particularly damaging for spring wheat because, unlike winter wheat, roots in spring wheat are not well developed at that time thus restricting access to water from the deeper soil layers (Chawade et al., 2018). Higher rainfall during the wheat season, especially in North America, will require varieties with higher yield potential responding to moisture availability (Morgunov et al., 2018).

Growing number of studies describe climate change impacts on crop yield, but the impacts on the nutritional value of the crops has received much less attention, even though this is a critical aspect of food security (Haddad et al., 2016). Increase of temperatures together with changes of CO_2 and precipitations in combination with novel genotypes can increase wheat yield by 7% and thus protein content by 2%, however, protein concentration would then be decreased by 1.1 percentage points (8,6%). Circumstances related to climate change that boost grain yield, may have negative effect on grain quality. Therefore the breeding programs need to focus on increasing the rate of grain filling, which in turn could increase grain yield and protein content (Asseng et al., 2018). Wheat provides close to 20% of protein for humans in the world (Tilman et al., 2011).

Both low temperatures and water deficits after flowering were reported to negatively affect protein content in organic winter wheat in France (Casagrande et al., 2009) and spring wheat in Canada (Fernandez et al., 2019). In Canada there was no negative association found between protein concentration and grain yield (Fernandez et al., 2019).

Maintaining grain quality of wheat under climate change is critical for human nutrition, end-use functional properties, as well as commodity value (Nuttall et al., 2017). Climate change represents a significant challenge for delivering grain of consistent quality in the future due to the complex interactions of atmospheric CO_2, changing temperature and rainfall patterns on yield and quality (Nuttall et al., 2017).

In a recently published article, Kornhuber et al. (2020) mention that behaviour of atmospheric Rossby waves have a major influence on weather. They can lead to heat waves, droughts and floods in different places at the same time. Normally low harvests in one region are expected to be balanced out by good harvests elsewhere but these waves can cause reduced harvests in several important breadbaskets simultaneously, creating risks for global food production.

3. AIMS OF THE THESIS

This thesis reports on different field experiments conducted with spring wheat at the Estonian Crop Research Institute during different periods, the longest of these period, 29 years (1991–2019). It also analyses the resultant observations and calculations on these spring wheat trials.

It is well-known that legumes can contribute to the soil N pool for the successive crop seasons. However, knowledge of the response of spring wheat (*Triticum aestivum* L.) to different preceding leguminous pre-crops is limited. There is a paucity of information on the contributions of annual species such as Alexandria and crimson clover to the yield and quality characteristics of spring wheat in organic farming conditions **(I, II).**

One purpose of the next study was to conduct comparable assessments of spring cereals cultivated in conventional and organic farming systems, where the latter was able to address the needs of organic cereal farmers. The experiments on which this work was based were one of the first studies to simultaneously investigate spring wheat in both farming systems. The following parameters were assessed in both conditions during 2005–2008: grain yield and grain quality characteristics (thousand kernel weight, volume weight and protein content) (**IV, V**).

The objective of the long-term conventional trial series was to assess the impact of weather on yield, and protein content of spring wheat over 29 years (1991–2009, upgraded up to 2019) (**III**).

Hypothesis:

1. Other legume species besides the traditional red clover have potential as high quality green manure in organic crop rotations.

2. Six leguminous pre-crops, including the less commonly used annual Alexandria and crimson clovers, have different impacts on yield, protein content, volume weight and TKW of the subsequent spring wheat in the organic crop rotation.

3. Spring wheat yield and quality characteristics are lower in organic compared to conventional farming system.

4. Increased yearly fluctuations of weather conditions negatively impact yield and protein content of spring wheat.

The main objectives of the thesis are:

(1) To determine the effect of six leguminous pre-crop species on grain yield and quality characteristics of subsequent spring wheat compared to other cereals in organic crop rotation.

(2) To select the optimal leguminous pre-crops for spring wheat cultivation in organic conditions.

(3) To compare grain yield and quality characteristics of spring wheat varieties in organic and conventional conditions.

(4) To investigate the impact of weather (precipitation, sum of effective temperatures, sunshine hours) on yield, length of growing period, and protein content of spring wheat cultivated in conventional conditions over a period of 29 years.

4. MATERIALS AND METHODS

A brief description is given in this chapter, more details are in the publications.

4.1. Experimental site, design and subjects

All the field trials were carried out in the Estonian Crop Research Institute at Jõgeva, located in north-eastern Europe (58°45'N, 26°24'E). The trial area was located on Calcaric Cambic Phaeozem soil (IUSS 2015). The soil characteristics in the leguminous pre-crop trial were as follows: pH_{KCl} 6.7, P 65, K101, Ca 3834 mg kg^{-1}, C_{org} 3.5% and N_{total} 0.27%.

Different characteristics were measured in the study period and spring wheat was among the other cereals included in the different trials (Tables 1 and 2).

Table 1. Estimated characteristics in the publications (I–V).

I pre-crop*	**II** pre-crop*	**III** weather*	**IV** conv/org*	**V** conv/org*
	yield	yield	yield	yield
protein		protein	protein	protein
TKW			TKW	TKW
volume weight			volume weight	volume weight
		days from sowing to heading days from heading to maturity days from sowing to maturity		

*the main factors in the publications

Table 2. Cereals species included in the publications (I–V).

I	II	III	IV	V
spring wheat	**spring wheat**	**spring wheat**	**spring wheat**	**spring wheat**
barley	barley	barley	barley	barley
oats	oats	oats	oats	oats
winter wheat	winter wheat			
winter rye	winter rye			

Leguminous pre-crop trial (I, II).

The trial was divided into three cycles: (i) establishment of plots with perennial leguminous pre-crops in 2011 and annual leguminous pre-crops in 2012, in order to test the potential of pre-crops as green manure; (ii) sowing of winter cereals in 2012 and spring cereals in 2013 on the plots of leguminous pre-crops in order to test the first-year after-effect of the legumes to grain yield and quality of subsequent cereal species (I, II); (iii) second-year after-effect with oat and barley (not analysed in this thesis). The focus in this thesis was on results of spring wheat and a detailed analysis of other cereals has not been performed.

The trial was arranged as a split-plot design with six legume pre-crops (with non-legume control) as main plots (130 m^2) followed by five cereals (two varieties per crop) on 5 m^2 subplots in three replicates. The trial included three perennial legume species – red clover (*Trifolium pratense* L.), alsike clover (*Trifolium hybridum* L.), Washington lupine (*Lupinus polyphyllus* Lindl.), biennial white sweet clover (*Melilotus albus* Medik.) and annuals Alexandria clover (*Trifolium alexandrinum* L.) and crimson clover (*Trifolium incarnatum* L.). Timothy (*Phleum pratense* L.), which has no nitrogen-fixing ability, was used as a control. The trial cycle started with the sowing of perennial and biennial leguminous species – red clover 'Jõgeva 433', alsike clover 'Jõgeva 2', Washington lupine 'Lupi' and white sweet clover 'Kuusiku 1' in July 2011. In the following spring (April 2012), annual Alexandria clover 'Alex' and crimson clover 'Contea' were sown. Timothy was sown at the same time as the perennial green manure crops. In the area for the sowing of spring cereals red, alsike and sweet clover were cut, chopped and left in the field. The same operations were carried out using lupine on 20 June. The aftermaths of lupine and the primary growth of annual clovers were not cut in autumn and were ploughed in before the sowing of cereals in the spring of 2013. The spring wheat varieties 'Manu' and 'Uffo', were sown in May of 2013. All the cereal varieties were sown after each legume species.

Farming systems comparison trials (IV, V).

Field experiments were conducted over four years from 2005 to 2008 and established on 5 m^2 plots in 4 replications by randomized complete block design. The trials included 13 spring wheat, barley and oat varieties. The following spring wheat varieties were studied: 'Helle', 'Meri', ‘Mooni’ (Finnish-Estonian collaboration); ‘Vinjett’, ‘Tjalve’, ‘Zebra’, ‘SW Estrad’ (Sweden); ‘Munk’, ‘Triso’, ‘Monsun’ (Germany); ‘Manu’, ‘Mahti’ (Finland) and ‘Baldus’ (The Netherlands).

The average P content of the soil was good, the level of K average, the organic matter content medium and the pH slightly acid. The pre-crop in the organic trial was red clover in 2005 and 2006 and was followed by buckwheat in 2007 and 2008. Mechanical weed control by repeated harrowing was carried out after germination and in the 3–4 leaf stage. The pre-crops in the conventional trials were potato and rapeseed. The fertilizer level $N_{90}P_{20}K_{38}$ for wheat was used in the conventional trial. Weeds were controlled by herbicides and insects were controlled only in the years of severe attacks.

Weather trials (III). The results of the varieties ‘Satu’ (Sweden) and ‘Munk’ (Germany) were selected for analyses. Fertilizer level $N_{70}P_{16}K_{29}$ was used for oat and $N_{90}P_{20}K_{38}$ for barley and wheat. Chemical control of weeds was carried out every year and insects were controlled only in the years of severe attacks. Seeding rate of 500 (barley) and 600 (wheat, oat) germinating seeds per m² was used. The plot size was 10 m² in 3 replicates. Data collected included: grain yield, protein content, the days from sowing to heading and from heading to maturity.

4.2. Analyses

Chemical analyses from above- and below-ground biomass were determined as follows: nitrogen and carbon by the TUMAS ISO/TC 16634-2:2009 method, P and K by inductively coupled plasma optical emission spectrometry after pressure digestion **(I, II).** Cereal plots were harvested with a combine harvester (Hege 140). Plot yields were dried and cleaned. Grain yield (kg ha^{-1}) was recorded and adjusted for 14% of moisture content. Cereal samples were taken from each plot and protein concentration was measured using near-infrared (NIR) transmittance technology (**I, II, III, IV, V**).

N and C concentrations of the biomass (above-ground and roots) of legumes was determined by the ISO/TC 16634-2:2009 method (Estonian Centre for Standardisation, 2009) (**I, II**). TKW of cereals were determined by EVS-EN ISO 520:2010 (Estonian Centre for

Standardisation, 2010a), volume weight by EVS-EN ISO 7971-3:2010 (Estonian Centre for Standardisation, 2010b) (**I, II, III, IV, V**).

4.3. Meteorological conditions

Meteorological data were registered from the meteorological weather station of ECRI located about 1 km from the trial area. Data are presented in the table 2 in **I,** Table 1 in **II,** Figures 1 and 2 in **III,** Figure 1 in **V.**

4.4. Data analyses

For statistical analysis of the data, Agrobase versions Generation II™ 37.2.4 and SQL 36.5.1 were used. Statistical analysis of the results used correlation (**III, IV, V**), and single and multifactorial analysis of variance (**I, II, III, IV, V**). A significance level of 0.05 was used to find boundary differences. Coefficients of variation were calculated to evaluate the variability of long-term variables.

5. RESULTS

5.1. Influence of pre-crop (I, II)

Characteristics of leguminous pre-crops are important in evaluating their effect on the subsequent cereal species. Higher than average precipitation with average temperatures were favourable for the production of biomass of the legumes in 2012. The weather conditions of the main trial year 2013 were favourable as well, although periodic shortages of moisture occurred, in the first half of the vegetation period, thus decreasing N uptake by cereals.

The highest DMY, C, N, P and K content of legume species biomass measured before spring cereals, was observed in perennial and biennial legume (red, alsike, sweet clover and lupine) variants (Table 3). DMY and nutrient content of annual clovers remained significantly lower than that for other legumes. The nitrogen uptake of red and alsike clover was high, 321.8 and 322.7 kg ha^{-1}, respectively, compared to annual crimson clover (87 kg ha^{-1}). Alexandria clover normally has a longer growing period and it continued biomass accumulation until the end of its vegetation season. Annual crimson and Alexandria clover produced lower DMY and lower amounts of C and N, indicating less potential as green manure crops compared to other legumes.

As DMY consisted of above- and below-ground biomass, the relative proportions of shoots and roots can be important in assessing the potential of legumes for producing green manure. While most legume species produced relatively smaller amounts of roots compared to shoots, Washington lupine differed from other legumes by producing relatively higher proportion of roots (54%). All the legumes showed a decrease in the proportion of roots by the time October rolled around.

The C:N ratio of all the tested leguminous species was between 18 and 23. The smaller the C:N ratio and the greater the nitrogen content in biomass, the more nitrogen is mineralized into soil. Highly significant positive correlations were found between DMY, C, N, P and K content of legumes ($r = 0.88 - 0.99$; $p<0.05$).

Table 3. Dry matter yield (t ha^{-1}) and content of carbon (C, kg ha^{-1}), nitrogen (N, kg ha^{-1}), phosphorus (P, kg ha^{-1}), potassium (K, kg ha^{-1}) and carbon/nitrogen ratio (C:N) in biomass (green mass + roots) of pre-crops sampled before sowing of spring cereals.

Pre-crop	DMY	C	N	C:N	P	K
Red clover[a]	13.9*	6474*	321.8*	20*	41.3*	279.6*
Alsike clover[a]	13.4*	5993*	322.7*	19*	42.0*	296.0*
Lupine[a]	12.0*	4871*	268.0*	18*	30.6*	178.2*
Sweet clover[b]	11.8*	5302*	275.4*	19*	33.2*	263.7*
Crimson clover[c]	4.6	2004*	87.2*	23*	6.7	76.7*
Alexandria clover[c]	10.6*	3336*	160.9*	21*	12.4*	99.0*
Control (timothy)	5.4	1667	38.0	44	6.2	32.6
$LSD_{0.05}$	0.8	374	22.5	17	2.8	21.4

LSD: least significant difference
[a]perennial; [b]biennial; [c]annual
*means within columns are significantly different from control at p<0.05 (Fisher's LSD test)

5.1.1. Impact on yield (II)

Spring wheat and all other cereal species produced significantly higher grain yields in the subsequent year after the pre-crop of legumes, compared to the control (Table 4). The extra yields of spring wheat were in the range of 1550–2960 kg ha^{-1} and increased the most after perennial red and alsike clover (115 and 119%, respectively), compared to control (timothy). The third best was lupine (85%) followed by biannual sweet clover (72%). Even the annual species crimson and Alexandria clover had significant positive effects on yield increase (72 and 60%, respectively).

Interestingly, spring and winter cereals were influenced differently by perennial, biennial and annual legume species. Contrary to spring wheat and barley, oat benefited less from legume pre-crops and produced quite uniform extra yields (46–58%), independently of preceding legume species.

In addition, the grain yield of spring cereals had a strongly significant correlation with DMY (r = 0.72; p<0.001), C (r = 0.76; p<0.001) and N content (r = 0.80; p<0.001) of legume pre-crops in our trial. Other legumes, besides traditional red clover, demonstrated some potential as green manure. All the six tested legume species significantly increased the yield of spring wheat.

Table 4. The grain yield (kg ha^{-1}) of cereals after different legumes.

Pre-crop	Barley	**Spring wheat**	Oat	Rye	Winter wheat
Red clover[a]	5850*	**5530***	4580*	3600*	3490*
Alsike clover[a]	5790*	**5630***	4320*	3820*	4360*
Lupine[a]	5710*	**4750***	4450*	4020*	5710*
Sweet clover[b]	5430*	**4420***	4360*	4380*	6140*
Crimson clover[c]	4130*	**4430***	4270*	4120*	6220*
Alexandria clover[c]	4900*	**4120***	4210*	4870*	5700*
Control (timothy)	2520	**2570**	2890	920	2470
$LSD_{0.05}$	180	**350**	220	500	340

LSD: least significant difference
[a]perennial; [b]biennial; [c]annual
*means within columns are significantly different from control at $p<0.05$
(Fisher's LSD test)

5.1.2. Impact on quality (I)

Protein content. The variation in protein content of spring wheat and all other tested cereals was significantly influenced by the pre-crop (A) (**I** Table 5). The protein content of spring wheat was in the range of 9.3–12.2% and increased significantly after perennial legume species (Table 5). Only red and alsike clover provided the successive spring wheat with a sufficient amount of N to produce enough protein (11.4 and 12.2% respectively) to meet the regulatory specification that guarantees marketing of spring wheat for food purposes (>11%). The lowest protein content (9.3%) of spring wheat was measured after Alexandria clover. The protein content of spring wheat in the experiment was significantly more depending on the pre-crop than other spring and winter cereals. The influence of variety (B) on protein content was also significant for spring wheat and for most of the other cereals.

Table 5. Protein content (%) of cereals after different legumes.

Pre-crop	Barley	**Spring wheat**	Oat	Rye	Winter wheat
Red clover	10.4a	**11.4a**	11.3a	8.8a	11.4a
Alsike clover	10.2a	**12.2b**	11.1a	8.2b	11.3ab
Washington lupine	10.2a	**10.8c**	11.0ab	8.8a	11.4a
White sweet clover	10.5a	**9.9d**	10.3bc	8.9a	11.5a
Crimson clover	9.7b	**9.8d**	10.5bc	8.2b	11.1b
Alexandria clover	9.6b	**9.3e**	10.4bc	8.3b	11.1b
Control	9.4b	**9.6de**	9.8c	8.6ab	10.2c
$LSD_{0.05}$	0.3	**0.4**	0.7	0.4	0.3

LSD – least significant difference
Within columns, mean values followed by the same letter are not significantly different at $p<0.05$

Volume weight. The average volume weight of spring wheat grown following pre-crop legumes was 78.4 kg hl^{-1}, ranging from 76.9 to 79.5 kg hl^{-1} (Table 6). All variants, including the control, exceeded the marketing requirement for food wheat. Volume weight of spring wheat increased significantly after all legumes except crimson clover. Washington lupine (79.5 kg hl^{-1}) and Alexandria clover variant (79.2 kg hl^{-1}) showed the highest volume weight, exceeding the control by 4%. Pre-crop and variety had a significant impact on the variation of volume weight of all the cereals (**I** Table 7). Different from other cereals, A x B interaction remained significant for spring wheat. The first-year after-effect of all the leguminous pre-crops on volume weight was significantly positive compared to the control in most cases but there were no clear trends.

In this study, winter wheat had higher volume weight compared to spring wheat, however, both wheat types achieved the necessary quality requirements of the food industry (75.0 kg hl^{-1}).

Table 6. Volume weight (kg hl^{-1}) of cereals after different legumes.

Pre-crop	Barley	**Spring wheat**	Oat	Rye	Winter wheat
Red clover	69.4a	**78.1a**	51.6a	69.3a	79.3a
Alsike clover	70.3b	**78.7b**	52.4ab	71.0b	81.5b

Washington lupine	69.5a	**79.5c**	51.2a	69.5a	81.7b
White sweet clover	68.6cd	**78.2a**	51.2a	69.4a	81.7b
Crimson clover	68.3c	**76.9d**	53.7b	70.0a	81.2b
Alexandria clover	69.0ad	**79.2c**	53.0b	70.5b	81.1b
Control	67.6e	**76.5d**	49.3c	66.2c	79.5a
$LSD_{0.05}$	0.5	**0.6**	1.3	0.8	0.6

LSD – least significant difference
Within columns, mean values followed by the same letter are not significantly different at p<0.05.

Thousand kernel weight. The TKW of spring wheat after legumes was in the range of 36.3–38.7 g (Table 7). All the green manure pre-crops increased significantly the TKW of spring wheat similar to barley and winter wheat. For spring wheat, the grains with the highest TKW were measured after perennial species: alsike clover (38.7 g), red clover (37.7 g) and Washington lupine (37.3 g).

Variation in TKW of the tested cereals, except oats, was significantly influenced by the pre-crop (A) (**I** Table 9). The influence of variety (B) was also significant for all the cereals.

Table 7. Thousand kernel weight (g) of cereals after different legumes.

Pre-crop	Barley	**Spring wheat**	Oat	Rye	Winter wheat
Red clover	49.8a	**37.7ab**	44.0a	37.1a	45.8a
Alsike clover	51.1b	**38.7b**	43.9a	34.2b	45.9a
Washington lupine	51.1b	**37.3ac**	43.7a	37.3a	46.5b
White sweet clover	50.3ab	**36.3c**	44.3a	36.9ad	47.1c
Crimson clover	48.1c	**36.9ac**	43.9a	34.8bcd	45.8a
Alexandria clover	49.8ab	**36.5ac**	43.9a	35.8d	45.9a
Control	46.8d	**33.9d**	44.5a	38.2a	43.3d
$LSD_{0.05}$	1.0	**1.3**	1.1	1.1	0.6

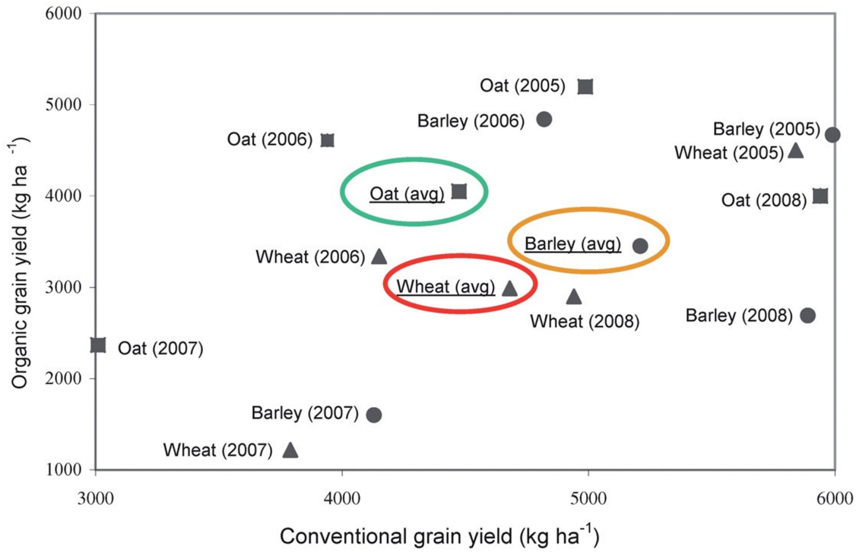
LSD – least significant difference
Within columns, mean values followed by the same letter are not significantly different at p<0.05.

5.2. Influence of farming system (IV, V)

5.2.1. Impact on yield

Yield data from two farming systems was collected in 2005–2008 (Figure 1). In organic conditions the yield of spring wheat varied between 1220–4500 kg ha^{-1} and in conventional system between 3700–5840 kg ha^{-1}. The mean spring wheat yield across the years was 2990 kg ha^{-1} in the organic trial and 4680 kg ha^{-1} in the conventional trial. Nutritional needs of wheat are the highest among the tested spring cereals. The yield differences between the farming systems were high as an average grain yield of spring wheat and barley in organic conditions constituted only 64% and 66% of that of the conventional yield, respectively. Oat was the least influenced by the two management systems and produced quite similar yields in both conditions. Difference in grain yield of oat was only 10%.

The yields of spring wheat in conventional systems were higher than in the organic systems by 23%, 20%, 68% and 33%, respectively in the tested years of 2005, 2006, 2007 and 2008. The yields of spring cereals in organic conditions was largely influenced by the pre-crop and weather conditions. In the first trial year (2005) after the favourable pre-crop (red clover) and favourable weather conditions, all the cereals produced yields higher than 4500 kg ha^{-1}. The lowest average yields (1220 kg ha^{-1} spring wheat) were produced after buckwheat in 2007, caused by heavy soil crust during germination and early drought before heading. In the last year of the trial cycle (2008) after an unsuitable pre-crop (buckwheat) the yields were higher (2900 kg ha^{-1} spring wheat) than in 2007.



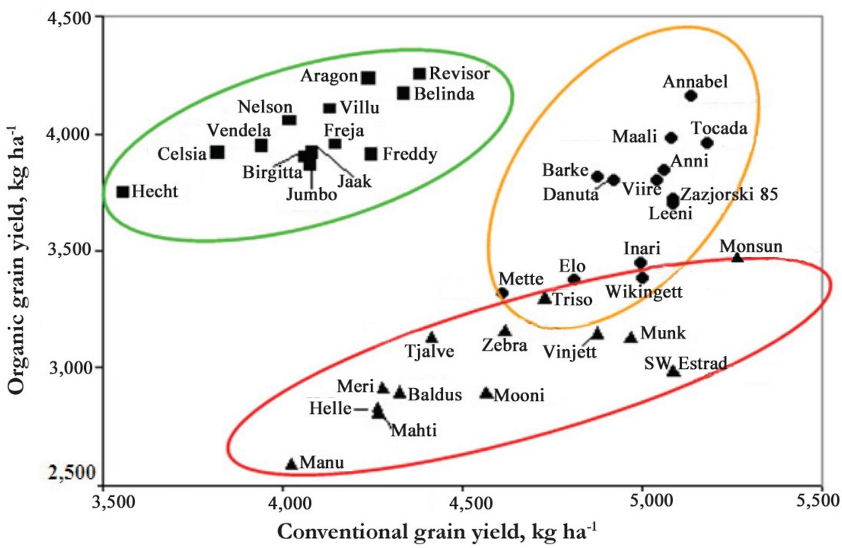
▲ – wheat ● – barley ■ – oat

Figure 1. Grain yields (kg ha^{-1}) of spring cereals in organic and conventional conditions during 2005–2008 ($LSD_{0.05}$ for 2005=212, 2006=186, 2007=159, 2008=128, average =132 kg ha^{-1}).

Significant differences between organic and conventional yield results were found in trial years and four years averages for all the spring cereals except differences in yield for barley between farming systems in 2006.

Considerable differences in grain yield were found between the varieties and the majority of them yielded similarly under both growing conditions. There were found positive correlations between grain yields (2005–2008) in organic and conventional trials ($r = 0.71$; $p<0.01$ for spring wheat and oat, $r = 0.63$; $p<0.05$ for barley).

The varieties of different spring cereals tested during 2005–2007 formed quite clear groups (Figure 2) while comparing the yields of the two management systems. The ranking of the varieties by yield was comparable in the two farming systems. Several spring wheat varieties produced higher yields than oat varieties in conventional trial, but all were lower in organic trial. In both management conditions increased grain yield of spring wheat was associated with late maturity. The correlation coefficient between yield and length of growing period of wheat was 0.73 ($p<0.01$) in organic and 0.79 ($p<0.01$) in conventional trial. No significant correlation between yield and length of growing period of oat and barley was found.



▲ – wheat ● – barley ■ – oat

Figure 2. Comparison of organic and conventional grain yields (kg ha^{-1}) of the varieties of spring cereals (LSD$_{0.05}$ = 402 kg ha^{-1}) as an average of 2005–2007.

5.2.2. Impact on quality

Grain quality. Some quality characteristics of spring cereals were different in organic and conventional conditions. Spring wheat was the most sensitive to different management systems among spring cereals for the production of protein. The biggest dissimilarity was found in protein content. It was significantly lower in the organic trial in all the tested years, being 12.6% (organic) and 15.0% (conventional) as the average of 2005–2008 (Table 8). The same tendency occurred in all the trial years.

The average TKW of spring wheat in the organic trial was bigger (35.8 g) compared to the conventional one (34.2 g). The number of grains per head in organic conditions was smaller but the grains grew larger. Significant difference in volume weight between organic and conventional (76.7 and 78.3 kg hl^{-1}) trial was not measured.

Grain quality of the same varieties was high in both management conditions. There were strong positive correlations between grain quality traits in organic and conventional conditions of all the crops (protein r = 0.85; p<0.001, TKW r = 0.93; p<0.001, volume weight r= 0.78; p<0.01).

Table 8. The grain quality characteristics of spring cereals in conventional and organic conditions as an average of 2005–2008 crop years.

Characteristic	Conventional			Organic			
	Oat	Barley	**Wheat**	Oat	Barley	**Wheat**	$LSD_{0.05}$
1000 kernel weight, g	35.0	45.3	**34.2**	36.0	44.8	**35.8**	1.0
Volume weight, kg hl^{-1}	49.8	67.4	**78.3**	47.2	67.5	**76.7**	2.3
Protein content, %	12.2	12.0	**15.0**	11.3	11.3	**12.6**	0.3

5.3. Influence of weather (III)

5.3.1. Impact on yield

The effect of weather conditions has been studied for the 19 year period (1991–2009), additional data for the following 10 years, were included (2010–2019).

Across all field-years, in season (from sowing to maturity) precipitation varied from 71 to 530 mm as average of 19 years (1991–2009) (Figure 3). During the followed 10 years (2010–2019) the lowest amount of precipitation (60 mm) was measured in 2018. Variation in yield was high during the trial period (1991–2009). Yield variation depended mostly on the year (F = 109.63; p<0.001), but the influence of the crop (F = 230.82; p<0.001) and crop x year interaction (F = 28.71; p<0.001) were also significant. The yields differed more than two-fold for wheat (Table 9). The years of high yield capacity (above 5500 kg ha^{-1}) for spring wheat were 1993, 1997, 2003 and during the last decade the years 2012, 2014, 2017 and 2019 were also included. Higher yields were produced in the years without extremely low or high amount of precipitation. All the cereals reached maximum yield in these years exceeding 7 t ha^{-1}. In the least unfavourable years (1992, 1995) the yield of wheat was close to 3.4 t ha^{-1} and even below 3 t ha^{-1} in the later periods (2016, 2018).

Table 9. Variation of grain yield (kg ha^{-1}) and protein content (%) of spring cereals during 1991–2009.

	Grain yield kg ha^{-1}			Protein content %		
	Wheat	Barley	Oat	**Wheat**	Barley	Oat
Mean	**4695**	5533	5009	**14.2**	12.0	11.6
Min	**3360**	2590	2490	**10.6**	9.5	9.3
Max	**7000**	7840	7100	**16.7**	14.5	14.3
*CV**	**22**	22	29	**11**	10	12

* *CV* – coefficient of variation

The yields of all the crops in these trials (1991–2009) were low in the years of drought (1992, 1999, 2002), in the years of early drought in 2007 and in 2016 (last decade). Among the following 10 years 2018 is also included in drought years with low yield capacity.

Unsuitable for supporting production of higher yields were also the years of excess precipitation (1998, 2001). During the succeeding decade, below average precipitation in the first half of season and above average precipitation in July-August may have been responsible for the observed decrease in yield during 2016. In all of these years moderate to severe lodging was estimated.

Both stress conditions – drought and excess precipitation, caused decreases of yield of spring wheat. The highest yields formed in the 200–350 mm precipitation range from sowing to maturity.

The yields of wheat varied less (*CV* = 22%) than yield of oat (*CV* = 29%), which was the most unstable because of susceptibility to severe lodging and serious drought. Although the spring crops reacted to some extent differently, significant positive correlations were still found between the grain yields of the three crops over the years ($r = 0.65–0.75$; $p<0.01$) (**III** Table 3).

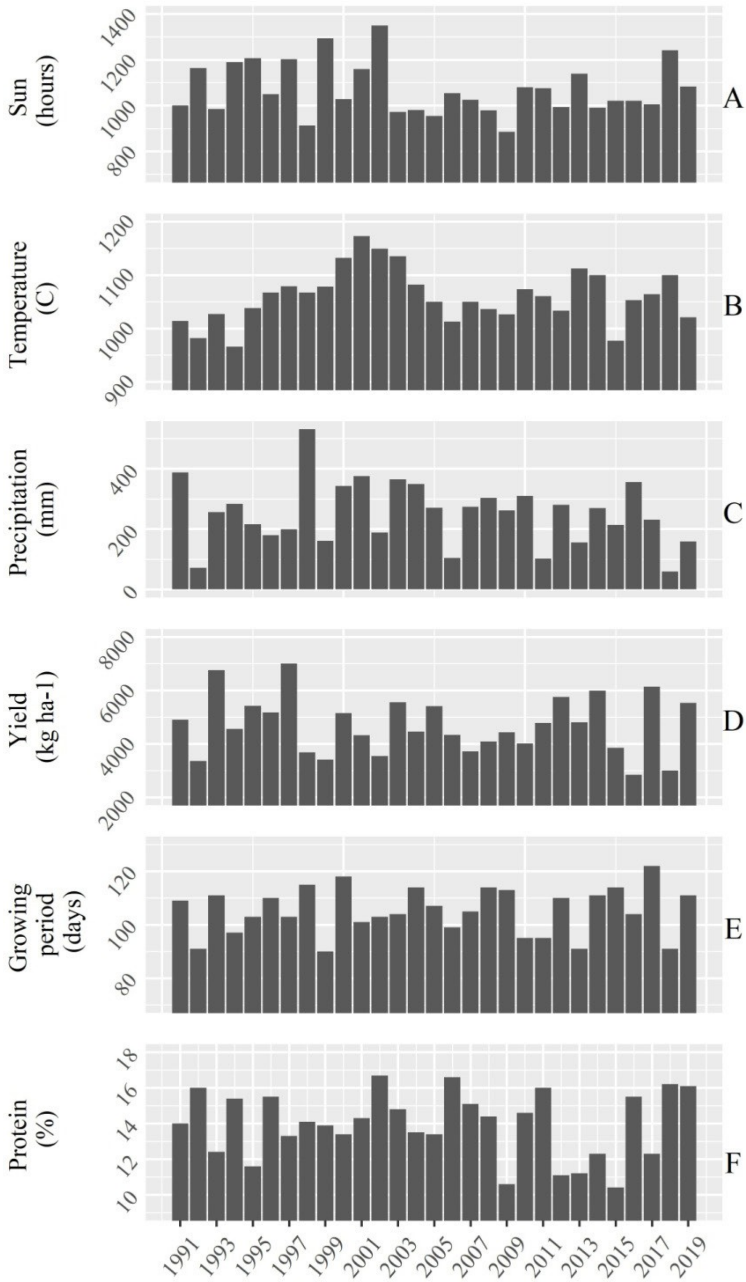


Figure 3. Average weather data of 1991–2019 (ECRI weather station): (**A**) sunshine hours, (**B**) effective temperatures, (**C**) precipitation, (**D**) yield, (**E**) length of growing period, (**F**) protein content.

The yields of oat and barley demonstrated negative correlations with sunshine hours in June (for oat r = –0.60; p<0.01, for barley r = –0.58; p<0.05). The same correlation for wheat was not significant.

5.3.2. Impact on quality

Protein content. The variation of protein content was significantly dependent on weather conditions of the year (F = 60.89; p<0.001), crop (F = 493.38; p<0.001) and their interaction (F = 9.27; p<0.001). The protein content was higher in the dryer and warmer years when the yield was lower (1992, 2002, 2006) and when there was drought early in the season in June (2007).

Protein content was inversely associated with yield (r = –0.45; p<0.05 for wheat and oat; r = –0.46; p<0.05 for barley). A positive correlation between sunshine hours in June and protein content (for oat r = 0.5; p<0.05, for barley r = 0.59; p<0.05) was found, but the same correlation for spring wheat was not significant. Average protein content of wheat was over two percentage points higher than that of barley and oat. The variation coefficients of the crops were similar (10–12%). The crops responded to the weather conditions by rather similar patterns. There were positive correlations between the crops (r = 0.65 – 0.67; p<0.05) (**III** Table 3). Exceptionally low protein content, especially for wheat, was measured in 2009 and 2015 (10.6% and 10.4% respectively). Spring wheat protein was below the minimum requirement for food (11%) in only two years and met the highest quality requirement (14%) in 16 years out of 29.

5.3.3. Impact on the length of growing period

Growing period from sowing to heading. Sowing to heading time intervals were similar for all the cereals (59–60 days) (Table 10). In the drought years the period was 51–52 days and in cooler and more rainy years it extended up to 65–68 days. The length of this period was mainly dependent on the weather of the year (F = 302.93; p<0.001). Sunny weather in June decreased the period from sowing to heading. Growing period correlated negatively with sun hours in June for spring wheat (r = – 0.58; p<0.05) and both other cereals.

Table 10. The variation of growing period (days) of spring cereals during 1991–2009.

	S to H[1]			H to M[2]			S to M[3]		
	Wheat	Barley	Oat	**Wheat**	Barley	Oat	**Wheat**	Barley	Oat
Avg	**60**	59	60	**46**	35	39	**106**	94	99
Min	**52**	51	52	**34**	28	28	**90**	83	80
Max	**66**	68	65	**57**	53	60	**118**	113	120
CV	**7**	7	6	**13**	17	22	**7**	8	11

[1] days from sowing to heading
[2]days from heading to maturity
[3] days from sowing to maturity

Growing period from heading to maturity. The average of this period for wheat was longer than that of barley and oat (respectively 46, 36 and 39 days). The longest period from heading to maturity of any cereal was in 2008 (53–60 days) exceeding the crop average by 11–21 days. The difference in length of the period from heading to maturity exceeded 3–4 weeks. Compared to the period from sowing to heading, it varied more – CV = 13% for wheat, 17% for barley, and as much as 22% for oat. This period depended not only on the weather of the year ($F = 60.82$; $p<0.001$), but also on the crop ($F = 268.15$; $p<0.001$).

Growing period from sowing to maturity. Spring wheat had the longest period from sowing to maturity in most of the years. The spring crops length of growing period differed at maximum from 28–40 days. Cool and wet weather increased the length of total growing period. Whole growing period correlated positively with sum of precipitation from sowing to maturity ($r = 0.49$; $p<0.05$ for wheat, $r = 0.46$; $p<0.05$ for oat, $r = 0.40$; $p<0.05$ for barley). The shortest growing period was in the years of drought. The variation of this period depended on the weather of the year ($F = 408.72$; $p<0.001$) but also on the crop ($F = 1244$; $p<0.001$). The length of growing period varied similarly. The correlation coefficients of this trait between the crops were high ($r = 0.76–0.90$; $p<0.001$) (**III** Table 3).

6. DISCUSSION

6.1. Influence of pre-crop (I, II)

N release from legume residues during a previous crop year after incorporation will improve the subsequent management of organic cereals and their nitrogen reserves. There is a lack of information in the Northeast of Europe on how to introduce more legume species into crop rotations and their influence on yield and quality of succeeding cereal crops (Preissel at al., 2015; Squire et al., 2019). The current results presented in this thesis on the green-manure potential of annual clovers are valuable, since there is little previous research on these species in the region.

6.1.1. Impact on yield (II)

Average DMY, C and N content of perennial (red and alsike clover, Washington lupine) and biannual (white sweet clover) leguminous species were higher compared to annual clovers (crimson clover and Alexandria clover) (Table 3). Other studies have found similar values for perennial leguminous species (Skudiene et al., 2012; Lauringson et al., 2013; Bender & Tamm, 2014). Annual crimson and Alexandria clover produced lower DMY, C and N content indicating lower potential as green manure crops compared to other legumes in these field trials. Possible reasons include having lower biomass production potential of annual species due to the shorter life cycles of these species. Previous research confirms significantly lower biomass production of crimson clover compared to red clover grown (Coombs et al., 2017).

Spring wheat requirements for a pre-crop grown under organic conditions are high. N availability impacts wheat development throughout its life cycle from tillering until the ripening phase. The positive effect of pure sowings of leguminous pre-crops on yield, as implemented in our present study, has been shown to be considerably higher compared to the effect of legumes as catch crops (Känkänen et al., 2001; Olesen et al., 2007; Løes et al., 2011).

The yields of spring wheat increased the most after red and alsike clover (115–132%), compared to control (timothy). In the recent study by Feiziene et al. (2016) there was a considerably lower effect of leguminous pre-crop species (yellow lupine) on grain yield of spring wheat, which could be explained by the poor establishment of the legume stands.

The C:N ratio of all the tested legumes was favourable (20–25 depending on the species), being comparable to previously detected C:N ratios by other researchers (Nykänen et al., 2008; Skuodiene et al., 2012; Talgre et al., 2012).

6.1.2. Impact on quality (I)

Protein. Grain yield and protein content are often inversely related. As average yield after leguminous pre-crops was quite high (4670 kg ha^{-1}), the protein content of spring wheat in this experiment remained moderate (10.6%). Although protein content of wheat remains generally lower in organic compared to conventional management. Organic farmers often gain a higher selling price for a slight increase in protein content (Mazzoncini et al., 2015) and thus even small improvement should be considered (Tosti et al., 2016). Lammerts van Bueren et al. (2002) suggested that organic cultivars should have larger and more active root systems for increased nutrient uptake in order to cope with the lower nutrient levels of organic fields. Therefore, further root studies of field grown plants are merited, like spring wheat and the other cereals that were included in these organic trials.

Volume weight. High values of volume weight increase market grade and price. It is influenced by many factors, including agronomic practice and weather conditions, disease infection, kernel shape and density (Gaines et al., 1997; Ingver, 2007). Pre-crop and variety had a significant impact on the variation of volume weight of all the cereals. The pre-crop and variety interaction was significant only for spring wheat in the trial. The first-year after-effect of all the leguminous pre-crops on volume weight was significantly positive in most variants compared to control. Spring wheat had the highest volume weight following Washington lupine (79.5 kg hl^{-1}) and the lowest after crimson clover (76.9 kg hl^{-1}). Low grain volume weight can also reduce wheat market price.

Thousand kernel weight (TKW). The weather conditions in 2013 were quite favourable for formation of bigger than average grains. All the green manure pre-crops significantly increased the TKW of spring wheat. TKW (as mean of all the leguminous pre-crops) was the highest for barley (50.0 g) followed by winter wheat (46.2 g), oat (44.0 g), spring wheat (37.2 g) and rye (36.0 g). The largest grains of spring wheat were measured following alsike clover (38.7 g) and red clover (37.7 g). Previous researchers of red clover have found positive effects on TKW of winter and spring wheat and winter rye (Skuodiene & Nekrošiene, 2009; Talgre et al., 2009; 2010), thus supporting our findings.

6.2. Influence of farming system (IV, V)

The amount of land devoted to organic agricultural production has grown significantly worldwide over the past decade, despite crop yields being reported to be lower with organic than with conventional management practices (Mäder et al., 2002; de Ponti et al., 2012; Seufert et al., 2012; Campiglia et al., 2015; Ponisio et al., 2015; Fernandez et al., 2019).

Organic systems differ from conventional farming systems in several important aspects, including the methods used to enhance soil fertility. Organic farming, to be competitive, relies on legume green manures or other organic manures as a way to increase the soil N content. The highly variable yield and quality differences which have been reported between organic and non-organic systems appear to depend on the particular management practices employed as well as the site characteristics (Seufert et al., 2012; Campiglia et al., 2015; Fernandez et al., 2019). In organic farming, nitrogen is derived only from the legumes, crop residues, manure and compost, which usually do not supply enough nitrogen, lowering crop yields in comparison to the conventional farming (Tsvetkov et al., 2018). There is an increasing demand for more sustainable resource use in intensive modern agriculture, which includes breeding of adapted varieties along with development of production systems that reduce risks and thereby enhance resilience and sustainability (Shiferaw et al., 2013).

6.2.1. Impact on yield

The mean spring wheat yield across all years (2005−2008) was 2990 kg ha^{-1} in the organic trial and 4680 kg ha^{-1} in the conventional trial. In organic conditions average grain yield of spring wheat constituted only 64% of that of the conventional yield. In the meta-analyses by Ponisio et al. (2015) organic wheat yield was on average 27% less than conventional yield, although the yield gap varied widely (from −60 to +30%). Murphy et al. (2007) found that the yields of winter wheat in conventional systems were greater than in the organic systems by approximately 38% and 60% for two different locations. Nutritional needs of wheat were the highest among the tested spring cereals. There was strong significant correlation ($r = 0.71$; $p<0.01$ (2005–2008) and $r = 0.80$; $p<0.01$ (2005−2007)) between organic and conventional grain yield of spring wheat. Most varieties ranked similarly in both growing conditions. Under both management conditions higher grain yields were associated with late maturity. In our three-year trial cycle (2005−2007) under the conventional conditions barley was the highest yielding followed by wheat and oat. Oat was less influenced by the two management systems and produced quite similar yields in both. Organic spring wheat produced 36% lower yield than conventional wheat, organic barley 34% respectively and oat only 10% lower yield. Some varieties produced comparatively higher yields and good quality in organic conditions. To achieve the best possible yields for a given site, growers use varieties that are adapted to that particular environment and to nutrient levels, which fluctuate with the seasons (Lammerts van Bueren, 2003). Kamran et al. (2014) studied 32 Canadian spring wheat cultivars under organic and conventional conditions. The significant cultivar x environment interaction for grain yield found in this study suggests that some cultivars can tolerate nutrient, weed and disease pressure better than other cultivars. Better performance of certain cultivars under organic field conditions has been reported previously (Mason et al., 2007). Therefore, breeding for organic farming system should be conducted on organically managed trials (Lammerts van Bueren et al., 2011; Kirk et al., 2012; Kamran et al., 2014; Crespo-Herrera & Ortiz, 2015).

Mean spring wheat grain yield in Canada over the six years (2010–2015) of the organic trial was 2305 kg ha^{-1}. Yield was highest in 2010 (3820 kg ha^{-1}), and in the following year, and lowest in 2015 (1212 kg ha^{-1}), the least favourable year for crop emergence and growth due to a dry spring and early summer (Fernandez et al., 2019). Those data were similar to that obtained in our four year cycle in organic trial. The highest was in 2005 (4500 kg ha^{-1}) and the lowest in 2007 (1220 kg ha^{-1}). In 2007 wheat may have been stressed by lack of water during the early part of the growing season. However, in the comparison of two trial systems carried out with winter wheat at Cornell University, the yield of organic wheat was more competitive, with only a 13% lower yield than conventional wheat in 2016 but similar or greater yields in 2018 (Cox et al., 2019). Mäder et al. (2007) showed that the yield of wheat was 14% lower in an organic versus conventional production system in a 21 year trial in central Europe. However, there were no consistent differences in winter wheat yield among cropping systems in the trials carried out in the mid-Atlantic region of the United States (Cavigelli et al., 2008).

The lower grain N% in organic compared with conventional wheat in both years of the study indicates that researchers should focus on N management strategies to provide adequate N to organic wheat during the stem elongation through anthesis stage to maximize grain yields (Cox et al., 2019). Averaged over the four years of the study in northeast England, yield of winter wheat from the organic production system was 40% lower than that achieved from the conventional system by an average 3.1 t ha^{-1} (7.9 vs. 4.8 t ha^{-1}) (Bilsborrow et al., 2013).

Several researchers (Bilsborrow et al., 2013; Campiglia et al., 2015; Fernandez et al., 2019) have concluded that it was not just conventional fertiliser making the differences in yield and quality, but it is a product of management, weather and previous crops. Similarly, in our Estonian comparison trial, heavy soil crust after sowing, early drought before heading and unsuitable pre-crop (buckwheat) in 2007 decreased yields the most. In favourable conditions all the spring cereals were able to produce comparatively high yields also in organic cultivation. Subjected to unfavourable weather conditions and with an unsuitable pre-crop, yield differences between the two cultivation regimes were greater.

6.2.2. Impact on quality

The main challenge to both organic and conventional farmers is production of wheat with high quality due to its importance as a staple food and core ingredient in many products for human consumption. Grain protein content, volume weight and thousand kernel weight are considered among the most important quality traits in breeding and selection of spring wheat cultivars (Gupta et al., 1991).

Grain quality parameters such as grain volume weight and grain protein content are important end-use quality indicators with marketing implications. N levels and weather conditions during the plant's reproductive phase can influence the values of volume weight which is a traditional standard grain quality measurement worldwide.

Protein. Concerning the quality characteristics, protein content was the most influenced by the cultivation regime. Compared to conventional, it was lower in organic trial of all the spring cereals but the biggest decrease was found in the spring wheat plots (12.6% in organic versus 15.0% in conventional). The same tendency occurred in all the trial years. There were positive correlations between protein content in organic and conventional trials ($r = 0.85$; $p<0.001$ for wheat, $r = 0.85$; $p<0.001$ for oat and $r = 0.64$; $p<0.05$ for barley). The other quality characteristics were less influenced by the management regime. Similar results were obtained by other researchers in studies where protein content in organic cultivation was estimated to be 2–3 percentage points lower compared to conventional cultivation due, partially, to insufficient nitrogen supply (Mäder et al., 2002; Bilsborrow et al., 2013). Field experiments conducted under organic management at four site–years in Canada found that organic spring wheat breeding lines greater ability to assimilate N did not translate into higher protein content (Arncken et al., 2012; Wiebe et al., 2017). In an organic trial performed by Fernandez et al. (2019) the mean wheat protein concentration for all treatments and years (2011–2015) in the organic trial was 14.2%. In 2011, the highest mean protein content (15.9%) coincided with the highest grain yield (3155 kg ha^{-1}), while in 2014 results had the lowest protein content (11.8%) and the second lowest grain yield (1613 kg ha^{-1}). The latter year had a mean air temperature during the growing season lower than that recorded during the other three years (Fernandez et al., 2019). These results are inconsistent with the inverse relationship of grain yield with protein content as found in our research and commonly reported by others (Lollato & Edwards, 2015; Iqbal et al., 2017). A 21 year agrosystem comparison between organic and conventional farming carried out in central Europe found that protein content and baking quality were not affected by the farming systems employed during grain production. These findings by Mäder et al. (2007) indicate that high wheat quality in organic farming is achievable with lower inputs, thereby safeguarding natural resources. In France a positive correlation was found between winter wheat grain protein content and crop nitrogen status in organic conditions (Casagrande et al., 2009).

TKW. Kernel weight of wheat increased in this organic and conventional comparison, 34.2 and 35.8 g respectively. In a study carried out in Maryland (USA) conventional compared with organic wheat had 1.0 g greater kernel weight with recommended inputs, but 2.7 g greater kernel weight with high inputs. Overall, kernel weight averaged about 4 g greater in 2018 compared with 2016. Kernel weight did not correlate with yield both in 2016 ($p = 0.11$) or in 2018 ($p = 0.47$) (Cox et al., 2019). TKW mean values ranged from 35.4–36.8 g, but there were no significant differences between organic and conventional in most years (Fernandez et al., 2019). In organic spring wheat, significant differences were also observed for TKW where lines bred for organic conditions had significantly higher kernel mass at all four site–years. A slight positive correlation ($r = 0.29$; $p<0.01$) was observed between kernel mass and grain yield (Wiebe et al., 2017). Kirk et al. (2012) also found that wheat selected under organic management had higher kernel mass than the same populations selected under conventional management. The reverse was claimed by Arncken et al. (2012) as 10% and 7% reduction in thousand kernel weight was found in two organic systems (bio-dynamic and bio-organic).

Volume weight. In the four years trial (2005–2008) the volume weight was somewhat lower in organic cultivation, 76.7 kg hl^{-1} compared to 78.3 kg hl^{-1} in the conventional trial. There was a strong positive correlation between volume weight in organic and conventional conditions for spring wheat. Fernandez et al. (2019) found that there were either no significant differences between volume weight and farming systems or they were not consistent. Mean test weight for all years and organic tillage–rotation systems was high – 79.6 kg hl^{-1}. Murphy et al. (2007) found that conventional systems had significantly higher test weights at two locations and lower weights in one location and no difference in another two locations. Differences for test weight among genotypes were found in each location. Genotype system interactions were found for test weight between systems in four of five locations.

Averaged across the three harvest years hectolitre weight of wheat was only slightly reduced (3.0 and 2.5%) (Arncken et al., 2012). This is consistent with the findings reported by Mason & Spaner (2006). The reverse was true in one study where the organic system gave a higher weight than the conventional system in all years and especially in 2007 and 2008 where it was 2.4 and 2.6 kg hl^{-1} higher respectively (Bilsborrow et al., 2013).

6.3. Influence of weather (III)

The results of this research (1991–2009) underlined that the grain yield and grain quality characteristics were generally sensitive to year-by-year variations caused by the cyclonic activity in Estonia. Prevailing weather conditions (the climate) are a major factor in determining, which crops are able to be grown and produce high yield with good quality in the region. Temperature and precipitation play an important role whether by increasing or decreasing the yield. This research describing the effect of weather conditions on yield and quality characteristics was collected from 1991–2009 which includes the years of the farming system trials (2005–2008). Adding the pre-crop trial (2011–2013) and upgraded with data up to 2019, the study summarizes the weather data for a time span of 29 years. All the trial periods conclude that weather conditions are the largest, or one of the largest, impacts on yield and quality of spring wheat and other spring and winter cereals. The uncertainty about weather conditions is one of the key risk factors associated with crop production. In the last decades, extreme dry as well as extreme wet periods have occurred in Estonia. The increase of the annual number of extreme wet and dry days over 1957–2006 indicate a rising trend of extreme precipitation events in Estonia (Tammets, 2007) and up to year 2009 (Tammets & Jaagus, 2013). Changes in sunshine duration might be changing the climatic driver of regional wheat yield. Analysing weather data has improved our understanding of the climatic drivers of spring wheat yield and what changes it might be sensitive to in the future (Shimoda et al., 2015).

6.3.1. Impact on yield

Large differences in weather conditions were observed during the research period. Producing higher yields under conventional conditions were mainly hampered by weather conditions.

The yield varied during this study period (1991–2019), ranging from 3.3 t ha^{-1} (1992) and 7.0 t ha^{-1} (1997). The highest yields of all the spring crops were formed in the years with moderate precipitation and temperature (1993, 1997). Similar conclusion was drawn by Campiglia et al. (2015) noting that the best wheat yield performance was observed in both organic and conventional cropping systems when rainfall was well distributed throughout the wheat cropping period.

Heavy soil crust during germination, early water stress before heading and an unsuitable pre-crop (buckwheat) in 2007 caused the most decrease in grain yield. Spring wheat suffered the most among the spring cereals. The experimental period (1991–2009) was characterized by frequent extremes of weather. Six years had above-average rainfall and four years had drought. Nine years had closer to average rainfall which was more evenly distributed during the growing season. The unfavourable effects of weather anomalies (drought, over-abundance of water) on yield and quality were registered.

All crops are sensitive to drought for any significant period especially during stem elongation, heading and flowering when the leaves are exposed to high temperatures, photosynthesis slows down and plant respiration increases (Forsberg & Reeves, 1995; Araus, 2002; Kutchera et al., 2010; Senapati & Semenov, 2020). The result is a reduction in yield. Increased temperatures during grain filling also decreased yield, likely because of decreased allocation of carbohydrates to the developing grains (Lollato et al., 2019). The yields of all the crops in our trials were low in the years of drought (1992, 1999, 2006) and in 2007 which had early drought in June around heading time. In the Czech Republic only extremely dry seasons lead to a significant reduction of the spring barley yields. Furthermore, their forty years (1961–2000) of data showed the tendency for more intensive droughts at the majority of the analyzed stations (Trnka et al., 2007). Comparison between high- and low-yielding field-years (6.8 vs. 4.3 t ha^{-1}) suggested that the weather during the jointing-to-anthesis and anthesis-to-physiological maturity intervals (i.e. reproductive period) had greater influence on grain yield of winter wheat than the weather during the entire growing season or vegetative stages (Lollato et al., 2019).

The years of excess precipitation (1998 especially for spring wheat), 2001 and 2003 (oat and barley) also had low yields. Moderate to severe lodging was detected during each of the study years. Correspondingly, the yield drop in Hungary (Márton, 2008), in a very wet year was 43%. However, in our study only a 22% drop for wheat and oat was estimated in a very wet year (1998). A reliable negative correlation between precipitation and the spring wheat yield was also found in Lithuania (Staugaitis et al., 2017).

There was a significant effect of growing season on the yield of winter wheat grown in the long-term trial (2002–2008) in England, producing the highest yield (6.7 t ha^{-1}) in 2004 and the lowest (5.7 t ha^{-1}) in 2007 (Bilsborrow et al., 2013). Maximum temperature during grain fill was the most important meteorological variable influencing wheat yields across the dataset. The highest winter wheat yields (7.2 t ha_{-1}) were achieved in fields in which mean temperature during grain fill was <27 °C and growing season precipitation was <440 mm (Lollato et al., 2019). Growing season precipitation >440 mm under similar cool grain-filling conditions resulted in grain yield of 5.6 to 6.9 t ha_{-1} (Lollato et al., 2019).

Senapati & Semenov (2020) explained that site and regional variations in wheat genetic yield potential and yield gap across Europe could be explained by variations in the local optimal wheat physiology, determined by local environmental conditions. For example, the highest yield potential in north-west and central-west Europe are due to the most favourable climatic conditions (air temperature, precipitation etc.) with minimum heat and drought stresses around flowering time. Despite intensive wheat breeding efforts, current local cultivars were found to be far from their optimum, and a large genetic yield gap (3.5–5.2 t ha^{-1}; about 30–40% of genetic yield potential) still exists in Europe. Heat and drought tolerance around flowering time improved root water uptake and reduced leaf senescence due to water stress were identified as key traits for genetic adaptation to achieve genetic yield potentials.

6.3.2. Impact on quality

Protein. The variation of protein content depended essentially on weather of the year in the trial. In a study with 11 winter wheat varieties over 5 years the share of year in total variation was even higher than in the present study with spring wheat (Koppel & Ingver, 2010). The protein content was higher in the dryer years when the yield was lower (1992, 2002, 2006 and 2007 – early drought). The inverse relationship of grain yield with protein content commonly reported (Lollato & Edwards, 2015; Iqbal et al., 2017) was also confirmed in our study.

Negative correlation of protein content with yield of spring wheat (r = –0.45*) was found similar to other spring cereals. Mean protein content of wheat was over two percent points higher than that of barley and oat. The variation coefficient of spring wheat protein was moderate (11%) similar to oat and barley. The years 2009 and 2015 resulted in low grain protein below critical market requirement. These were cooler years and the number of accumulated sunshine hours during the whole growing period was the lowest in 2009 among the tested 29 years. In analysing future trends a negative impact on protein yields were predicted at high latitude locations associated with some positive yield impacts (Asseng et al., 2018). The protein content was below the critical market protein requirement only in one year and fulfilled the highest, first grade requirements, in six out of the 19 trial years.

All the spring cereals reacted to the weather conditions by rather similar patterns. There were positive correlations between the crops (r = 0.65*–0.67**). Weather conditions had the biggest influence on the grain quality.

In the year that had a lower mean air temperature during the growing season the lowest protein content (11.8%) was measured during a four years trial (Fernandez et al., 2019).

Under baseline climate (weather data of 1961–1990), the pattern of precipitation might be random for spring wheat, with more than 40% rain falling during the growing season (May to August). The climate change scenarios showed an increase in annual precipitation, compared to the baseline period for all sites (He et al., 2012). In the majority of the studied stations, annual precipitation has also increased significantly in Estonia (Jaagus, 2006). Total precipitation is predicted to increase 52% above the baseline climate while the precipitation in July and August would decrease for all scenarios in the biggest spring wheat cultivation region in Canada (He et al., 2012).

In conclusion, this thesis has demonstrated it is possible to conduct cereal management experiments that ensue over decadal periods. This experiment also showed that the prevailing weather conditions in these specific areas of the Estonian landscape has a profound effect on grain yields thus confounding the observations for other variables like soil nitrogen or pre-crop genotypes.

CONCLUSIONS

As was hypothesized, other legume species besides traditional red clover were found to have potential as high quality green manure for spring wheat in organic crop rotations. The yield of spring wheat increased the most after traditional red, but also alsike clover (115 and 119%, respectively). This resulted in significantly higher, almost 3000 kg ha^{-1}, extra yield than in the non-legume control variant. Even the annual species crimson clover and Alexandria clover had significant positive effect on yield, producing extra yields of 1860 and 1550 kg ha^{-1}, respectively. By the results of our study the proper selection of green manure species enabled an increased grain yield by subsequent cereal crop and thereby improved efficiency of organic crop rotation.

The hypothesis that six leguminous pre-crops, including the less commonly used annual Alexandria and crimson clovers, have different impacts on quality of spring wheat, was fully supported. A significant increase of the protein content, different from the increase of yield, was measured only after perennial species like alsike clover, red clover and Washington lupine (2.6, 1.8 and 1.2% points respectively). But only red and alsike clover provided subsequent spring wheat with sufficient N to produce enough protein (11% or higher) to guarantee marketing of spring wheat for food purposes. The fertilization value of biennial white sweet clover and annual crimson and Alexandria clovers was not enough to increase protein content of subsequent spring wheat.

All the legume pre-crops, except crimson clover, increased volume weight of spring wheat. The legume pre-crops increased TKW from 2.4 g after white sweet clover to 4.8 g after alsike clover.

The study partly supported the hypothesis that spring wheat yield and quality characteristics are lower in organic compared to conventional farming system. The reaction of spring wheat to different management systems was the most sensitive among the spring cereals. Conventional spring wheat had a higher grain yield compared to organic, although the size of the yield gap between the two farming systems was variable over the years. In organic conditions, the four years average grain yield of wheat constituted only 64% compared of that of the conventional yield. Concerning the quality characteristics, protein content was the most influenced by the cultivation regime. It was lower in the organic trial for all the cereals. The biggest decrease was found in spring wheat (2.4% points). The other quality characteristics (TKW and volume weight) were less influenced by the management regime. The kernel weight of spring wheat even increased under organic conditions.

The hypothesis that increased yearly fluctuations of weather conditions over a 29 year period negatively impacted on yield and protein characteristics of spring wheat was partly correct. Both stress conditions, drought and excess precipitation, caused decrease of yield of spring wheat. The highest yields formed in the 200–350 mm precipitation range in the period from sowing to maturity. Spring wheat reached the yield maximum in these years up to 7 t ha^{-1}. The main yield limiting factor was the amount of precipitation. In the years of substantially lower than average precipitation (drought) the yields were only close to 3 t ha^{-1} (1992, 1999, 2018) and in case of early drought (2007, 2016).

The protein content of spring wheat was higher in the dryer years when the yield was lower (1992, 2002, 2006, 2018 and early drought 2007, 2016). Protein content was inversely associated with yield (r = –0.45* for spring wheat). Average protein content of wheat was over 2% points higher than that of barley and oat. Exceptionally low protein content (10.6%), for wheat, was measured in 2009. This was a cool year and the number of accumulated sunshine hours was the lowest during the 29 years. The highest average protein content (16.7%) was measured in 2002 when the highest sum of effective temperatures (above 5 °C) was measured. The grain protein was below the critical market protein requirement (11%) only twice and fulfilled the highest, first grade requirement (14%) in 16 out of 29 years.

The period of spring wheat from sowing to heading was 60 days on average. Differences between the years were up to two weeks depending on the weather conditions. The period from heading to maturity was 46 days differing more than three weeks. Spring wheat had the longest growing period from sowing to maturity (106 days) among spring cereals. The maximum difference in the length of growing period was 28 days.

Issues requiring further research

Since spring wheat development and life cycle in conventional and organic systems differs due to the use of synthetic agrochemicals and fertilizers in one system, it is important to continue further studies of yield, quality and stress tolerance under different weather conditions and find solutions to increase them.

As spring wheat has higher nutrient demand compared to other (spring) cereals, to achieve the protein content needed for marketing the crop, it is relevant to determine what other measures can increase the valuable protein content, but also yield and other quality characteristics, in organic cultivation. More research and novel approaches are needed to identify cultivars that are adaptable and competitive in the absence of mineral fertilizers and herbicides which would greatly benefit organic growers.

As different cereals react somewhat differently to weather conditions, cultivation of various crops can minimize risks for farmers. Thus, farmers must consider the changeability of the climate in order to optimize their crop and variety selection and management. Continuation of the studies by breeders form the bulk of data enabling understanding of the natural variability patterns of spring wheat. This data can be used to build crop models specific to the region. This helps to identify what characteristics need to be included in breeding programs for adaptation for climate change.

Application of the research results

Results of this thesis have relevant practical value. They give important information for organic farmers about the selection of different leguminous species as pre-crops for optimizing spring wheat cultivation in crop rotations. Diversified rotations are more capable of buffering climate stresses. With increasing pressure to reduce inputs is shifting from fertilizers to legumes recommended also for a conventional farming to promote sustainable agriculture.

The debate over organic versus conventional farming is heavily polarized in academic circles. Meta-analyses are based on comparison such as this research. The role of such meta-analyses is to understand the role of organic agriculture, or other farming system, to reduce negative environmental impacts and achieving sustainable food production in the future.

Monitoring the weather characteristics during spring wheat growth and development is extremely important. This enables a better understanding of the influences of precipitation, temperature and sunshine duration on spring wheat yield and quality and are also useful for climatic prediction purposes.

REFERENCES

Alexandratos, N. & Bruinsma, J. 2012. World Agriculture towards 2030/2050: The 2012 Revision. ESA Working Paper No. 12-03, Agricultural Development Economics Division, Food and Agriculture Organization of the United Nations (FAO), Rome. http://www.fao.org/fileadmin/templates/esa/Global_persepctives/world_ag_2030_50_2012_rev.pdf. (Accessed 12.11.2019).

Angus, J.F., Kirkegaard, J.A, Hunt, J.R., Ryan, M.H, Ohlander, L., Peoples, M.B. 2015. Break crops and rotations for wheat. Crop & Pasture Science, 66, 523–552.

Araus, J.L. 2002. Physiological Basis of the Processes Determining Barley Yield Under Potential and Stress Conditions: Current Research Trends on Carbon Assimilation. In: Slafer, A., Molina-Cano, J.L., Savin, R., Araus, J.L., Ramagosa, I. (Eds.). Barley Science: Recent Advances from Molecular Biology to Agronomy of Yield and Quality. Food Products Press, USA, 269–306.

Arncken, C.M., Mader, P., Mayerb, J., Weibel, F.P. 2012. Sensory, yield and quality differences between organically and conventionally grown winter wheat. J. Sci. Food Agric., 92, 2819–2825.

Asseng, S., Ewert, F., et al. 2015. Rising Temperatures Reduce Global Wheat Production. Nature Climate Change, 5, 143–147.

Asseng, S., Martre, P., et al. 2018. Climate change impact and adaptation for wheat protein. Glob. Change Biol., 1–19.

Barbieri, P., Pellerin, S., Nesme, T. 2017. Comparing crop rotations between organic and conventional farming. Scientific Reports, 7, 3761.

Beach, E. 1961. Beccari of Bologna The Discoverer of Vegetable Protein. Beccari, I. B. Bologna Commentaries, 1745, Tom. II, Pars I, 122–127. De frumento. [Transl. „On Wheat“]. Journal of the History of Medicine and Allied Sciences, XVI (4),354–373.

Bender, A. & Tamm, S. 2014. Fertilization value of early red clover, Washington lupin and crimson clover as green manure crops. Research for Rural Development 2014. Annual 20th International Scientific Conference Proceedings, 1, 84–88.

Bicego, B., Sapkota, A., Torrion, J.A. 2019. Differential Nitrogen and Water Impacts on Yield and Quality of Wheat Classes. Agron. J., 111, 1–12.

Bilsborrow, P., Cooper, J., Tetard-Jones, C., Srednicka-Tober, D., Baranski, M., Eyre, M., Schmidt, C., Shotton, P., Volakakis, N., Cakmak, I., Ozturk, L., Leifert, C., Wilcockson, S. 2013. The effect of organic and conventional management on the yield and quality of wheat grown in a long-term field trial. Eur. J. Agron., 51, 71–80.

Borrelli, K., Koenig, R., Burke, I., Gallagher, R.S., Pittmann, D., Snyder, A., Fuerst, E.P. 2014. Transition cropping system impacts on organic wheat yield and quality. Renewable Agriculture and Food Systems, 30, 461–472.

Braun, H-J., Kosina P., Payne, T., Bonjean, A.P. 2016. The international wheat trade - historical, current and prospective trends. In: Bonjean, A.P., Angus, W.J., van Ginkel M. (Eds.). The World Wheat Book. A History of Wheat Breeding, 3, Paris, Lavoisier, 1558−1596.

Campiglia, E., Mancinelli, R., De Stefanis, E., Pucciarmati, S., Radicetti, E. 2015. The Long-Term Effects of Conventional and Organic Cropping Systems, Tillage Managements and Weather Conditions on Yield and Grain Quality of Durum Wheat (Triticum durum Desf.) in the Mediterranean Environment of Central Italy. Field Crops Research, 176, 34–44.

Casagrande, M., David, C., Valantin-Morison, M., Makowski, D., Jeuffroy, M.H. 2009. Factors limiting the grain protein content of organic winter wheat in south-eastern France: a mixed-model approach. Agronomy for Sustainable Development, 29, 565–574.

Casebow, R., Hadley, C., Uppal, R., Addisu, M., Loddo, S., Kowalski, A., Griffiths, S., Gooding, M. 2016. Reduced height (Rht) alleles affect wheat grain quality. PLoS One, 11 (5): e0156056.

Cavigelli, M.A., Teasdale, J.R., Conklin, A.E. 2008. Long-term agronomic performance of organic and conventional field crops in the mid-Atlantic region. Agron. J., 100, 785–794.

Cavigelli, M.A., Mirsky, S.B., Teasdale, J.R., Spargo, J.T., Doran, J. 2013. Organic grain cropping systems to enhance ecosystem services. Renew. Agric. Food Syst., 28, 145–159.

Chawade, A., Armonienė, R., Berg, G., Brazauskas, G., Frostgård, G., Geleta, M., Henriksson, T., Himanen, K., Ingver, A., Johansson, E., Nistrup, L., Jørgensen, L., Koppel, M., Koppel, R., Makela, P., Ortiz, R., Podyma, W., Roitsch, T., Ronis, A., Svensson, J.T., Vallenback, P., Weih, M. 2018. A transnational and holistic breeding approach is needed for sustainable wheat production in the Baltic Sea region. Physiologia Plantarum, 164 (4), 442–451.

Coombs, C., Lauzon, J.D., Deen, B., Van Eerd, L.L. 2017. Legume cover crop management on nitrogen dynamics and yield in grain corn systems. Field Crops Res., 201, 75–85.

Cox, W., Cherney, J., Sorrells, M. 2019. Organic Compared with Conventional Wheat Had Competitive Yields during the Early Years of Organic Production in the Northeast USA. Agronomy, 9, 380.

Crespo-Herrera, L. & Ortiz R. 2015. Plant breeding for organic agriculture: something new? Agriculture and Food Security, 4, 25.

Crowder, D.W. & Reganold, J.P. 2015. Financial competitiveness of organic agriculture on a global scale. Proc. Natl. Acad. Sci. U.S.A., 112, 7611–7616.

Demone, J.J., Wan, S., Nourimand, M., Hansen, A.E., Shu, Q.Y., Altosaar, I. 2018. New breeding techniques for greenhouse gas (GHG) mitigation: plants may express nitrous oxide reductase. Climate, 6 (4), 80.

de Ponti, T., Rijk, B., van Ittersum, M. 2012 The crop yield gap between organic and conventional agriculture. Agric. Syst., 108, 1–9.

Dubcovsky, J. & Dvorak, J. 2007. Genome plasticity a key factor in the success of polyploidy wheat under domestication. Science, 316, 1862–1866.

Eensaar, A. 2016. Temporal and Spatial Variability of Air Temperatures in Estonia during 1756–2014. Journal of Climatology, 1−11.

Estonian Centre for Standardisation. 2009. Food products – Determination of the total nitrogen content by combustion. DUMAS ISO/TC 16634-2:2009. [Internet]. [cited 2018 March 15]. Available from: https://www.evs.ee/preview/iso-ts-16634-2-2009-en.pdf.

Estonian Centre for Standardisation. 2010a. Cereals and pulses. Determination of the mass of 1000 grains. EVS-EN ISO 520:2010. [Internet]. [cited 2018 March 15]. Available from: https://www.evs.ee/products/evs-en-iso-520-2010-et.pdf.

Estonian Centre for Standardisation. 2010b. Cereals – Determination of bulk density, called mass per hectolitre. EVS-EN ISO 7971-3:2010. [Internet]. [cited 2018 March 15]. Available from: https://www.evs.ee/eelvaade/evs-en-iso-7971-3-2010-en.pdf.

EUROSTAT. 2018. Statistics explained. Organic farming statistics. https://ec.europa.eu/eurostat/statistics-explained/index.php/Organic_farming_statistics. (Accessed 20.03.2020).

FAOSTAT. 2019. Crop database. Food and Agriculture Organisation of the United Nations. http://www.fao.org/faostat/en/#data. (Accessed 14.12.2019).

Feiziene, D., Feiza, V., Povilaitis, V., Putramentaite, A., Janusauskaite, D., Seibutis, V., Slepetys, J. 2016. Soil sustainability changes in organic crop rotations with diverse crop species and the share of legumes. Acta Agric. Scand., Sect. B, 66 (1), 36–51.

Fernandez, M.R., Zentner, R.P., Schellenberg, M.P., Leeson, J.Y., Aladenola, O., McConkey, B.G., St. Luce, M. 2019. Grain Yield and Quality of Organic Crops Grown under Reduced Tillage and Diversified Sequences. Agron. J., 111, 793–804.

Forsberg, R.A. & Reeves, D.L. 1995. Agronomy of oats. In: Welch, W. (ed.). The Oat Crop. Production and utilization. Chapman and Hall, London, 224–251.

Fowler, D.B. 2003. Crop nitrogen demand and grain protein concentration of spring and winter wheat, Agron. J., 95, 260–265.

Gaines, C.S., Finney, P.L., Andrews, C. 1997. Influence of kernel size and shriveling on soft wheat milling and baking quality. Cereal Chem., 74 (6), 700–704.

Gupta, P.K., Altosaar, I., Garg, D.K. 1991. Molecular Genetics of Wheat. In: Tsuchiya, T. and Gupta, P.K. (Eds.). Chromosome Engineering in Plants: Genetics, Breeding, Evolution. Part A. Amsterdam: Elsevier Science, 263–289.

Haddad, L., Hawkes, C., Webb, P., Thomas, S., Beddington, J., Waage, J., Flynn, D. 2016. A new global research agenda for food. Nature, 540, 30–32.

Harkness, C., Semenov, M., Areal, F., Senapati, N., Trnka, M., Balek, J., Bishop, J. 2020. Adverse weather conditions for UK wheat production under climate change. Agricultural and Forest Meteorology, 282–283, 107862.

He, Y., Wang, H., Qian, B., McConkey, B., DePauw, R. 2012. How Early Can the Seeding Dates of Spring Wheat Be under Current and Future Climate in Saskatchewan, Canada? PLoS ONE, 7 (10), e45153.

Hirel, B., Tétu, T., Lea, P.J., Dubois, F. 2011. Improving nitrogen use efficiency in crops for sustainable agriculture. Sustainability, 3, 1452–1485.

Iqbal, M., Raja, N.I., Yasmeen, F., Hussain, M., Ejaz, M., Shah, M.A. 2017. Impacts of heat stress on wheat: a critical review. Adv. Crop Sci. Tech., 5, 251–259.

Ingver, A. 2007. Difference in yield and quality of spring wheat in organic and conventional trial. In: Ess, M. (Ed.). Suitability of crops and their varieties for organic farming. OÜ Vali Press, Jõgeva, 10–15. (In Estonian)

Ingver, A. 2020. Spring wheat. In: Bender, A. (Ed.). The Estonian Crop Research Institute 100. AS Rebellis, Jõgeva, 74–76. (In Estonian)

Ingver, A. & Koppel, R. 2020. Wheat. In: Bender, A. (Ed.). The Estonian Crop Research Institute 100. AS Rebellis, Jõgeva, 67−69. (In Estonian)

Ingver, A., Koppel, R., Annamaa, K. 2016. The History of Wheat Breeding in Estonia. In: Bonjean, A.P., Angus, W.J., van Ginkel M. (Eds.). The World Wheat Book. A History of Wheat Breeding, 3, Paris, Lavoisier, 157−191.

Jaagus, J. 1998. Climatic fluctuations and trends in Estonia in the 20th century and possible climate change scenarios. In: Kallaste, T., Kuldna, P. (Eds.). Climate change studies in Estonia. Tallinn, Stockholm Environment Institute Tallinn Centre, 7–12.

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

Jaagus, J., Sepp, M., Tamm, T., Järvet, A., Mõisja, K. 2017. Trends and regime shifts in climatic conditions and river runoff in Estonia during 1951–2015. Earth Syst. Dynam., 8, 963–976.

Kamran, A., Kubota, H., Yang, R-C., Randhawa, H.S., Spane, D. 2014. Relative performance of Canadian spring wheat cultivars under organic and conventional field conditions. Euphytica, 196, 13–24.

Kirk, A.P., Fox, S.L., Entz, M.H. 2012. Comparison of organic and conventional selection environments for spring wheat. Plant Breeding, 131, 687–694.

Kolberg, D., Persson, T., Mangerud, K., Riley, H. 2019. Impact of projected climate change on workability, attainable yield, profitability and farm mechanization in Norwegian spring cereals. Soil & Tillage Research, 185, 122–138.

Koppel, R. & Ingver, A. 2010. Stability and predictability of baking quality of winter wheat. Agronomy Research, 8 (3), 637–644.

Kornhuber, K., Coumou ,D., Vogel, E., Lesk, C., Donges, J.F., Lehmann, J., Horton, R.M. 2020. Amplified Rossby waves enhance risk of concurrent heatwaves in major breadbasket regions. Nature Climate Change, 10, 48–53.

Krejčířová, L., Capouchová, I., Petr, J., Bicanová, E., Kvapil, R. 2006. Protein composition and quality of winter wheat from organic and conventional farming. Žembdirbysté, 93, 285–296.

Kutchera, H.R., Warlandb, J.S., Brandtc, S.A. 2010. Temperature and precipitation effects on canola yields in Saskatchewan, Canada. Agricultural and Forest Meteorology, 150 (2), 161–165.

Känkänen, H., Eriksson, C., Räkköläinen, M., Vuorinen, M. 2001. Effect of annually repeated undersowing on cereal grain yields. Agric. Food Sci. Finland, 10, 197–208.

Lammerts van Bueren, E.T., Struik, P.C., Jacobsen, E. 2002. Ecological concepts in organic farming and their consequences for an organic crop ideotype. Neth. J. Agric. Sci., 50, 1–26.

Lammerts van Bueren, E.T., Struik, P.C., Jacobsen, E. 2003. Organic propagation of seed and planting material: an overview of problems and challenges for research. NJAS – Wageningen J. Life Sci., 51, 263–277.

Lammerts van Bueren, E.T., Jones, S.S., Tamm, L., Murphy, K.M., Myers, J.R., Leifert, C., Messmer, M.M. 2011. The need to breed crop varieties suitable for organic farming, using wheat, tomato and broccoli as examples: A review. NJAS - Wageningen J. Life Sci., 58, 3–4.

Lauringson, E., Talgre, L., Makke, A. 2013. Large-leaved lupin (Lupinus polyphyllus Lindl.) and early red clover (Trifolium pratense L.) as green manure crops. Proceeding Latvian Acad. Sci. Sect. B, 67 (3), 242–246.

Liu, B., Asseng, S. et al. 2016. Similar estimates of temperature impacts on global wheat yield by three independent methods. Nat. Clim. Chang., 6, 1130.

Løes, A.K., Henriksen, T.M., Eltun, R., Sjursen, H. 2011. Repeated use of green-manure catch crops in organic cereal production – grain yields and nitrogen supply. Acta. Agric. Scand., Sect. B, 61 (3), 164–175.

Lollato, R.P. & Edwards, J.T. 2015. Maximum attainable wheat yield and resource-use efficiency in the Southern Great Plains. Crop Sci., 55, 2863–2876.

Lollato, R.P., Figueiredo, B.M., Dhillon, J.S., Arnall, D.B., Raun. W.R. 2019. Wheat grain yield and grain-nitrogen relationships as affected by N, P, and K fertilization: A synthesis of long-term experiments. Field Crops Res., 236, 42– 57.

Márton, L. 2008. Effect of Precipitation and Fertilization on the Changes in Soil Organic Carbon (SOC). Cereal Research Communications, 36 (4), 611–622.

Mason, H.E. & Spaner, D. 2006. Competitive ability of wheat in conventional and organic management systems: a review of the literature. Can. J. Plant Sci., 86 (2), 333–343.

Mason, H., Navabi, A., Frick, B., O'Donovan, J., Niziol, D., Spaner, D. 2007. Does growing Canadian western hard red spring wheat under organic management alter its breadmaking quality? Renew. Agr. Food. Syst., 22, 157–167.

Mazzoncini, M., Antichi, D., Silvestri, N., Ciantelli, G., Sgherri, C. 2015. Organically vs 16 conventionally grown winter wheat: Effects on grain yield, technological quality, and on phenolic composition and antioxidant properties of bran and refined flour. Food Chem., 175, 445–451.

Morgunov, A., Sonder, K. et al. 2018. Effect of climate change on spring wheat yields in North America and Eurasia in 1981–2015 and implications for breeding. PLoS ONE, 13 (10), e0204932.

Murphy, K.M., Campbell, K.G., Lyon, S.R., Jones, S.S. 2007. Evidence of varietal adaptation to organic farming systems. Field Crops Res., 102, 172–177.

Mäder, P., Fliebach, A., Dubois, D., Gunst, L., Fried, P., Niggli, U. 2002. Soil Fertility and Biodiversity in Organic Farming. Science, 296, 1694–1697.

Mäder, P., Hahn, D., Dubois, D., Gunst, L., Alfoldi, T., Bergmann, H., Oehme, M., Amado, R., Schneider, H., Graf, U., Velimirov, A., Fließbach, A., Niggli, U. 2007. Wheat quality in organic and conventional farming: results of a 21 year field experiment. Journal of Science of Food and Agriculture, 87, 1826–1835.

Nelson, J.C., Mcclung, A.M., Fjellstrom, R.G., Moldenhauer, K.A.K., Boza, E., Jodari, F., Oard, J.H., Linscombe, S., Scheffler, B.E., Yeater, K.M. 2011. Mapping QTL main and interaction influences on milling quality in elite US rice germplasm. Theor. Appl. Genet., 122, 291–309.

Nuttall, J.G., O'Leary, G.J., Panozzo, J.F., Walker, C.K., Barlow, K.M., Fitzgerald, G.J. 2017. Models of grain quality in wheat - A review. Field Crop. Res., 202 (2), 136–145.

Nykänen, A., Granstedt, A., Jauhiainen, L., Laine, A. 2008. Residual effect of clover-rich 24 leys on soil nitrogen and successive grain crops. Agric. Food Sci., 17, 73–87.

Olesen, J.E., Hansen, E.M., Askegaard, M., Rasmussen, I. 2007. The value of catch crops and organic manures for spring barley in organic arable farming. Field Crops Res., 100, 168–178.

Organic Farming in Estonia. 2018. (Eds.) Vetemaa, A., Mikk, M., Peetsmann, E. Estonian Organic Farming Foundation, 59.

Peltonen-Sainio, P., Jauhiainen, L., Honkavaara, E., Wittke, S., Karjalainen, M., Puttonen. E. 2019. Pre-crop Values From Satellite Images for Various Previous and Subsequent Crop Combinations. Front. Plant Sci., 10, 462.

Peña-Bautista, R.J., Hernandez-Espinosa, N., Jones, J.M., Guzmán, C., Braun, H.J. 2017. CIMMYT Series on Carbohydrates, Wheat, Grains, and Health: Wheat-Based Foods: Their Global and Regional Importance in the Food Supply, Nutrition, and Health. Cereal Foods World, 62 (5), 231–249.

Pimentel, D., Hepperly, P., Hanson, J., Douds, D., Seidel, R. 2005. Environmental, energetic, and economic comparisons of organic and conventional farming systems. Bioscience, 55 (7), 573–582.

Pinto, J.G.C.P., Munaro, L.B., Jaenisch, B.R., Lollato, R.P. 2019. Wheat Variety Response to Seed Cleaning and Treatment after Fusarium Head Blight Infection. Agrosyst. Geosci. Environ., 2, 190034.

Ponisio, L.C., M'Gonigle, L.K., Mace, K.C., Palomino, J., de Valpine, P., Kremen, C. 2015. Diversification practices reduce organic to conventional yield gap. Proc. R. Soc. B, 282, 20141396.

Preissel, S., Reckling, M., Schläfke, N., Zander, P. 2015. Magnitude and farm-economic value of grain legume pre-crop benefits in Europe: a review. Field Crops Research, 175, 64-79.

Rajczak, J. & Schär, C. 2017. Projections of future precipitation extremes over Europe: A multimodel assessment of climate simulations. Journal of Geophysical Research: Atmospheres, 122 (20), 10773–10800.

Reckling, M., Bergkvist, G., Watson, C.A., Stoddard, F.L., Bachinger, J. 2020. Re-designing organic grain legume cropping systems using systems agronomy. European Journal of Agronomy, 112, 125951.

Reganold, J.P. & Wachter, J.M. 2016. Organic agriculture in the twenty-first century. Nat. Plants, 2, 15221.

Reid, T.A., Navabi, A., Cahill, J.C., Salmon, D., Spaner, D. 2009. A genetic analysis of weed competitive ability in spring wheat. Can. J. Plant Sci., 89, 591–599.

Rice, W.A., Olsen, P.E., Bailey, L.D., Biederbeck, V.O., Slinkard, A.E. 1993. The use of annual legume green-manure crops as a substitute for summerfallow in the Peace River region. Can. J. Soil Sci., 73, 243–252.

Ross, S.M., King, J.R., Izaurralde, R.C., O'Donovan, J.T. 2009. The green manure value of seven clover species grown as annual crops on low and high fertility temperate soils. Can. J. Plant Sci., 89, 469–476.

Saue, T., Jauhiainen, L., Kadaja, J., Peltonen-Sainio, P. 2016. Projected lengthening of spring cereals growing season in Estonia and accompanying high impact events of elevated temperatures around heading. In: Röckermann, M., Köppen, S. (Eds.). 1st Baltic Earth Conference Proceedings, 9: 1st Baltic Earth Conference Multiple drivers for Earth system changes in the Baltic Sea region. International Baltic Earth Secretariat Publications, 126−127.

Scherer, L.A., Verburg, P.H., Schulp, C.J.E. 2018. Opportunities for sustainable intensification in European agriculture. Global Environmental Change, 48, 43–55.

Schrama, M., De Haan, J., Kroonen, M., Verstegen, H., Van der Putten, W.H. 2018. Crop yield gap and stability in conventional and organic farming systems. Agric. Ecosyst. Environ., 256, 123–130.

Senapati, N. & Semenov, M.A. 2020. Large genetic yield potential and genetic yield gap estimated for wheat in Europe. Global Food Security, 24, 100340.

Seufert, V., Ramankutty, N., Foley, J.A. 2012. Comparing the yields of organic and conventional agriculture. Nature, 485, 229–232.

Seufert, V. & Ramankutty, N. 2017. Many shades of gray–The context-dependent performance of organic agriculture. Sci. Adv., 3, e160263.

Shewry, P. 2009. Wheat. Journal of Experimental Botany, 60, 1537–1553.

Shiferaw, B., Smale, M., Braun, H.-J., Duveiller, E., Reynolds, M., Muricho, G. 2013. Crops that feed the world 10. Past successes and future challenges to the role played by wheat in global food security. Food Sec., 5, 291–317.

Shimoda, S., Hamasaki, T., Hirota, T., Kannoc H., Nishioa, Z. 2015. Sensitivity of wheat yield to temperature changes with regional sunlight characteristics in eastern Hokkaido. Int. J. Climatol. 35, 4176–4185.

Singh, B.K. & Jenner, C.F. 1984. Factors controlling endosperm cell number and grain dry weight in wheat: Effects of shading on intact plants and of variation in nutritional supply to detached, cultured ears. Aust. J. Plant Physiol. 11, 151–163.

Skuodiene, R. & Nekrošiene, R. 2009. Effect of preceding crops on the winter cereal productivity and diseases incidence. Acta Agric. Slov., 93 (2), 169–179.

Skuodiene, R., Nekrošiene, R., Repšiene, R. 2012. Residual effects of perennial grasses as green manure on soil agrochemical properties and spring barley. Agriculture, 99 (3), 237–246.

Smith, O.M., Cohen, A.L., Rieser, C.J., Davis, A.G., Taylor, J.M., Adesanya, A.W., Jones, M.S., Meier, A.R., Reganold, J.P., Orpet, R.J., Northfield, T.D., Crowder, D.W. 2019. Organic Farming Provides Reliable Environmental Benefits but Increases Variability in Crop Yields: A Global Meta-Analysis. Front. Sustain. Food Syst., 3, 82.

Sommer, R., Glazirina, M. et al. 2013. Impact of climate change on wheat productivity in Central Asia. Agric. Ecosyst. Enviro., 178, 78–99.

Squire, G.R., Quesada, N., Begg, G.S., Iannetta, P.P.M. 2019. Transitions to greater legume inclusion in cropland: Defining opportunities and estimating benefits for the nitrogen economy. Food Energy Secur., 8, e00175.

Stagnari, F., Maggio, A., Galieni, A., Pisante, M. 2017. Multiple benefits of legumes for agriculture sustainability: an overview. Chemical and Biological Technologies in Agriculture, 4 (1), 1–13.

Statistics Estonia 2019. www. stat. ee. http://andmebaas.stat.ee/Index.aspx?lang=en

Staugaitis, G., Aleknavičienė, L., Brazienė, Z., Marcinkevičius, A. 2017. The influence of climate conditions and fertilizer rates calculated by different methods on spring wheat crop. Žemės ūkio mokslai / Agricultural Sciences, 24 (4), 133–142.

Talgre, L., Lauringson, E., Roostalu, H., Astover, A., Eremeev, V., Selge, A. 2009. The effects of pure and undersowing green manures on yields of succeeding spring cereals. Acta Agric Scand Sect B. 59 (1), 70–76.

Talgre, L., Lauringson, E., Makke, A. 2010. Amounts of nitrogen and carbon returned to soil depending on green manure and the effect on winter wheat yield. Agronomy Research, 8, 487−492.

Talgre, L., Lauringson, E., Roostalu, H., Astover, A., Makke, A. 2012. Green manure as a nutrient source for succeeding crops. Plant Soil Environ., 58, 275–281.

Tamm, I., Tamm, Ü., Ingver, A. 2008. Volume weight of spring cereals and factors influencing it. Agronoomia 2008. (Ed) Jõudu, J. Saku, AS Rebellis, 76–79. (In Estonian)

Tamm, I., Tamm, Ü., Ingver, A. 2009. Spring cereals performance in organic and conventional cultivation. Agronomy Research, 7 (1), 522–527.

Tamm, I., Tamm, Ü., Ingver, A., Koppel, R., Tupits, I., Bender, A., Tamm, S., Narits, L., Koppel, M. 2016. Different leguminous pre-crops increased yield of succeeding cereals in two consecutive years. Acta Agriculturae Scandinavica, Section B – Soil & Plant Science, 66 (7) 593–601.

Tammets, T. 2007. Distribution of extreme wet and dry days in Estonia in last 50 years. Proc. Estonian Acad. Sci., 13 (3), 252–259.

Tammets, T. & Jaagus, J. 2013. Climatology of precipitation extremes in Estonia using the method of moving precipitation totals. Theoretical and Applied Climatology, 111, 623–639.

Tarand, A., Jaagus, J., Kallis, A. 2013. Estonian climate in the past and today. Tartu Ülikooli Kirjastus, 387–453. (In Estonian)

Taugtes, N.E., Borrelli, K., Burke, I.C, Fuerst, E.P. 2018. Nitrogen fertility effects of alfalfa, pea green manure, and poultry manure on organic wheat productivity in a semiarid climate. Agroecology And Sustainable Food Systems, 42 (2), 169–188.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S. 2002. Agricultural sustainability and intensive production practices. Nature, 418, 671–677.

Tilman, D., Balzer, C., Hill, J., Befort, B. L. 2011. Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences of the United States of America, 108, 20260–20264.

Tosti, G., Farneselli, M., Benincasa, P., Guiducci, M. 2016. Nitrogen Fertilization Strategies for Organic Wheat Production: Crop Yield and Nitrate Leaching. Agron. J., 108 (2), 770–781.

Trnka, M., Hlavinka, P., Semerádová, D., Dubrovský, M., Žalud, Z., Možný, M. 2007. Agricultural drought and spring barley yields in the Czech Republic. Plant soil environ., 53 (7), 306–316.

Tsvetkov, I., Atanassov, A., Vlahova, M., Carlier, L., Christov, N., Lefort, F., Rusanov, K., Badjakov, I., Dincheva, I., Tchamitchian, M., Rakleova, G., Georgieva, L., Tamm, L., Iantcheva, A., Herforth-Rahmé, J., Paplomatas, E., Atanassov, I. 2018. Plant organic farming research – current status and opportunities for future development, Biotechnology & Biotechnological Equipment, 32 (2), 241–260.

Van Stappen, F., Loriersb, A., Mathotb, M., Planchonb, V., Stilmantb, D., Debodec, F. 2015. Organic versus conventional farming: the case of wheat production in Wallonia (Belgium). Agriculture and Agricultural Science Procedia, 7, 272–279.

Voisin, A.-S., Guéguen, J. et al. 2014. Legumes for feed, food, biomaterials and bioenergy in Europe: a review. Agron. Sustain. Dev., 34, 361–380.

Wiebe, L., Fox, S.L., Entz, M.H. 2017. Organic selection may improve yield efficiency in spring wheat: a preliminary analysis. Can. J. Plant Sci. 97, 298–307.

Wilbois, K.-P. & Schmidt, J.E. 2019. Reframing the Debate Surrounding the Yield Gap between Organic and Conventional Farming. Agronomy, 9 (2), 82.

Willer, H. & Lernoud, J. 2019. Organic Agriculture Worldwide: The World of Organic Agriculture. Statistics and Emerging Trends 2018 Research Institute of Organic Agriculture FiBL, IFOAM–Organics International, Switzerland, 354.

SUMMARY IN ESTONIAN

VILJELUSSÜSTEEMI, EELVILJA JA ILMASTIKUTINGIMUSTE MÕJU SUVINISU SAAGILE JA KVALITEEDILE

Sissejuhatus

Nisu tootmine maailmas on alates 1960ndatest aastatest ühtlaselt kasvanud. Nisu on maailmas üks enam kasvatatav ja turustatav põllukultuur (Braun et al., 2016) ning oma eriliste omaduste tõttu mitmekülgselt kasutatav teravili (Peña-Bautista et al., 2017). Tarbijate nõudlus tervisliku ja ohutu toidu järele kasvab ning inimesed on valmis oma toitumisharjumusi muutma. Mahetoit on kogu maailmas muutunud populaarsemaks ning maheviljelus on üks kiiremini kasvavaid põllumajanduse sektoreid (Crowder & Reganold, 2015; Van Stappen et al., 2015; Reganold & Wachter, 2016).

Eestis on mahemaa pindala viimase kümne aasta jooksul suurenenud enam kui 2.5 korda, ulatudes 2018. aastal 207 tuhande hektarini, mis moodustab ligi 21% kogu põllumajandusmaast (EUROSTAT, 2018). Suviteraviljade mahe- ja tavaviljeluse võrdluskatsetega alustati Eesti Taimekasvatuse Instituudis 2005. aastal.

Ilmastiku muutlikkus on põllumajanduses peamine riskiallikas, avaldades kõige ilmsemat mõju saagikusele ja kvaliteedile. Põllumajanduse konkurentsivõime ja jätkusuutlikkuse tagamiseks tuleks uurida ja tootmisse kaasata ka uusi põllukultuuride liike (Borrelli et al., 2014; Ingver et al., 2016; Demone et al., 2018; Taugtes et al., 2018).

Külvikorrad on viimase 50 aasta jooksul oluliselt lihtsustunud. Maheviljelus on alternatiivne tootmissüsteem, mis soodustab ka põllukultuuride mitmekesistamist. Mahekülvikordades kasutatakse enam õhulämmastikku siduvaid liike, mis jätavad mulda lämmastikku neile järgnevatele kultuuridele (Barbieri et al., 2017). Varem kasvatati liblikõielisi oluliselt rohkem, kuid nende osakaal hakkas vähenema, kui 1940ndatel võeti kasutusele sünteetiline lämmastik. Tänapäeval on huvi lämmastikku siduvate kultuuride vastu taastumas, kuna väetamise kulud on suurenenud ja on tekkinud vajadus säästlikumate põllumajandussüsteemide järele. See on eriti oluline mahepõllumajanduses, kus liblikõielised on külvikorras ühed peamised lämmastiku allikad. Viimastel aastatel on paljud uuringud keskendunud liblikõieliste kasutamisele külvikordades. Nende kasvatamine suurendab järgnevate kultuuride saagikust ja parandab kvaliteedinäitajaid (Angus et al., 2015; Preissel et al., 2015).

Käesoleva uurimistöö üldeesmärk oli viljelusviiside, liblikõieliste eelviljade ja ilmastiku mõju väljaselgitamine suvinisu saagile ja kvaliteedile. Eestis ja ka põhjaregiooni riikides on siiani olnud vähe uurimusi selle kohta, kuidas üheaastased, aga ka kahe- ja mitmeaastased liblikõieliste liigid mõjutavad järgneva teravilja, sealhulgas suvinisu, terasaaki ja kvaliteeti. Antud teema uurimuse vajaduse tõstatasid põllumehed.

Selle uurimistöö uudsus on:

1. Viie suvi- ja taliteravilja, sh suvinisu, terasaagi ja kvaliteedi samaaegne võrdlus kuue liblikõielise liigi järel kasvatades.

2. Suvinisu jt suviteraviljade sortide omaduste hindamine nelja-aastases katsete sarjas samaaegselt nii mahe- kui ka tavaviljeluse tingimustes. Need olid ühed esimesed suviteraviljade viljelussüsteemide vahelised võrdlevad uuringud Eestis (põldkatsed 2005–2008).

3. Pikaajalise, 29 aastase uuringu tulemusena hinnati ilmastikutingimuste mõju ulatust kolme peamise suviteravilja saagikusele jt näitajatele.

Uurimustöö hüpoteesid on:

1. Traditsiooniliselt liblikõielise eelviljana kasvatatava punase ristiku kõrval on teisi väärtuslikke liike, mis sobivad haljasväetiseks mahekülvikorras.

2. Kuus liblikõielise liiki, sealhulgas vähetuntud üheaastased aleksandria ja inkarnaatristik, omavad mahekülvikorras eelviljadena erinevat mõju järgneva suvinisu saagile, proteiinisisaldusele, mahumassile ja 1000 tera massile.

3. Maheviljeluses kasvatamisel jäävad suvinisu saak ja kvaliteet madalamaks kui tavaviljeluses.

4. Ilmastikunäitajate suurenenud aastased kõikumised mõjutavad negatiivselt suvinisu saagikust jt omadusi.

Tulenevalt püstitatud hüpoteesidest *oli uurimustöö eesmärkideks*:

1. Selgitada välja kuue liblikõielise eelvilja mõju suvinisu saagikusele ja kvaliteedinäitajatele võrreldes teiste teraviljadega mahekülvikorras.

2. Valida suvinisu maheviljeluses kasvatamiseks parimad liblikõielised eelkultuurid.

3. Selgitada välja suvinisu sortide terasaagi ja kvaliteedinäitajate erinevused tava- ja maheviljeluses kasvatamisel.

4. Hinnata 29 aasta ilmastikutingimuste (sademed, efektiivsete temperatuuride summa, päikesepaiste kestvus) mõju ulatust tavaviljeluses kasvatatud suvinisu saagikusele, kasvuperioodi pikkusele ja proteiinisisaldusele.

Metoodika

Liblikõieliste eelviljade põldkatse (I ja II).

Doktoritöös kasutatud liblikõieliste eelviljade andmed pärinevad mahekatsest, mis viidi läbi Eesti Taimekasvatuse Instituudis aastatel 2011–2013. Analüüsiti põhiliselt suvinisu katsetulemusi. Põhjalikumaid järeldusi teiste katses olnud teraviljade kohta antud uurimuses ei tehtud. Uuritavad haljasväetiskultuurid olid mitmeaastased liigid, punane ristik (*Trifolium pratense* L.) ja roosa ristik (*Trifolium hybridum* L.) ning hulgilehine lupiin (*Lupinus polyphyllus* Lindl.), kaheaastane valge mesikas (*Melilotus albus* Medik.) ja üheaastased aleksandria ristik (*Trifolium alexandrinum* L.) ning inkarnaatristik (*Trifolium incarnatum* L.). Kontrollvariant oli timut kui lämmastikku mittesiduv liik. Mitmeaastased eelviljad ja kaheaastane valge mesikas külvati 2011. a, üheaastased eelviljad 2012. a. Vegetatsiooniperioodi lõpus määrati eelviljadel nii maapealne kui ka maa-alune biomass ja taimetoiteelementidest N, P, K ja C sisaldus. Kõik eelviljad künti mulda suviteraviljade külvieelsel kevadel 2013. a. Katses olid suvinisu sordid ’Manu’ (Soome) ja ’Uffo’ (Läti). Katse viidi läbi kolmes korduses 5 m^2 katselappidel. Umbrohutõrjeks äestati suviteravilju kaks korda – külvieelselt ja taimede 3–4 lehe kasvufaasis. Laboris määrati mahumass, 1000 tera mass ja proteiinisisaldus. Liblikõieliste külvijärgne areng oli vaatamata suhteliselt kõrgetele õhutemperatuuridele ja sademete puudusele 2011. aastal ühtlane. 2012. a olid tingimused liblikõieliste kasvuks soodsad. 2013. a kasvuperioodil jaotusid vähesed sademed ühtlaselt, tagades sobivate eelviljade järel suhteliselt kõrged suviteraviljade saagid.

Mahe- ja tavaviljeluse võrdluskatsed (IV ja V).

Katses hinnati 13 suvinisu, kaera ja odra sordi omadusi nii mahe- kui ka tavatootmise tingimustes aastatel 2005–2008. Sordid külvati 4 korduses 5 m² lappidele. Mahevariandi eelviljadeks olid 2005. ja 2006. aastal punane ristik ning 2007. ja 2008. aastal tatar. Tavakatsete eelviljadeks olid raps ja kartul. Umbrohutõrjeks äestati mahekatset oraste tärkamise eel ja teraviljade 3–4 lehe kasvufaasis. Tavakatses kasutati keemilist umbrohutõrjet, vajadusel ka kahjuritõrjet. Tavavariandis anti suvinisule külvieelselt liitväetist normiga $N_{90}P_{20}K_{38}$.

Pikaajaline ilmastiku mõju katse (III).

Katses hinnati tavatingimustes ilmastiku mõju suviteraviljade saagile ja kvaliteedile aastatel 1991–2009. Uurimusele lisati täiendavalt ka viimase kümne aasta andmed (2010–2019). Suvinisu ja odra jaoks kasutati väetistaset $N_{90}P_{20}K_{38}$, kaera tarbeks $N_{70}P_{16}K_{29}$. Umbrohtude keemiline tõrje viidi läbi igal aastal, kahjuritõrjet tehti ainult nende arvuka esinemise korral. Kasutati külvisenormi 600 (nisu, kaer) ja 500 (oder) idanevat tera ruutmeetri kohta. Katse rajati kolmes korduses 10 m² suurustele katselappidele. Peamised kogutud andmed olid terasaak, proteiinisisaldus, kasvuaeg päevades külvist loomiseni, loomisest küpsuseni ja kogu kasvuaja pikkus. Analüüsideks valiti kahe suvinisu sordi 'Satu' (Rootsi) ja 'Munk' (Saksamaa) tulemused.

Andmete statistiliseks analüüsiks kasutati tarkvaraprogrammi Agrobase versioone Generation II™ 37.2.4 ja SQL 36.5.1. Tulemuste statistilisel analüüsil kasutati korrelatsioon- (III, IV, V) ja ühe ning mitmefaktorilist dispersioonanalüüsi (I, II, III, IV, V). Piirdiferentside leidmisel võeti olulisusnivooks 0.05. Pikaajaliste näitajate varieeruvuse hindamiseks arvutati variatsioonikoefitsiendid.

Tulemused ja arutelu.

Liblikõieliste eelviljade mõju katse (I, II).

Terasaak. Suvinisu keskmine terasaak oli liblikõieliste eelviljade järel 4120–5530 kg ha^{-1} ja see jäi kontrollvariandis oluliselt madalamaks (2570 kg ha^{-1}) (tabel 4). Teraviljad, sh suvinisu, andsid kõigi liblikõieliste eelviljade järel kontrollvariandiga (timut) võrreldes statistiliselt usutavalt suurema terasaagi. Suvinisu enamsaagid võrreldes kontrolliga jäid vahemikku 1550–2960 kg ha^{-1} (60–119%) ja olid kõige suuremad punase ning roosa ristiku järel (vastavalt 115 ja 119%). Võrreldes suvinisuga jäid kaera enamsaagid väiksemaks (46–58%) ja ei sõltunud oluliselt liblikõielise eelvilja liigist. Erinevalt suviteraviljadest suurenes taliteraviljade saak enam kaheaastase valge mesika ja üheaastaste ristikute järel.

Proteiinisisaldus. Suvinisu terade proteiinisisaldus suurenes kontroll-variandiga võrreldes usutavalt (1.2–2.6%) vaid mitmeaastaste liblikõieliste eelviljade järel (tabel 5). Hea toidukvaliteedi tagamiseks on suvinisu eelvilja suhtes teistest suviteraviljadest nõudlikum. Vaatamata headele eelviljadele jäi 2013. a. suvinisu keskmine proteiinisisaldus toiduvilja kõrgeima kategooria nõuet (14%) silmas pidades madalaks. Liblikõieliste eelviljade variantide keskmine proteiinisisaldus oli nisul 10.6%, jäädes vahemikku 9.3–12.2%. Kõige suurem oli proteiinisisaldus roosa ristiku variandis (12.2%), järgnesid punase ristiku (11.4%) ja lupiini variant (10.8%). Kõige madalamaks jäi proteiinisisaldus aleksandria ristiku järel (9.3%). Suvinisu proteiinisisaldus sõltus katses liblikõielise eelvilja liigist oluliselt rohkem kui teistel suvi- ja taliteraviljadel, sh talinisu proteiinisisalduses ei olnud erinevate liblikõieliste järel kasvades usutavaid erinevusi.

Mahumass. Suvinisu variantide keskmine mahumass liblikõieliste eelviljade järel oli 78.4 kg hl^{-1}, jäädes vahemikku 76.9–79.5 kg hl^{-1} (tabel 6). Suvinisu kokkuostul peaks mahumass olema vähemalt 75.0 kg hl^{-1}. Kõik katsevariandid, sh kontrollvariant, ületasid seda nõuet. Suvinisu mahumass tõusis statistiliselt usutavalt kõigi liblikõieliste eelviljade, v.a inkarnaatristik, järel. Suurimad mahumassid saadi lupiini (79.5 kg hl^{-1}) ja aleksandria ristiku variandis (79.2 kg hl^{-1}), kus need olid 4% suuremad kui kontrollvariandis.

1000 tera mass. Antud katseaasta ilmastikutingimused olid soodsad suure ja hästi täitunud tera moodustumiseks. Suvinisu 1000 tera massid jäid vahemikku 36.3–38.7 g (tabel 7). Liblikõielised eelviljad suurendasid usutavalt suvinisu ja odra 1000 tera massi, kaeral jäid erinevused kontrollvariandiga võrreldes katsevea piiridesse. Suurim suvinisu 1000 tera mass saadi roosa ristiku järel (38.7 g), järgnes punase ristiku (37.7 g) ja lupiini variant (37.3 g), ületades kontrollvarianti vastavalt 14%, 11% ja 10%.

Viljelusviisi mõju (IV, V).

Terasaak. Suviteraviljad andsid mahetingimustes katseaastate keskmisena suhteliselt head saaki (joonis 1). Suvinisu keskmine saak mahekatses (2990 kg ha^{-1}) jäi väiksemaks tavakatse tulemusest (4680 kg ha^{-1}). Kõigi teraviljade saagitasemed olid mahekatses siiski väiksemad kui tavakatses. Nisu ja odra erinevused olid viljelusviiside vahel üsna suured, mahesaak moodustas tavaviljeluse saagitasemest vastavalt 64 ja 66%. Kaera terasaagid erinesid mahe- ja tavatingimustes vähe, vaid 10%.

Suviteraviljade, sh suvinisu saagitasemed sõltusid mahetingimustes üksikutel katseaastatel suurel määral eelviljast ja ilmastikutingimustest. Esimesel katseaastal olid kõigi teraviljade saagid hea eelvilja (punane ristik) järel üle 4500 kg ha^{-1}. Aastatel 2007 ja 2008 oli mahekatse eelviljaks teravili (tatar) ja seetõttu olid saagitasemed neil aastatel tunduvalt madalamad. Kõige väiksemad olid terasaagid mahekatses 2007. aastal, mil saagikust vähendas tugev põud ja kevadel tekkinud mullakoorik, mis takistas tärkamist. Suvinisu terasaagid jäid sel aastal väga madalaks, olles vaid 1220 kg ha^{-1}. Katsetsükli viimasel, 2008. aastal, olid ilmastikutingimused soodsamad kui 2007. aastal ja seetõttu olid ka saagitasemed kõrgemad. Suvinisu terasaak oli 2008. a mahekatses 2900 kg ha^{-1}.

Suviteraviljade sordid moodustasid terasaakide alusel viljelusviiside võrdluses (2005–2007) selged grupid (joonis 2). Mitmed suvinisu sordid andsid tavakatses suurema terasaagi kui kaera sordid, kuid mahekatses olid kõik kaerast väiksema saagiga.

Tera kvaliteet. Tera kvaliteedinäitajate tasemed olid mahe- ja tavatingimustes kasvatatud viljal mõnevõrra erinevad. Suvinisu katseaastate keskmised 1000 tera massid olid mahetingimustes (35.8 g) usutavalt suuremad kui tavatootmises (34.2 g), aga mahumasside vahel (vastavalt 76.7 ja 78.3 kg hl^{-1}) usutavaid erinevusi ei olnud (tabel 8). Terade proteiinisisaldused jäid kõigil suviteraviljadel mahetingimustes madalamaks kui tavaviljeluses. Suvinisu proteiinisisaldus oli mahekatses tunduvalt väiksem kui tavakatses (erinevus 2.4%). Seevastu kaeral ja odral olid erinevused proteiinisisalduses kahe viljelusviisi vahel suhteliselt väikesed (vastavalt 0.9 ja 0.7%).

Ilmastiku mõju (III).

Sademete kogus külvist küpsuseni varieerus vaadeldud 19 aasta (1991–2009) jooksul vahemikus 71 kuni 530 mm (joonis 3). Järgnenud 10 aasta jooksul (2010–2019) oli kõige vähem sademeid (60 mm) 2018. aastal. Efektiivsete temperatuuride summa jäi vaadeldud 29 aasta jooksul vahemikku 966–1173 °C. Päikesepaiste tundide arv varieerus samuti suures ulatuses (885–1349 tundi).

Terasaak. Suvinisu terasaagid olid katseperioodil (1991–2009) 3.4–7.0 t ha^{-1}, erinedes üle kahe korra. Võrreldes nisuga olid kaera ja odra ilmastikust tingitud saagierinevused veelgi suuremad.

Dispersioonanalüüsi tulemused näitasid, et suviteraviljade saagi varieerumine sõltus peamiselt aastast ($F=109.63$; $p<0.001$), kuid oluline oli ka teravilja liigi ja aasta koostoime ($F=28.71$; $p<0.001$). Teravilja liigil (suvinisu, oder, kaer) oli saagi varieerumisele väiksem mõju. Eeltoodud tulemused näitavad, et kõigi suviteraviljade saagitasemed sõltusid peamiselt katseaastate ilmastikutingimustest. Suviteraviljad reageerisid muutuvatele ilmastikutingimustele erinevalt, kuid nende keskmised saagitasemed olid suhteliselt sarnased. Katseaastate keskmisena olid nisu, odra ja kaera terasaagid vastavalt 4.7, 5.5 ja 5.0 t ha $^{-1}$ (tabel 9). Suvinisu oli katses kõrge saagikusega aastatel 1993, 1997 ja 2003 ning järgnenud kümneaastasel perioodil aastatel 2012, 2014, 2017 ja 2019. Suurem saak saadi enamasti aastatel, kus sademete kogused ei olnud oluliselt üle või alla keskmise ja efektiivsete temperatuuride summa ei ületanud oluliselt keskmist taset. Ebasoodsate ilmastikutingimuste (põud, liigniiskus) mõju suvinisu saagikuse ja kvaliteedi kujunemisele sõltus taimede arengufaasist ja ilmastikuolude kestvusest.

Suvinisu saagid olid madalad põua aastatel (1992, 1999) ja varajase põua korral (2007). Suvinisu saakide varieerumine oli parema seisu- ja põuakindluse tõttu väiksem (CV = 22%) kui kaeral (CV = 29%).

Proteiin. Suvinisu proteiinisisaldused jäid katseperioodil vahemikku 10.6–16.7%, jäädes vaid ühel aastal madalamaks toidunisule esitatud miinimumnõudest. Dispersioonalalüüsi tulemustest selgus, et suviteraviljade proteiinisisalduse varieeruvus sõltus peamiselt aastast ($F = 60,89$; $p<0,001$) ja teravilja liigist ($F = 498.38$; $p<0.001$), aga ka nende mõlema koosmõjust ($F = 9.27$; $p<0.001$). Suviteraviljade proteiinisisaldused reageerisid ilmastikuoludele sarnaselt. Teraviljade proteiinisisalduste vahel olid positiivsed korrelatsioonid ($r = 0.65$ –0.67; $p<0.05$). Suviteraviljade proteiinisisalduse variatsioonikoefitsiendid olid sarnased (CV = 10–12%). Õhutemperatuuril on positiivne mõju N talletamisel teradesse. Suvinisu proteiinisisaldus oli kõrgem kuivematel ja soojematel aastatel, kui saagitase oli madalam (1992, 1999, 2002 ja 2006). Erakordselt madalad proteiinisisaldused määrati suvinisul 2009. ja 2015. aastal. Need olid jahedad aastad ning 2009. a oli kogu kasvuperioodi jooksul kogunenud päikesepaiste tundide arv uuritud 29 aasta madalaim. Suvinisu proteiin jäi toidunisule esitatud miinimumnõudest (11%) madalamaks ainult kahel aastal ja vastas kõige kõrgemale kvaliteedinõudele (14%) 16 aastal uuritud 29st. Nisul leiti saagi ja proteiinisisalduse vahel negatiivne korrelatsioon ($r = -0.45$; $p<0.05$). Sarnane seos oli ka teistel teraviljadel. Nisu keskmine proteiinisisaldus oli enam kui 2% võrra kõrgem kui odral ja kaeral.

Kasvuaeg. Suvinisu kasvuperiood külvist loomiseni oli keskmiselt 60 päeva ning erinevused aastate vahel olid sõltuvalt ilmastikuoludest 2 nädalat. Ajavahemik loomisest küpsuseni oli lühem, keskmisena 46 päeva, erinevus aastate vahel oli rohkem kui 3 nädalat. Suvinisu oli teiste suviteraviljade seas pikima kasvuperioodiga ja keskmiselt kulus külvist küpsuseni 106 päeva. Maksimaalne erinevus kasvuperioodi pikkuses oli 28 päeva.

Töös püstitatud eesmärkidest lähtuvalt saab teha järgmised järeldused:

Uurimustulemused toetasid hüpoteesi, et lisaks traditsioonilisele punasele ristikule on ka teisi liblikõielisi liike, mis sobivad hästi haljasväetisena suvinisu eelviljaks mahekülvikorras. Kõigi teraviljade saagikus suurenes peale punase ristiku ka teiste katsetatud liblikõieliste liikide: roosa ristiku, hulgilehise lupiini, valge mesika ja aleksandria ning inkarnaatristiku järel.

Suvinisu terasaak suurenes enim punase ja roosa ristiku järel. Ka hüpotees, et kuue liblikõielise eelkultuuri mõju suvinisu kvaliteedile on erinev, leidis kinnitust. Erinevalt saagikuse suurenemisest tõusis suvinisu proteiinisisaldus ainult mitmeaastaste liikide, roosa ja punase ristiku ning hulgilehise lupiini, järel. Suvinisu proteiinisisaldus suurenes ainult punase ja roosa ristiku järel tasemele (>11%), mis võimaldaks seda toidunisuna turustada.

Mahe- ja tavaviljeluse võrdlev uuring toetas vaid osaliselt püstitatud hüpoteesi, et suvinisu saak ja kvaliteet on mahetingimustes madalamad. Suvinisu reaktsioon erinevatele viljelusviisidele (mahe või tava) oli suviteraviljade seas kõige tundlikum. Tavaviljeluse katse suvinisu saak oli oluliselt kõrgem kui mahekatse saak, kuigi see erinevus varieerus aastati. Mahetingimustes oli 4-aastase uurimuse keskmine suvinisu terasaak tavaviljeluse saagikusega võrreldes ainult 64%. Kvaliteedinäitajate osas mõjutas viljelusviis kõige enam proteiinisisaldust. Suvinisul, nagu ka kõigil teistel suviteraviljadel, oli proteiin mahekatsetes madalam. Erinevused kontrollvariandiga võrreldes olid suvinisul suuremad kui teistel teraviljadel. Teisi kvaliteedinäitajaid, 1000 tera massi ja mahumassi, mõjutas viljelusviis vähem. Suvinisu tera mass mahetingimustes isegi suurenes võrreldes tavakatse tulemustega.

Hüpotees, et ilmastikuolude suurenenud aastased kõikumised mõjutavad negatiivselt suvinisu saagikust ja kvaliteedinäitajaid, leidis kinnitust vaid osaliselt. Mõlemad stressitingimused – põud ja liigsed sademed, vähendasid suvinisu saagikust. Suuremad terasaagid saadi kui sademete hulk külvist küpsuseni oli lähedane pikaajalisele keskmisele ja efektiivsete temperatuuride summa ei olnud oluliselt keskmisest suurem. Suvinisu saavutas nendel aastatel maksimaalse saagikuse, ületades 7 t ha^{-1}. Peamine saagikust piirav tegur oli ebapiisav sademete hulk. Keskmisest oluliselt väiksemate sademetega (põua) aastatel oli saagikus vaid 3 t ha^{-1} lähedal.

Samas oli suvinisu proteiinisisaldus kõrgem just põuastel aastatel, kui saak oli madalam (1992, 1999, 2002 ja 2006). Nisu keskmine proteiinisisaldus oli üle 2% kõrgem kui odral ja kaeral. Erakordselt madal (10.6%) oli suvinisu proteiinisisaldus jahedal ja päikesevaesel 2009. aastal. Kõrgeim keskmine proteiinisisaldus (16.7%) määrati suurima efektiivsete temperatuuride summaga 2002. aastal. Suvinisu proteiin jäi katseaastatel toidunisule esitatud miinimumnõudest madalamaks ainult ühel aastal ja vastas kõige kõrgemale kvaliteedinõudele (14%) kuuel aastal 19-st.

Suvinisu oli teiste suviteraviljade seas pikima kasvuajaga, mis katseaastati erines perioodil külvist loomiseni kuni kaks ja külvist küpsuseni kuni kolm nädalat.

Teemad, mis vajavad edasist uurimist.

Saagikuse ja proteiinisisalduse tõstmiseks on vaja jätkata uuringuid täiendava teabe saamiseks suvinisu kui suure toitainete vajadusega teravilja kasvatamisel maheviljeluses ja leida lahendusi sordiaretuse ning uudsete agrotehniliste võtete abil, sh külvikorra mitmekesistamine uute liblikõieliste kultuuridega.

Suviteraviljad, sealhulgas suvinisu, reageerivad ilmastikuoludele mõnevõrra erinevalt ja seega aitab nende põllukultuuride iseärasuste tundmine ja kasvatamine vähendada tootjate riske. Teraviljaliikide käitumise uuringud jätkuvate kliima muutuste tingimustes võimaldavad põllumehel optimeerida erinevate kultuuride ja nende sortide valikut ning kasvatamist. Sordiaretajate uuringute põhjal kogutavat andmestikku on vaja pidevalt täiendada ja see annab võimaluse analüüsida ja mõista suvinisu näitajate varieeruvuse põhjusi ja ulatust ning rakendada seda informatsiooni mudelite ja prognooside väljatöötamisel. Kogutud info aitab välja selgitada, milliseid omadusi tuleb aretusprogrammidesse lülitada uute suvinisu sortide adaptsioonivõime tõstmiseks.

Uurimistöö tulemuste kasutamine:

Antud uurimistöö tulemused omavad olulist praktilist väärtust. Erinevate liblikõieliste liikide uurimine annab mahetootjatele täiendavat teavet nende sobivuse kohta suvinisule eelviljadeks mahekülvikorras. Külvikordade mitmekesistamine aitab paremini toime tulla muutuva kliima tingimustes. Surve sisendite vähendamiseks ja säästva põllumajanduse arendamiseks suurendab õhulämmastikku siduvate liblikõieliste kasvatamise olulisust ka tavaviljeluse külvikorras.

Mahe- ja tavaviljeluse võrdlus on akadeemilistes ringkondades tugevalt polariseeritud teema. Selliseid uuringuid nagu antud viljelusviiside võrdlus, kasutatakse meta-analüüside tegemiseks, et mõista, milline on mahepõllumajanduse või mingi teise põllundussüsteemi roll tulevikus, et vähendada negatiivseid keskkonnamõjusid ja saavutada jätkusuutlik toidutootmine tulevikus.

Suvinisu kasvu- ja arenguaegsete ilmastikunäitajate jälgimine ja fikseerimine on äärmiselt oluline. See võimaldab paremini mõista sademete, temperatuuri ja päikesepaiste kestuse mõju suvinisu saagikusele ja kvaliteedile ning kogutud infot on võimalik kasutada kliimaprognooside koostamisel.

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And finally I would like to acknowledge the loving support and encouragement of all my family.

Life is a gift and a mystery. I dedicate this thesis to you.

I

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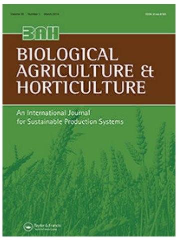

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Leguminous pre-crops improved quality of organic winter and spring cereals

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ABSTRACT

The aim of this research was to assess the effect of leguminous pre-crop species on quality characteristics of subsequent spring and winter cereals. The experiment was carried out in an organic crop rotation in north-eastern Europe. The influence of biomass dry matter yield, carbon and nitrogen content of perennial red clover (*Trifolium pratense* L.), alsike clover (*Trifolium hybridum* L.), Washington lupin (*Lupinus polyphyllus* Lindl.), biennial white sweet clover (*Melilotus albus* L.), annual crimson clover (*Trifolium incarnatum* L.) and Alexandria clover (*Trifolium alexandrinum* L.) on protein concentration, bulk density and thousand grain weight of subsequent cereals were assessed. Barley, oats, winter rye, spring and winter wheat were grown in the first post-legume year and barley and oats in the second post-legume year. In the first year after perennial and biennial pre-crops, the protein concentration of the cereals, except for rye, increased by 0.8–2.6 percentage points compared with the control. The largest increases in protein concentration of the cereals were after red and alsike clovers. The legumes increased the bulk density of all of the cereals, while thousand kernel weights were increased only for barley, spring and winter wheat. All the legume species had a positive second-year after-effect on the protein concentration of barley and oats, with the largest effect after red and alsike clover at 1.0–1.3 percentage points. The results showed that all of the leguminous pre-crops were suitable for increasing the quality of cereals. The effect was greater after perennial and biennial species compared with the annual species.

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Cereal quality; green manure; leguminous pre-crop; organic cultivation

Introduction

Green manuring has been an agricultural practice among European farmers for more than two thousand years (Pieters 1927). In recent years, the interest among organic as well as conventional stockless farmers in using alternative nutrient sources such as green manures has increased in popularity. Almost any crop can be used for green manuring, but legumes are often preferred because of their ability to fix atmospheric nitrogen (N). Biological N fixation is one of the primary sources of N in organic farming (Berry et al. 2002). Legumes provide significant amounts of N for the subsequent crop and are thus a valuable source of N in organic cultivation and they can also reduce the use of chemical fertilisers in conventional cultivation. Compared to N in mineral fertilisers, which is susceptible to nitrate leaching and denitrification, plant-derived N is relatively more stable (Drinkwater et al. 1998). However,

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some leaching may still occur depending on the soil type and the green manure crop used (Askegaard et al. 2005). This is an important consideration in cereal cultivation, which faces risks of increasing occurrence of adverse and extreme agro-climatic events (Trnka et al. 2014), such as intense rainfall causing N-leaching (Tosti et al. 2016).

The climatic conditions in north-eastern Europe are favourable for the production of leguminous species and also for cereal cultivation. One of the most important positive impacts of climate change is the prolongation of the growing season, which creates the need to test the potential of widely cultivated and new leguminous crop species for organic crop rotations in the region. There is a wide range of leguminous species that can be drawn upon, each with their particular traits.

The initiative for the experiments reported here came from organic farmers, aiming to diversify the selection of species and seasonal types of legumes suitable for green manure. A trial was established, which included six pure-sown leguminous pre-crop species and five spring and winter cereals.

Red clover (*Trifolium pratense* L.) is one of the most commonly grown leguminous green manures in northern Europe and countries with similar climate (Nykänen et al. 2008; Talgre et al. 2012). Some other clovers are also cultivated because they may offer particular advantages in specific circumstances. Alsike clover (*Trifolium hybridum* L.) is well adapted to wet acid soils (Döring and Boufartigue 2013) and white sweet clover (*Melilotus albus* L.) to wide range of soils (Döring 2013). Biennial white sweet clover is suitable as a medium-term N fixer. Washington lupin (*Lupinus polyphyllus* Lindl.) is relatively more tolerant to several abiotic stresses compared to other legumes (Kurlovich et al. 2008). The fertilisation value of Washington lupin fresh green mass was considered to be equal to the same weight of cattle manure (Bender and Tamm 2014). Short-term fertility building crops, such as crimson and Alexandria clover, are new species for cultivation in the Nordic latitudes and their use in the region has so far been insufficiently investigated (Coombs et al. 2017). In the northern regions crimson clover or Italian clover (*Trifolium incarnatum* L.) is cultivated as an annual crop (Clark 2007), suitable as a short-term N fixer that is commonly used as a break in intensive and organic systems. Alexandria clover (*Trifolium alexandrinum* L.), also called Egyptian or berseem clover, requires warmer temperatures although it may give reasonable yields in colder environments, where it is sown in spring (Piano and Pecetti 2010).

There is relatively modest amount of published information about cereal quality traits under organic management conditions, especially after different leguminous pre-crops.

Grain quality is a complex of quantitative characteristics, depending on the physical parameters of the grain, like bulk density and thousand kernel weight (TKW), and their chemical composition (protein concentration).

Organic methods of farming can have negative effects on the grain quality, especially in the case of protein concentration. The proportion of protein in grain is reduced because of the limited availability of soluble N (Krejčířová et al. 2006; Bilsborrow et al. 2013). According to a number of studies, protein concentration remained considerably lower in organic conditions compared with conventional farming (Talgre et al. 2009; Tamm et al. 2009; Jones et al. 2010; Bilsborrow et al. 2013).

Bulk density is an important criterion of cereal quality (Gaines et al. 1997). High bulk density values increase market grade and price for all the investigated cereal species (wheat, rye, oats, barley). Bulk density affects the productivity and efficiency of flour milling and therefore provides a good indication of grain quality of cereals for bread making (Halverson and Zeleny 1988).

Kernel weight, usually expressed as grams per 1000 kernels (TKW), is a function of kernel size and density. Large and dense kernels normally have a higher ratio of endosperm (Andersson et al. 1999; Halverson and Zeleny 1988). TKW is a valuable physical indicator of grain for the processing industry (malting, milling etc.) (Nuttall et al. 2017). Bulk density and TKW have been found to be less dependent on the cultivation system and pre-crop and may be even higher in organic conditions (Talgre et al. 2009; Tamm et al. 2009; Bilsborrow et al. 2013).

For organic production to be competitive, the produce has to meet certain quality criteria, which do not vary between conventional and organic products. However, organic products that meet the same criteria receive a much higher premium. Currently, organic food is becoming more popular all over the world and consumers often value quality over cost (Crowder and Reganold 2015).

The aim of this research was to assess the effect of leguminous pre-crop species on quality characteristics of the subsequent spring and winter cereals. It was hypothesised that: (1) the preceding legume species, including the less commonly used annual Alexandria and crimson clovers, increase protein concentration, bulk density and TKW of the subsequent cereals in the organic crop rotation and (2) the increase in protein concentration, bulk density and TKW of the subsequent cereals depend on the species of the leguminous pre-crop. In relation to the second hypothesis, the aim was to identify, which of the six green manure pre-crops had the greatest effect on grain quality (protein concentration, bulk density and TKW) and was most suitable for the five subsequent cereals.

Materials and methods

The experiment was carried out during the period of 2011–2014 in an organic crop rotation at the Estonian Crop Research Institute at Jõgeva, Estonia, located in north-eastern Europe (58°45′N, 26°24′E) on clay loam (40–50% of clay) classified as Calcaric Cambic Phaeozem (Loamic) soil ([IUSS] Working Group WRB 2015). The trial field has been certified for organic agriculture since 2009. Cereals and legumes have been grown in crop rotation. A crop of oats was cultivated one year before the legume trial was started. The mean characteristics of the soil horizon were as follows: pH_{KCl} 6.7, P 65, K 101, Ca 3834 mg kg^{-1}, C_{org} 3.5% and total N 0.27%. Soil pH_{KCl} was determined by the ISO 10390 (International Standard 2005); P, K and Ca by Mehlich III (Mehlich 1984); C_{org} by the Tjurin method (Tjurin 1937) and N by ISO 11261 (International Standard 1995).

Six legume species followed by cereals in crop rotation were sown as sole crops (according to the common practice of farmers): early diploid red clover (*Trifolium pratense* L., perennial), cv. Jõgeva 433 (400 seeds m^{-2}), alsike clover (*T. hybridum* L., perennial) cv. Jõgeva 2 (700 seeds m^{-2}), Washington lupin (*Lupinus polyphyllus* Lindl., perennial), cv. Lupi (95 seeds m^{-2}), white sweet clover (*Melilotus albus* Medik., biennial), cv. Kuusiku 1 (950 seeds m^{-2}), crimson clover (*T. incarnatum* L., annual), cv. Contea (600 seeds m^{-2}) and Alexandria clover (*T. alexandrinum* L., annual), cv. Alex (600 seeds m^{-2}). Timothy (*Phleum pratense* L.), cv. Jõgeva 54 (1000 seeds m^{-2}), as a grass species with no N-fixing ability, was used as a control. All crops were drilled in rows. Five cereals were used to test the first-year after-effect (Year 1): winter rye (cv. Sangaste and Elvi; 500 seeds m^{-2}), winter wheat (cv. Ada and Skagen; 450 seeds m^{-2}), spring wheat (cv. Manu and Uffo; 600 seeds m^{-2}), barley (cv. Grace and Maali; 500 seeds m^{-2}) and oats (cv. Ivory and Kalle; 500 seeds m^{-2}). One variety of barley (cv. Maali) and one of oats (cv. Kalle) were used to test the second-year after-effect (Year 2). Each cereal plot in Year 1 was divided into two plots in Year 2 (barley and oats). The trial was arranged as a split-plot design with six legume pre-crops and a non-legume control as main plots (130 m^{-2}) followed by five cereals (two varieties per crop) on 5 m^{-2} subplots in three replicates. The experiment was divided into three consecutive phases – establishment of the legume stands in 2011 (perennials, biennial) and 2012 (annuals) and the first post-legume year in 2013 (Year 1) followed by the second post-legume year in 2014 (Year 2) (Figure 1 and Table 1).

No pest and disease control interventions were carried out and no additional fertilisers were applied; the plant nutrition sources were based on accumulated nutrients from the preceding leguminous crops and the natural soil nutrient pools. A detailed description of the yield of cereals and biomass of leguminous crops can be found in Tamm et al. (2016).

Red, alsike and white sweet clover plants were chopped and ploughed into the soil at the end of flowering at the beginning of August, before the sowing of winter cereals. Washington lupin started flowering in mid-May already and to avoid seed ripening, the first cut was made in June. The growth of Washington lupin plants was hampered by an infection of anthracnose (*Colletotrichum lupini*), influencing the results and its potential fertilisation value was not fully realized. Washington lupin regrowth was ploughed in at the same time as the other legumes. In the area for sowing of spring cereals, red, alsike and white sweet clover were cut, chopped and left to the trial area in the beginning

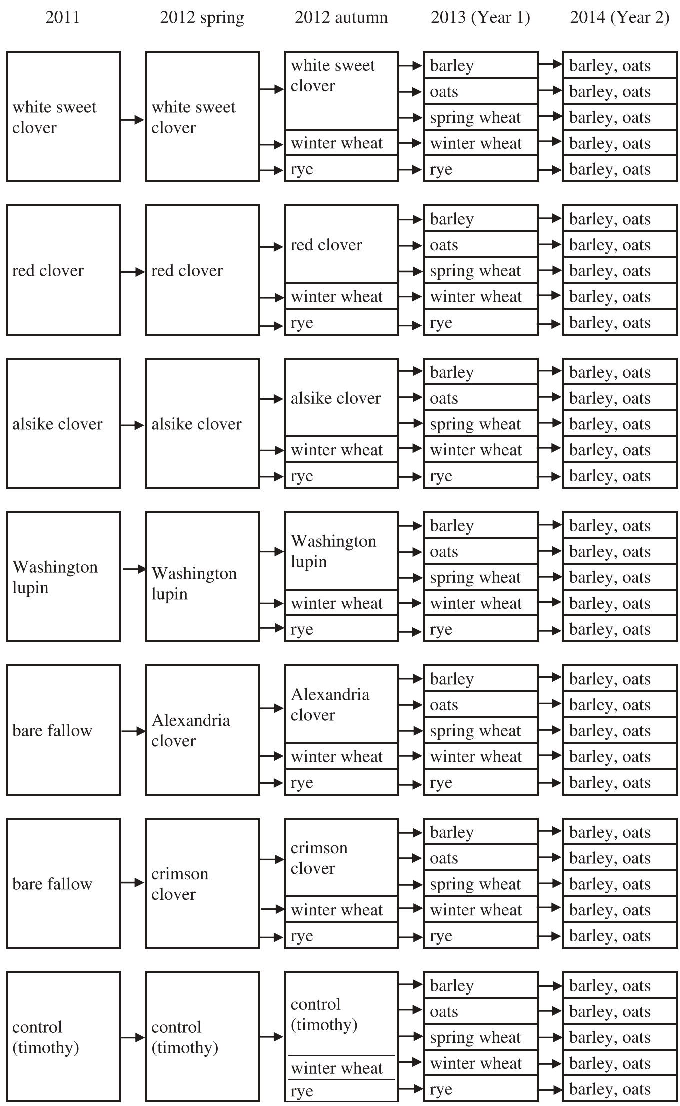

Figure 1. Crop sequence in the trial during 2011–2014.

of July. The same was done with Washington lupin in the end of June. The regrowth of Washington lupin and the primary growth of annual clovers were not cut in autumn and were ploughed in before sowing of the cereals in spring. The timothy grass in the control was sown and ploughed in at the same times as the perennial legumes.

In July (27 July) and October (3 October) 2012, before the incorporation of the green manures, a 6 m^2 area from each plot was cut to measure fresh above-ground biomass. One sample of approximately 1 kg per replicate plot was taken to measure dry matter yield. After weighing, the samples were dried at 105°C

Table 1. Sowing and incorporation dates of crops in the trial period of 2011–2014.

2011	2012 spring	2012 autumn	2013 (Year 1)	2014 (Year 2)
Sowing. 12 July 2011	7 May 2012	6 September 2012	9 May 2013	25 April 2014
Perennial and biennial legumes*: red clover alsike clover Washington lupin white sweet clover	**Annual legumes:** Alexandria clover crimson clover	**Winter cereals:** winter wheat rye	**Spring cereals:** spring wheat barley oats	**Spring cereals:** barley oats
Incorporation of legumes		1 August 2012	15 April 2013	

Note * – in the control, timothy was sown and incorporated at the same time.

to a constant weight and the dry matter yield (DMY) was calculated. To determine the below-ground biomass, rectangular soil blocks were taken from an area of 15 × 30 cm, in layers of 5 cm deep down to 25 cm (0–5 cm, 5–10 cm, 10–15 cm, 15–20 cm, 20–25 cm) by digging. One composite sample was taken in each replicate plot. The roots were washed on a sieve with a mesh size of 2 × 2 mm, dried as described above, and weighed (Vipper 1989). The same or similar methods have been used also by other researchers (Jensen et al. 2004; Talgre et al. 2010, 2012; Bender and Tamm 2014).

The cereal plots were harvested with a plot combine harvester (Hege 140). Plot yields were dried and cleaned. Cereal samples were taken from each plot and protein concentration was measured using near-infrared (NIR) transmittance technology. N and C concentrations of the biomass (above-ground and roots) of legumes were determined by the ISO/TC 16634–2:2009 method (Estonian Centre for Standardisation 2009). TKW of cereals was determined by EVS-EN ISO 520:2010 (Estonian Centre for Standardisation 2010a), bulk density by EVS-EN ISO 7971–3:2010 (Estonian Centre for Standardisation 2010b).

Statistical analyses were carried out by Agrobase Generation II SQL. One-way analysis of variance (ANOVA) was used to test the differences of DMY, C and N of leguminous pre-crops and multi-factorial ANOVA to test the first and second-year after-effect of leguminous pre-crops on cereal quality characteristics. The general linear mixed model of ANOVA was used for calculations of quality characteristics of cereals. Data for the different sampling times and years were analysed separately for quality characteristics of the green manures and the cereals. A Student t-test was used to determine significant effect of leguminous pre-crop life cycle type (perennial, biennial, annual) on DMY, C and N. Least significant differences were calculated for pre-crops DMY, C and N and cereal crop quality characteristics, in order to evaluate the statistical significance of differences. All quality characteristics of the cereal crops were calculated as the average of three replications of two varieties.

Results and discussion

The temperature and humidity conditions for germination of legumes were satisfactory despite of the above-average temperatures and shortage of precipitation in 2011 (Table 2). Higher than average precipitation and average temperatures were favourable for production of biomass of the legumes in 2012. The weather conditions of the main trial year 2013 (Year 1) were favourable as well, although periodic shortage of moisture occurred, especially in the first half of the vegetation period, thus decreasing N uptake by cereals. In 2014 (Year 2) the first part of the growing season was cool, encouraging formation of higher yields and bigger grains but the protein concentrations of the cereals remained low.

Dry matter yield, amount of C and N in leguminous pre-crops (2012)

In this investigation, the dry matter yield (DMY), C and N left in the soil by leguminous pre-crops, except for crimson and Alexandria clovers, was significantly higher compared with the control (Table 3). Average DMY and amounts of C and N in the perennial (red clover, alsike

Table 2. Weather data from 2011–2014 and long-term means (1922–2015) at Jõgeva, Estonia.

	Temperature (°C)					Precipitation (mm)				
Month	2011	2012	2013	2014	Long term mean	2011	2012	2013	2014	Long term mean
January	−4.9	−5.4	−7.0	−7.9	−6.4	72	82	41	35	41
February	−12.3	−11.3	−4.1	−0.4	−6.9	29	47	35	35	31
March	−2.2	−1.0	−8.7	1.9	−3.2	23	48	13	34	31
April	6.0	4.6	2.9	5.9	3.7	10	53	38	10	36
May	11.0	11.5	14.3	11.5	10.3	35	62	83	64	50
June	17.4	13.4	17.7	13.1	14.5	38	110	37	157	69
July	20.5	17.9	17.6	19.2	16.8	34	85	35	48	79
August	16.3	14.8	16.7	16.6	15.4	75	130	70	123	89
September	12.6	12.1	10.9	11.5	10.6	53	59	32	27	66
October	7.3	5.8	6.6	5.2	5.3	73	72	58	48	66
November	3.7	2.4	4.0	1.1	0.3	36	76	82	18	56
December	1.4	−7.2	1.2	−1.7	−3.8	118	51	56	63	47

Table 3. Dry matter yield (DMY) (t ha^{-1}) and amount of C and N (kg ha^{-1}) in biomass (green mass + roots) of pre-crops measured before winter (BWC) and spring (BSC) cereals.

	DMY (t ha^{-1})		C (kg ha^{-1})		N (kg ha^{-1})	
Pre-crop	BWC*	BSC**	BWC	BSC	BWC	BSC
Red clover	14.7 ab	13.9 a	6233 ac	6474 a	319 a	322 a
Alsike clover	13.8 b	13.4 a	5882 a	5993 b	246 b	323 a
Washington lupin	10.3 c	12.0 b	3975 b	4871 c	159 c	268 b
White sweet clover	14.9 ab	11.8 b	6503 c	5302 d	327 a	275 bc
Crimson clover	6.4 d	4.6 c	2666 d	2004 e	111 d	87 d
Alexandria clover	6.3 d	10.6 d	2591 d	3336 f	125 cd	161 e
Control	5.5 d	5.4 c	1828 e	1667 e	38 e	38 f
$LSD_{0.05}$	1.0	0.8	485	374	40	23

Notes: * – green mass + roots sampling 27 July 2012 (for lupin 20 June + 27 July).
** – green mass + roots sampling 3 October 2012.
LSD – least significant difference.
Within columns, mean values followed by the same letter are not significantly different at $p \leq 0.05$.

clover and Washington lupin) and biennial (white sweet clover) leguminous species were, in most cases, considerably higher than that of the annual clovers (crimson clover and Alexandria clover). Other studies have found similar high amounts of DMY, C and N of perennial leguminous species (Skuodiene and Nekrošiene 2009; Lauringson et al. 2013; Bender and Tamm 2014). Red and alsike clover showed relatively high comparable levels of DMY, C and N in the samples taken in July before sowing of winter cereals (BWC) as well as in the samples taken in October before spring cereals (BSC). Although white sweet clover showed the highest levels of DMY, C and N in July, there was a relatively larger decrease of the measured characteristics compared to other legumes by October. Washington lupin had relatively smaller DMY and amounts of nutrients in this experiment, especially in the samples taken in July (BWC). This may be related to the poorer initial development of the stand of this legume crop. These results indicated that red and alsike clover can be suitable for production of green manure as preceding crops for both winter and spring cereals, and white sweet clover primarily for winter cereals.

Annual crimson and Alexandria clover produced lower DMY and amounts of C and N, indicating less potential as green manure crops compared with the other legumes. One of the possible reasons may be lower biomass production potential due to the shorter life cycle of annual species. Previous research confirmed significantly lower biomass production of crimson clover compared with red clover (Coombs et al. 2017). The DMY, amounts of C and N in crimson clover produced in July BWC was higher than that in October BSC (the differences between the dates were not assessed statistically). At the end of August and in September crimson clover seeds mature, after which the plants die (Bender and Tamm 2014). Therefore, the optimum ploughing time for this green manure crop is at the full flowering stage which occurs in the second half of July in north-eastern Europe. Thus, crimson clover can be considered to be more suitable for the fertilisation of winter crops. The N produced by crimson clover before winter crops was the lowest compared to other legumes, but still reached up to 110 kg N ha^{-1} which was sufficient to increase cereal yield and quality. The effect of crimson clover as a green manure crop was also shown by Tamm et al. (2016). In contrast to crimson clover, the DMY and amounts of C and N of Alexandria clover increased during the growing season and were lower in July BWC and higher in October BSC (the differences between the dates were not assessed statistically), since it continued growing until the end of the season. Therefore, Alexandria clover can be more suitable for green manure production for spring cereals than for winter cereals. However, caution should be taken, as the species is sensitive to temperatures below – 6°C (Knight 1985). Annual, biennial and perennial legumes can fit in different niches in diverse crop rotations. Annual clover green manures may provide advantages in crop tillage systems where continuation of a legume beyond one year is undesirable (Ross et al. 2009). Annual legume crops as green manures can add diversity to temperate cropping systems where cereals and oilseeds are predominate (Rice et al. 1993).

Average DMY, C and N content of annual legumes were significantly lower than those of perennial and biennial leguminous pre-crops (Table 4). As DMY consisted of above- and below-ground biomass, the relative proportions of shoots and roots can be important in assessing the potential of legumes for producing green manure. While most legume species produced relatively smaller amounts of roots compared to shoots, Washington lupin differed in this respect from other legumes by producing relatively higher proportion of roots (Figure 2). The results of Lauringson et al. (2013) showed similar proportions of roots (54%) in the total biomass of pure sown Washington lupin. All the legumes showed a decrease in the proportion of roots by October. Crimson clover, the annual species, that produced the smallest biomass and finished growth earlier, had the smallest proportion of roots from the total biomass in the October samples. The other annual, Alexandria clover has a longer vegetation period and it continued active growth and flowering even in October.

The first-year after-effect of legumes (Year 1)

Protein concentration

The variation in protein concentration of all the tested cereals was significantly influenced by the pre-crop (A) (Table 5). The influence of variety (B) was significant for all the cereals, except rye. A x B interaction remained non-significant for most of the cereals, except barley, showing a similar reaction of cereal varieties to the pre-crop.

The weather conditions during the year of the first trial were quite favourable for comparatively high yield and the average of all the cereals was 4.8 t ha^{-1} (Tamm et al. 2016). Grain yield and protein concentration are often inversely related. Therefore, the protein concentration of the cereals remained moderate after all the legumes (Table 6). In general, protein concentration in organic cultivation is estimated to be 2–3 percentage points lower compared to conventional cultivation (Bilsborrow et al. 2013). The highest average protein was accumulated by winter wheat (11.1%) and the lowest by rye (8.5%). The protein concentration of all the cereals, except rye, increased significantly after perennial leguminous pre-crops by 0.8 to 2.6 percentage points

Table 4. Average dry matter yield (DMY) (t ha^{-1}) and amount of C and N (kg ha^{-1}) in biomass (green mass + roots) of perennial, biennial and annual pre-crops measured before winter (BWC) and spring (BSC) cereals.

	DMY (t ha^{-1})		C (kg ha^{-1})		N (kg ha^{-1})	
Life cycle type of pre-crop	BWC	BSC	BWC	BSC	BWC	BSC
Perennial	12.9 a	13.1 a	5363 a	5779 a	241 a	304 a
Biennial	14.9 a	11.8 a	6503 a	5302 a	327 a	275 a
Annual	6.4 b	7.6 b	2629 b	2670 b	118 b	124 b

Within columns, mean values followed by the same letter are not significantly different at $p \leq 0.05$ (t-test).

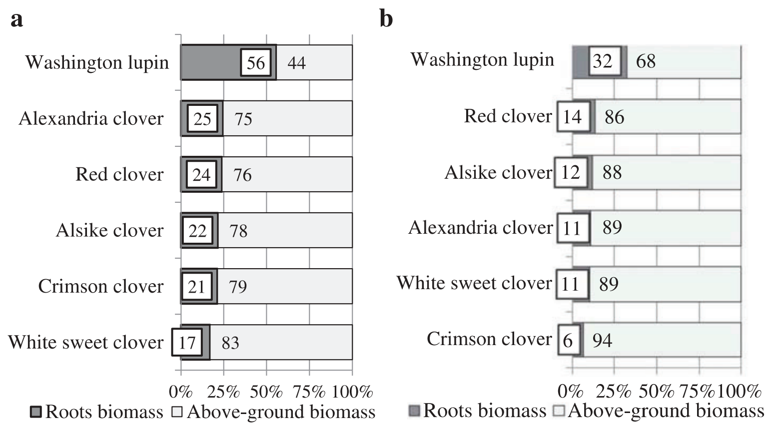

Figure 2. Proportions of roots and above-ground biomass from total dry matter yield of the leguminous pre-crops in July 2012, before of the winter cereals (a) and in October 2012, before spring cereals (b).

Table 5. Analyses of variance for protein concentration of cereals depending on leguminous pre-crop species (A), proceeding cereal variety (B) and their interaction (A x B) in Year 1.

Cereal	Source of the variation	df	SS	MS	F	*p*
Barley	Pre-crop (A)	6	6.478	1.080	15.91	0.000***
	Variety (B)	1	4.937	4.937	72.74	0.000***
	A x B	6	1.443	0.240	3.54	0.011*
Spring wheat	Pre-crop (A)	6	41.571	6.929	48.47	0.000***
	Variety (B)	1	16.594	16.594	116.09	0.000***
	A x B	6	0.439	0.073	0.51	0.794ns
Oats	Pre-crop (A)	6	10.672	1.779	3.21	0.017*
	Variety (B)	1	2.881	2.881	5.19	0.031*
	A x B	6	1.166	0.194	0.35	0.903ns
Rye	Pre-crop (A)	6	3.242	0.540	2.94	0.025*
	Variety (B)	1	0.002	0.002	0.01	0.915ns
	A x B	6	1.240	0.207	1.12	0.377ns
Winter wheat	Pre-crop (A)	6	8.451	1.409	17.36	0.000***
	Variety (B)	1	0.420	0.420	5.18	0.031*
	A x B	6	0.880	0.147	1.81	0.137ns

Notes: df – degrees of freedom; SS – sums of squares; MS – mean squares.
F – treatment mean square/error mean square.
p – significance probability value.
* – significant at $p < 0.05$; ** – significant at $p < 0.01$;*** – significant at $p < 0.001$.
ns – not significant.
Year 1 – the first-year after-effect of legumes.

compared with the control, whereas annual leguminous pre-crops had the most moderate effect on the protein concentration of the cereals. The results from this study confirmed earlier findings of Doltra et al. (2011) that leguminous green manure species had a positive effect on protein concentration of cereals in organic arable systems. The highest proteins as an average of all the cereals were formed after red and alsike clovers and the lowest after annual clovers.

In Estonia, the commonly used criterion for protein for marketing of high quality baking wheat is 13.0–14.0%. The protein concentration of spring wheat was in the range of 9.3–12.2% and increased the most after red and alsike clover, by 1.8 and 2.6 percentage points respectively, compared to the control. Protein concentration of winter wheat remained between 10.2–11.5%. In contrast to the

Table 6. Protein concentration (%) of cereals after different legumes in Year 1.

Pre-crop	Barley	Spring wheat	Oats	Rye	Winter wheat
Red clover	10.4 a	11.4 a	11.3 a	8.8 a	11.4 ab
Alsike clover	10.2 a	12.2 b	11.1 ab	8.2 b	11.3 ab
Washington lupin	10.2 a	10.8 c	11.0 abc	8.8 a	11.4 ab
White sweet clover	10.5 a	9.9 d	10.3 cd	8.9 a	11.5 b
Crimson clover	9.7 b	9.8 d	10.5 bcd	8.2 b	11.1 b
Alexandria clover	9.6 b	9.3 e	10.4 bcd	8.3 b	11.1 b
Control	9.4 b	9.6 de	9.8 d	8.6 ab	10.2 c
$LSD_{0.05}$	0.3	0.4	0.7	0.4	0.3

Notes: LSD – least significant difference.
Within columns, mean values followed by the same letter are not significantly different at p ≤ 0.05.
Year 1 – the first-year after-effect of legumes.
Within columns, mean values followed by the same letter are not significantly different at $p \leq 0.05$.

other cereals, winter wheat had significant increase in protein concentration (0.9–1.3 percentage points) after all the leguminous pre-crops. Maiksteniene and Arlauskiene (2004) reported lower (10.6%) and Talgre et al. (2010) higher (12.2%) protein concentration of winter wheat after red clover compared to the results reported here (11.4%). The differences could be explained by different weather conditions. The protein concentrations of winter wheat remained the lowest in the Lithuanian trial with moderate temperatures and optimal precipitation, whereas it was highest in Estonia in drought conditions. Although protein concentration of wheat remains generally lower in organic compared to conventional farming, it is quite usual for organic farmers to gain an increase in selling price for a slight increase of the protein concentration (Mazzoncini et al. 2015) and therefore even small improvement should be considered significant (Tosti et al. 2016).

Bulk density

Bulk density is influenced by many factors, including agronomic practice and weather conditions, disease infection, kernel shape and density (Gaines et al. 1997; Ingver 2007). Pre-crop and variety had a significant impact on the variation of bulk density of all the cereals (Table 7). A x B interaction remained non-significant for most of the cereals except spring wheat.

First-year after-effect of all the leguminous pre-crops on bulk density was significantly positive compared to the control in most cases but there were no clear trends (Table 8). Compared to the control species, the legume pre-crops resulted in the largest increases in bulk density in rye and oats. The bulk density of barley and rye increased the most after alsike clover, whereas, spring wheat achieved its highest bulk density after Washington lupin. However, the lowest bulk densities were obtained when winter wheat was grown after red clover, barley and spring wheat after crimson clover and oats after Washington lupin and white sweet clover.

In this study, winter wheat had higher (not assessed statistically) bulk density in Year 1 compared to spring wheat, since winter wheat suffered less from the early periodic shortage of moisture (Table 8). The negative influence of unfavourable growing conditions on the bulk density of wheat is a well-known phenomenon (Tipples 1986). However, both wheat types achieved the necessary quality requirements of the food industry (75.0 kg hL^{-1}). The marketing minimum for barley bulk density is 64.0 kg hL^{-1}. In Year 1, bulk density of barley was high after all the legumes. The recommended bulk density of oats for food purposes is 49.0 kg hL^{-1} or higher (Ganßmann and Vorwerck 1995). The bulk density values of the oats and the rye, following all of the legume species, fulfilled the minimum requirements.

Thousand kernel weight

Variation of TKW of the tested cereals, except oats, was significantly influenced by the pre-crop (A) (Table 9). The influence of variety (B) was significant for all the cereals. A x B interaction remained non-significant for most of the cereals except winter wheat.

Table 7. Analyses of variance for bulk density of cereals depending on leguminous pre-crop species (A), proceeding cereal variety (B) and their interaction (A x B) in Year 1.

Cereal	Source of the variation	df	SS	MS	F	*p*
Barley	Pre-crop (A)	6	28.876	4.813	15.81	0.000***
	Variety (B)	1	11.006	11.006	36.15	0.011*
	A x B	6	3.632	0.605	1.99	0.100ns
Spring wheat	Pre-crop (A)	6	45.983	7.664	22.10	0.000***
	Variety (B)	1	5.429	5.429	15.65	0.001***
	A x B	6	10.623	1.770	5.10	0.001**
Oats	Pre-crop (A)	6	74.909	12.485	7.92	0.000***
	Variety (B)	1	168.000	168.000	106.57	0.000***
	A x B	6	5.883	0.981	0.62	0.711ns
Rye	Pre-crop (A)	6	86.949	14.492	24.11	0.000***
	Variety (B)	1	152.381	152.381	253.53	0.000***
	A x B	6	3.749	0.625	1.04	0.423ns
Winter wheat	Pre-crop (A)	6	38.476	6.413	16.09	0.000***
	Variety (B)	1	108.804	108.804	272.92	0.000***
	A x B	6	3.916	0.653	1.64	0.177ns

Notes: df – degrees of freedom; SS – sums of squares; MS – mean squares.
F – treatment mean square/error mean square.
p – significance probability value.
* – significant at $p < 0.05$; ** – significant at $p < 0.01$;*** – significant at $p < 0.001$.
ns – not significant.
Year 1 – the first-year after-effect of legumes.

Table 8. Bulk density (kg hL^{-1}) of cereals after different legumes in Year 1.

Pre-crop	Barley	Spring wheat	Oats	Rye	Winter wheat
Red clover	69.4 a	78.1 a	51.6 a	69.3 a	79.3 a
Alsike clover	70.3 b	78.7 ac	52.4 ab	71.0 b	81.5 b
Washington lupin	69.5 a	79.5 bc	51.2 a	69.5 a	81.7 b
White sweet clover	68.6 cde	78.2 a	51.2 a	69.4 a	81.7 b
Crimson clover	68.3 cd	76.9 d	53.7 b	70.0 ac	81.2 b
Alexandria clover	69.0 ae	79.2 c	53.0 b	70.5 bc	81.1 b
Control	67.6 f	76.5 d	49.3 c	66.2 d	79.5 a
$LSD_{0.05}$	0.5	0.6	1.3	0.8	0.6

Notes: LSD – least significant difference.
Within columns, mean values followed by the same letter are not significantly different at $p \leq 0.05$.
Year 1 – the first-year after-effect of legumes.

The weather conditions were quite favourable for the formation of heavier than average grains. All the green manure pre-crops increased significantly TKW of barley, spring and winter wheat (Table 10). However, the effect of leguminous pre-crops on TKW of rye was negative and there was no significant effect of the legumes on the oats. Previous experiments with red clover have found positive effects on TKW of winter and spring wheat and winter rye (Skuodiene and Nekrošiene 2009; Talgre et al. 2009, 2010), thus partly confirming the findings of this study. TKW (as the mean of all the leguminous pre-crops) was the highest for barley (50.0 g) followed by winter wheat (46.2 g), oats (44.0 g), spring wheat (37.2 g) and rye (36.0 g). For barley and spring wheat, the grains with the highest TKW were measured after alsike clover and Washington lupin. Oats and rye are naturally less intensive types of cereals compared to barley and wheat, with a lower demand for nutrients.

The second-year after-effect of legumes (Year 2)

The benefits of legumes were carried over into the second year. All the legume species had a positive second-year after-effect on the protein concentration of barley and oats (Table 11), with the largest after-effect after red and alsike clover, which exceeded the control by 1.0–1.3 percentage points. The larger second-year positive after-effect of red and alsike clover on protein

Table 9. Analyses of variance for thousand kernel weight of cereals depending on leguminous pre-crop species (A), proceeding cereal variety (B) and their interaction (A x B) in Year 1.

Cereal	Source of the variation	df	SS	MS	F	*p*
Barley	Pre-crop (A)	6	89.956	14.993	13.16	0.000***
	Variety (B)	1	8.595	8.595	7.54	0.011*
	A x B	6	4.265	0.711	0.62	0.710ns
Spring wheat	Pre-crop (A)	6	80.451	13.409	8.33	0.000***
	Variety (B)	1	92.115	92.115	57.26	0.000***
	A x B	6	6.665	1.111	0.69	0.659ns
Oats	Pre-crop (A)	6	2.570	0.428	0.34	0.907ns
	Variety (B)	1	46.515	46.515	37.28	0.000***
	A x B	6	5.945	0.991	0.79	0.583ns
Rye	Pre-crop (A)	6	73.966	12.328	10.96	0.000***
	Variety (B)	1	306.180	306.180	272.21	0.000***
	A x B	6	4.357	0.726	0.65	0.693ns
Winter wheat	Pre-crop (A)	6	48.841	8.140	21.51	0.000***
	Variety (B)	1	560.275	560.275	1480.19	0.000***
	A x B	6	6.815	1.136	3.00	0.023*

Notes: df – degrees of freedom; SS – sums of squares; MS – mean squares.
F – treatment mean square/error mean square.
p – significance probability value.
* – significant at $p < 0.05$; ** – significant at $p < 0.01$;*** – significant at $p < 0.001$.
ns – not significant.

Table 10. Thousand kernel weight (g) of cereals after different legumes in Year 1.

Pre-crop	Barley	Spring wheat	Oats	Rye	Winter wheat
Red clover	49.8 a	37.7 ab	44.0 a	37.1 a	45.8 a
Alsike clover	51.1 b	38.7 b	43.9 a	34.2 b	45.9 a
Washington lupin	51.1 b	37.3 ac	43.7 a	37.3 a	46.5 b
White sweet clover	50.3 ab	36.3 c	44.3 a	36.9 ad	47.1 c
Crimson clover	48.1 c	36.9 ac	43.9 a	34.8 bcd	45.8 a
Alexandria clover	49.8 a	36.5 ac	43.9 a	35.8 d	45.9 ab
Control	46.8 d	33.9 d	44.5 a	38.2 a	43.3 d
$LSD_{0.05}$	1.0	1.3	1.1	1.1	0.6

Notes: LSD – least significant difference.
Within columns, mean values followed by the same letter are not significantly different at $p \leq 0.05$.
Year 1 – the first-year after-effect of legumes.

Table 11. The protein concentration, thousand kernel weight and bulk density of barley and oats in Year 2.

	Protein (%)		Thousand kernel weight (g)		Bulk density (kg hL^{-1})	
Pre-crop in 2012	Barley	Oats	Barley	Oats	Barley	Oats
Red clover	10.5 a	10.4 a	44.4 a	43.8 ab	67.9 a	48.8 ac
Alsike clover	10.5 a	10.3 a	44.3 a	43.8 ab	67.3 b	49.4 ab
Washington lupin	10.0 b	9.6 b	43.7 b	44.2 a	66.5 c	50.0 b
White sweet clover	10.2 ab	9.7 b	43.9 ab	44.3 a	66.8 bc	48.4 c
Crimson clover	10.0 b	9.6 b	44.1 ab	43.6 b	67.0 bc	49.6 b
Alexandria clover	10.0 b	9.4 bc	43.6 b	44.1 ab	66.7 cd	49.3 ab
Control	9.5 c	9.1 c	44.1 ab	43.8 ab	67.1 bc	47.9 c
$LSD_{0.05}$	0.4	0.3	0.5	0.5	0.5	0.7

LSD – least significant difference.
Within columns, mean values followed by the same letter are not significantly different at p ≤ 0.05.
Year 2 – the second-year after-effect of legumes.

concentration of barley and oats could be explained by the high DMY and N content of these legumes. There was an increase in the protein concentrations of barley and oats also after all other legumes, except for oats after Alexandria clover. In the second post-legume year, Bender and

Table 12. Quality characteristics of barley and oats after cereal pre-crops in Year 2.

	Protein(%)		Thousand kernel weight (g)		Bulk density(kg hL^{-1})	
Pre-crop in 2013	Barley	Oats	Barley	Oats	Barley	Oats
Barley	10.2 a	9.8 a	43.9 a	43.6 a	66.4 a	48.5 a
Oats	10.1 a	9.6 a	44.1 a	44.1 b	66.3 a	48.3 a
Spring wheat	10.2 a	9.7 a	44.0 a	43.8 ab	66.5 a	48.7 a
Winter wheat	9.9 a	9.6 a	44.0 a	43.9 ab	67.6 b	49.5 b
Rye	10.0 a	9.8 a	44.1 a	44.2 b	68.3 c	49.7 b
$LSD_{0.05}$	0.3	0.3	0.4	0.4	0.4	0.6

Notes: LSD – least significant difference.
Within columns, mean values followed by the same letter are not significantly different at $p \leq 0.05$.

Tamm (2014) found a positive effect of Washington lupin on the protein of barley, while red and crimson clover had no significant effect.

In the second year, the average bulk density of barley and oats decreased by 3.1% and 5.6%, respectively compared to that in Year 1 (though the significance of these differences were not statistically analysed). Most of the legume species had a positive significant second-year after-effect on oats bulk density (except white sweet clover) ranging from 48.4–50.0 kg hL^{-1}. Bulk density of barley increased only after red clover, remaining between 66.5–67.9 kg hL^{-1}. Barley also had the highest yields after red clover as shown in Tamm et al. (2016). Talgre et al. (2010) also detected a positive effect of red clover on barley bulk density.

The preceding legume crops had no significant effect on TKW of barley and oats in Year 2 compared to the control. The same tendency regarding barley was described in the study of Bender and Tamm (2014) and no effect of crimson clover to TKW of barley and spring wheat in the second year was found. In contrast to the findings reported here, Talgre et al. (2010) found a positive second-year after-effect of red and white sweet clover on barley TKW.

The winter and spring cereals (Year 1) sown after legumes, had no significant effect on the protein accumulation of the succeeding barley and oats (Year 2) (Table 12). Bulk density of oats and barley was higher after winter cereals compared to the spring cereals. The preceding cereals had no significant influence on TKW of barley, the differences remained modest also for oats.

Conclusions

The results of this study confirmed the hypotheses that various legume species were good pre-crops, offering improvement of the quality characteristics (protein concentration, bulk density and TKW) of the subsequent cereals. There were clear differences in the fertilisation value of the legumes, depending whether they were perennial, biennial or annual species. The N yield produced by perennial and biennial species was high, providing significant benefit to the quality of subsequent cereals. Even the short growing annual species (crimson and Alexandria clover) were able to accumulate considerable amounts of N, though it was not sufficient to increase the quality characteristics of most of the subsequent cereals. The average dry matter yield and amounts of C and N in the legume species were significantly higher compared to the non-legume control.

The first- and second-year after-effect of leguminous pre-crops on grain quality varied depending on the preceding legume and following cereal species. Perennial red and alsike clover proved to be suitable as green manure pre-crops for all the cereals tested. Biennial white sweet clover has the potential to produce a large amount of biomass and can be used as pre-crop for cereals similar to the perennial legumes, but it may be more suitable for winter cereals due to its intensive growth in the first part of the season. The results of this study on the potential of annual crimson and Alexandria clovers as green-manures are valuable, since there is almost no previous research on these species in the northern part of Europe. Out of all the legume species, perennial red and alsike clover had the most positive second-year after-effect on protein concentration and bulk density of barley and oats. The benefits of the legumes on the protein concentration were carried over to the second year.

Green manure leguminous species with high ability to increase soil fertility are key components in organic crop rotations and are important in order to maintain and improve grain quality in sustainable agriculture. This study demonstrated that cultivation of effective leguminous green manure species improved the grain quality of subsequent winter and spring cereals in an organic crop rotation. This study offered practical recommendations for diversifying the selection of leguminous pre-crop species for organic producers in conditions of climate change and prolongation of the growing season in north-east European areas.

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References

Andersson AAM, Elferson C, Andersson R, Regner S, Aman P. 1999. Chemical and physical characteristics of different barley samples. J Sci Food Agr. 79:979–986.

Askegaard M, Olesen JE, Kristensen K. 2005. Nitrate leaching from organic arable crop rotations: effects of location, manure and catch crop. Soil Use Manage. 21(2):181–188.

Bender A, Tamm S. 2014. Fertilization value of early red clover, Washington lupin and crimson clover as green manure crops. In: Treija S, Skujeniece S, editors. Research for Rural Development 2014. Proceedings of the Annual 20th International Scientific Conference. Vol. 1, May 21–23; Jelgava (Latvia): Latvia University of Agriculture. p. 84–88

Berry PM, Sylvester-Bradley R, Philipps L, Hatch DJ, Cuttle SP, Rayns FW, Gosling P. 2002. Is the productivity of organic farms restricted by the supply available nitrogen? Soil Use Manage. 18:248–255.

Bilsborrow PE, Cooper J, Tetard-Jones C, Srednicka-Tober D, Baranski M, Eyre M, Schmidt C, Shotton PN, Volakakis N, Cakmak I, et al. 2013. The effect of organic and conventional management on the yield and quality of wheat grown in a long-term field trial. Eur J Agron. 51:71–80.

Clark A. 2007. Managing cover crop profitability. In: Clark A, editor. National SARE outreach handbook series book 9. 3rd ed. Beltsville (MD): Sustain. Agric. Netw; 248.

Coombs C, Lauzon JD, Deen B, Laura L, Van ELL. 2017. Legume cover crop management on nitrogen dynamics and yield in grain corn systems. Field Crops Res. 201:75–85.

Crowder D, Reganold J. 2015. Financial competitiveness of organic agriculture on a global scale. Proc Natl Acad Sci Unit States Am. 112:7611–7616.

Doltra J, Lægdsmand M, Olesen JE. 2011. Cereal yield and quality as affected by nitrogen availability in organic and conventional arable crop rotations: A combined modelling and experimental approach. Eur J Agron. 34(2):83–95.

Döring T. 2013. Manifold green manures. Part IV: large birdsfoot trefoil, meadow pea and white sweet clover. Org Grow. 25:26–27.

Döring T, Boufartigue C. 2013. Manifold green manures. Part 2: alsike and crimson clovers. Org Grow. 23:28–29.

Drinkwater LE, Wagoner P, Sarrantonio M. 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature. 396:262–265.

Estonian Centre for Standardisation. 2009. Food products – determination of the total nitrogen content by combustion. *DUMAS ISO/TC 16634-2:2009*. [Internet]. [accessed 2018 Mar 15]. https://www.evs.ee/preview/iso-ts-16634-2-2009-en.pdf

Estonian Centre for Standardisation. 2010a. Cereals and pulses. Determination of the mass of 1000 grains. *EVS-EN ISO 520:2010*. [Internet]. [accessed 2018 Mar 15]. https://www.evs.ee/products/evs-en-iso-520-2010-et.pdf

Estonian Centre for Standardisation. 2010b. Cereals – determination of bulk density, called mass per hectolitre. *EVS-EN ISO 7971-3:2010*. [Internet]. [accessed 2018 Mar 15]. https://www.evs.ee/eelvaade/evs-en-iso-7971-3-2010-en.pdf

Gaines CS, Finney PL, Andrews LC. 1997. Influence of kernel size and shrivelling on soft wheat milling and baking quality. Cereal Chem. 74(6):700–704.

Ganßmann W, Vorwerck K. 1995. Oat milling, processing and storage. In: Welch RW, editor. The oat crop: production and utilization. Chapter 12. London: Chapman & Hall; p. 369–408.

Halverson J, Zeleny L. 1988. Criteria of wheat quality. In: Pomeranz Y, editor. Wheat chemistry and technology. Chapter 2. 3rd ed. St. Paul (MN): Am. Assoc. Cereal Chem; p. 15–45.

Ingver A. 2007. Suvinisu saagi ja kvaliteedi erinevus mahe- ja tavakatses. Ess M, koost. Põllukultuuride ja nende sortide sobivus maheviljeluseks. [Spring wheat yield and quality differences in organic and conventional experiments.]. In: Ess M, editor. Field crops and their varieties suitability for organic farming. Estonian; OÜ Vali Press; p. 10–15.

International Standard. 1995. ISO 11261. Soil quality – determination of total nitrogen - Modified Kjeldahl method. 4. Geneva, Switzerland: International Standardization Organization [Internet]. [accessed 2018 Mar 15] https://www.iso.org/standard/19239.html

International Standard. 2005. Soil quality – determination of pH. ISO 10390. Geneva, Switzerland: International Organization for Standardization; p. 7. [Internet]. [accessed 2018 Mar 15] https://www.iso.org/standard/18454.html

[IUSS] Working Group WRB. 2015. World reference base for soil resources 2014, update 2015 international soil classification system for naming soils and creating legends for soil maps. *World Soil Resour*. FAO, Rome. Reports. 106

Jensen CR, Joernsgaard B, Andersen MN, Christiansen JL, Mogensen VO, Friis P, Petersen CT. 2004. The effect of lupins as compared with peas and oats on the yield of the subsequent winter barley crop. Eur J Agron. 20:405–418.

Jones HM, Clarke SM, Haigh Z, Pearce H, Wolfe M. 2010. The effect of the year of wheat variety release on productivity and stability of performance on two organic and two non-organic farms. J Agric Sci. 148:303–317.

Knight WE. 1985. Registration of 'Bigbee' clover. Crop Sci. 25:571–572.

Krejčířová L, Capouchová I, Petr J, Bicanová E, Kvapil R. 2006. Protein composition and quality of winter wheat from organic and conventional farming. Žembdirbysté/Agriculture, Lithuania. 93(4):285–296.

Kurlovich B, Stoddard FL, Earnshaw P. 2008. Potential and Problems of *Lupinus polyphyllus* Lindl. Domestigation. In: Palta JA, Berger JD, editors. Lupins for health and wealth. Proceedings of the 12th International lupin conference. Sept 14–18; Fremantle (Western Australia); Canterbury, N.Z.: International Lupin Association; p. 304–307.

Lauringson E, Talgre L, Makke A. 2013. Large-leaved lupin (*Lupinus polyphyllus* Lind.) and early red clover (*Trifolium pratense* L.) as green manure crops. Subsequents of the Latvian academy of sciences. Sect B Nat Exact Appl Sci. 67(3):242–246.

Maiksteniene S, Arlauskiene A. 2004. Effect of preceding crops and green manure on the fertility of clay loam soil. Agron Res. 2(1):87–97.

Mazzoncini M, Antichi D, Silvestri N, Ciantelli G, Sgherri C. 2015. Organically vs conventionally grown winter wheat: effects on grain yield, technological quality, and on phenolic composition and antioxidant properties of bran and refined flour. Food Chem. 175:445–451.

Mehlich A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich-2 extractant. Comm Soil Sci Plant Anal. 15:1409–1416.

Nuttall JG, O'Leary GJ, Panozzo JF, Walker CK, Barlow KM, Fitzgerald GJ. 2017. Models of grain quality in wheat – A review. Field Crops Res. 202:136–145.

Nykänen A, Granstedt A, Jauhiainen L. 2008. Residual effect of clover-rich leys on soil nitrogen and successive grain crops. Agric Food Sci. 17:73–87.

Piano E, Pecetti L . 2010, Minor legume species. In: Boller B, Posselt UK, Veronesi F. editors, Fodder crops and amenity grasses. New York: Springer; Chapter 5, Handbook of Plant Breeding, p. 477–500.

Pieters AJ. 1927. Green Manuring. New York: John Wiley & Sons Inc; p. 356.

Rice WA, Olsen PE, Bailey LD, Biederbeck VO, Slinkard AE. 1993. The use of annual legume green-manure crops as a substitute for summerfallow in the Peace River region. Can J Soil Sci. 73:243–252.

Ross SM, King JR, Izaurralde RC, O'Donovan JT. 2009. The green manure value of seven clover species grown as annual crops on low and high fertility temperate soils. Can J Plant Sci. 89:465–476.

Skuodiene R, Nekrošiene R. 2009. Effect of preceding crops on the winter cereal productivity and diseases incidence. Acta Agric Slov. 93(2):169–179.

Talgre L, Lauringson E, Makke A. 2010. Amounts of nitrogen and carbon returned to soil depending on green manure and the effect on winter wheat yield. Agron Res. 8:487–492.
Talgre L, Lauringson E, Roostalu H, Astover A. 2009. The effects of green manures on yield and yield quality of spring wheat. Agron Res. 7(1):125–132.
Talgre L, Lauringson E, Roostalu H, Astover A, Makke A. 2012. Green manure as a nutrient source for succeeding crops. Plant Soil Environ. 58:275–281.
Tamm I, Ü T, Ingver A. 2009. Spring cereals performance in organic and conventional cultivation. Agron Res. 7 (1):522–527.
Tamm I, Ü T, Ingver A, Koppel R, Tupits I, Bender A, Tamm S, Narits L, Koppel M. 2016. Different leguminous precrops increased yield of succeeding cereals in two consecutive years. Acta Agric Scand Sect B Soil Plant Sci. 66(7):593–601.
Tipples KH. 1986. Testing candidate wheat cultivars for quality. A review. In: Slinkard AE, Fowler DB, editors. Proceedings of the Canadian wheat production symposium. Mar 3–5; Saskatoon (SK) (Canada): University of Saskatoon; p. 500–511
Tjurin IV. 1937. Soil organic matter and its role in pedogenesis and soil productivity. In:Study of soil humus. Moscow: Selkhozgiz; p. 287. Russian.
Tosti G, Farneselli M, Benincasa P, Guiducci M. 2016. Nitrogen fertilization strategies for organic wheat production: crop yield and nitrate leaching. Agron J. 108(2):770–781.
Trnka M, Roetter RP, Ruiz-Ramos M, Kersebaum KC, Olesen JE, Zalud Z, Semenov MA. 2014. Adverse weather conditions for European wheat production will become more frequent with climate change. Nat Clim Change. 4:637–643.
Vipper H. 1989. The research methods of studying root systems. In: Justi K, editor. Handbook of land cultivation. Tallinn: Valgus; p. 228–239. Estonian.

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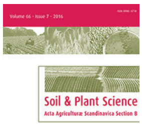

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ORIGINAL ARTICLE

Different leguminous pre-crops increased yield of succeeding cereals in two consecutive years

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ABSTRACT
Leguminous pre-crops are an important source of green manure in organic crop rotations for improving soil fertility and achieving high yields of cereals. We aimed to study the potential of various leguminous species, other than the traditionally cultivated red clover (*Trifolium pratense* L.), as green manure pre-crops for subsequent cereals. The use of different legume species enables to exploit advantages of specific legumes in organic cereal production. In order to test the legumes as pre-crops for cereals, we carried out trials located in the temperate climate zone of northeast Europe (58°44′59.41′′ N, 26°24′54.02′′ E). We sowed the following perennial legumes as pre-crops: red clover, alsike clover (*Trifolium hybridum* L.) and Washington lupine (*Lupinus polyphyllus* Lindl.), biennial white sweet clover (*Melilotus albus* Medik.) and annual Alexandria clover (*Trifolium alexandrinum* L.), and crimson clover (*Trifolium incarnatum* L.). Timothy (*Phleum pratense* L.) was used as a control. The leguminous pre-crops were followed by three spring cereals (barley, oat and spring wheat) and two winter cereals (rye and winter wheat). We tested the first-year after-effect (all cereals) and second-year after-effect (only barley and oat) of pre-crops on the grain yield of cereals. Perennial and biennial legume species produced the highest dry matter yield and contained the highest amount of nutrients, especially nitrogen, compared to annual species. All subsequent cereals produced significant extra yields after each leguminous pre-crop in the following two years, although the effect was smaller in the second year. The most suitable pre-crops for spring cereals were red and alsike clover followed by lupine, whereas the best pre-crops for winter cereals were sweet clover and annual clovers. Our results show the potential of various leguminous pre-crop species as valuable sources of green manure in organic crop rotation.

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Introduction

Crop rotations that include leguminous green manure species are important for organic productions in order to maintain and improve soil fertility, yield quality and quantity. Deep root systems of legumes enable the acquisition of nutrients from deeper soil layers and symbiotic nitrogen-fixing bacteria convert atmospheric nitrogen into a form that is directly available for plant uptake. Organic material left in the soil after ploughing improves humus content, structure, and physical and biological properties of the soil. By promoting beneficial soil biota, legumes reduce the abundance of weeds, pests and crop diseases.

The most frequently grown green manure crop in organic and conventional farming in northern Europe and other cold-temperate climate countries is red clover (*Trifolium pratense* L.) (Nykänen et al. 2008; Riesinger & Herzon 2010; Talgre et al. 2012). Red clover is a key crop in maintaining and building up soil fertility in organic farming (Billings et al. 2010). It grows well on various soil types, but prefers soil of pH 6–7 (Wyngaarden et al. 2015). The results of different studies show that its nitrogen-fixing capability can be up to 400 kg ha^{-1} yr^{-1} (Deprez et al. 2004; Kadziulene 2004; Billings et al. 2010). Alsike clover (*Trifolium hybridum* L.) is less sensitive to soil acidity than red clover, while also tolerating pH 5 (Fairey 1986) and high groundwater levels (Döring & Boufartigue 2013). Depending on climate and phenological phase, alsike clover is able to fix even more nitrogen than red clover (Rice 1980). Washington lupine (*Lupinus polyphyllus* Lindl.) also develops satisfactorily on slightly acid soils. The species has a remarkable nitrogen fixation ability of 250–350 kg ha^{-1} (Kurlovich et al. 2008). Lupine has a specific capacity to make relatively unavailable P sources available for the subsequent crop (Neumann et al. 1999; Lambers et al. 2013). White sweet clover (*Melilotus albus* Medik.) prefers loam

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soils with near-neutral pH 6.5–7.5 (Wyngaarden et al. 2015) for growth, but it will not thrive on poorly drained soils (Döring 2013). Its deep penetrating taproot opens up the subsoil, reaching nutrients that are not available to shallower rooting crops (Sweetclovers 2007). According to Viil and Võsa (2005), white sweet clover increased nitrogen supply of the soil in their study by 250 kg ha^{-1}.

Annual Alexandria clover (*Trifolium alexandrinum* L.) and crimson clover (*Trifolium incarnatum* L.) are almost uncultivated in Northern countries. Only a few studies have been carried out in Canada and the northern United States where annual clover species have been included, but further research is needed (Bullied et al. 2002; Ross et al. 2009). Alexandria clover is valued as green fodder crop (with nitrogen fixation of 33–66 kg ha^{-1}) (Graves et al. 1996). This species has a moderate tolerance of cold conditions, preferring regions where winter temperature is above −6°C. It grows best on fertile, medium- to heavy-textured soils of mildly acidic to neutral pH (Knight 1985; Hannaway & Larson 2004). Crimson clover is a cool season forage legume that is adapted to mild winter areas (Lloveras & Iglesias 2001). It prefers to grow on lighter well-drained soils. According to Brink (1990), its average nitrogen fixation ability is 155 kg ha^{-1} during the growing period. The preferable pH range is 6.0–7.0 (Döring & Boufartigue 2013).

In the case where the demand for organic cereals grows, the cultivation should be extended to less favourable soil conditions. The use of other legumes, besides traditional red clover, as green manure would increase the success of organic cereal production. If the growing period prolongs in the case of climate warming, new opportunities would open up to cultivate other types of legumes in order to supply succeeding crops with major plant nutrients.

The current research was initiated by organic farmers. We established a trial series that including six leguminous pre-crops and five spring and winter cereals. The objective of our research was to study the potential of various leguminous species as green manure pre-crops on the yields of subsequent cereals. We have hypothesized that: (1) other legume species besides red clover have potential as high-quality green manure in organic crop rotations and (2) spring and winter cereals benefit variously from different leguminous pre-crop species.

Materials and methods

The trials were carried out on certified organic area during the period of 2011–2014 in the Estonian Crop Research Institute, located in eastern Estonia (58° 44′59.41′′ N, 26°24′54.02′′ E). The trial site belongs to a temperate climate zone with an average annual temperature of 5.3°C and precipitation of 670 mm (Estonian weather service). The trial field is located on Calcaric Cambic Phaeozem (Loamic) soil (IUSS 2015) that is typical for the region. The soil characteristics were as follows: pH_{KCl} 6.7, P 65, K 101, Ca 3834 mg kg^{-1}, C_{org} 3.5% and N_{total} 0.27%. Soil pH_{KCl} was determined by the ISO 10390; P, K and Ca by Mehlich III; C_{org} by the Tjurin method and N by ISO 11261.

The trial was divided into three cycles: (i) establishment of plots with perennial leguminous pre-crops in 2011 and annual leguminous pre-crops in 2012, in order to test the potential of pre-crops as green manure; (ii) sowing of winter cereals in 2012 and spring cereals in 2013 (year 1) on the plots of leguminous pre-crops in order to test the first-year after-effect of the legumes and (iii) sowing of barley and oat varieties after each preceding cereal species in 2014 (year 2) to test the second-year after-effect of leguminous crops and combined effects of legumes and cereals.

The experiment was designed as a split-plot trial with six legume species (with non-legume control) as main plots (130 m^2 each) arranged in a randomized complete block design in three replications. The five cereal species (two varieties per species) were sown on 5 m^2 subplots on each main plot.

The trial included three perennial legume species (red clover, alsike clover and Washington lupine), one biennial legume (white sweet clover) and two annual legumes (Alexandria clover and crimson clover). Timothy (*Phleum pratense* L.), which has no nitrogen-fixing ability, was used as a control.

The trial cycle started with the sowing of perennial and biennial leguminous species – red clover 'Jõgeva 433' (400 seeds m^{-2}), alsike clover 'Jõgeva 2' (700 seeds m^{-2}), Washington lupine 'Lupi' (95 seeds m^{-2}) and white sweet clover 'Kuusiku 1' (950 seed m^{-2}) in July 2011. In the following spring (April 2012), annual Alexandria clover 'Alex' and crimson clover 'Contea' were sown (600 seeds m^{-2} each). Timothy was sown at the same time as the perennial green manure crops (1000 seeds m^{-2}).

Before the sowing of winter cereals, all legumes except lupine were chopped and ploughed in during flowering at the beginning of August 2012. Since lupine started flowering earlier than other perennial legumes, the first cut was made in June to avoid seed ripening. Lupine aftermath was ploughed in, together with other legumes. In the area for the sowing of

Table 1. Long-term monthly average of air temperature, sum of precipitation and deviations from the average during the trial period in 2011–2014.

	Temperature (°C)					Precipitation (mm)				
		Deviation					Deviation			
Month	Long-term average[a]	2011	2012	2013	2014	Long-term average[a]	2011	2012	2013	2014
I	−6.4	1.5	1.0	−0.6	−1.6	41	31	42	0	−5
II	−6.9	−5.5	−4.4	2.7	6.5	31	−2	16	5	4
III	−3.2	1.0	2.2	−5.5	5.1	31	−8	17	−18	3
IV	3.7	2.2	0.9	−0.9	2.2	36	−26	17	2	−26
V	10.3	0.7	1.2	4.0	1.2	50	−15	12	33	14
VI	14.5	3.0	−1.1	3.3	−1.4	69	−30	41	−31	89
VII	16.8	3.7	1.1	0.8	2.4	79	−45	6	−44	−31
VIII	15.4	0.9	−0.6	1.3	1.2	89	−14	41	−19	34
IX	10.6	2.0	1.6	0.4	1.0	66	−13	−7	−34	−39
X	5.3	1.9	0.5	1.3	−0.2	66	7	6	−8	−18
XI	0.3	3.3	2.1	3.7	0.8	56	−20	20	26	−38
XII	−3.8	5.1	−3.4	5.0	2.0	47	71	4	9	16

[a]Long-term average 1922–2015.

spring cereals red, alsike and sweet clover were cut, chopped and left in the field. The same operations were carried out using lupine on 20 June. The aftermaths of lupine and the primary growth of annual clovers were not cut in autumn and were ploughed in before the sowing of cereals in the spring of 2013.

The winter wheat varieties ‘Ada’ and ‘Skagen’ (450 seeds m^{-2}), and the rye varieties ‘Sangaste’ and ‘Elvi’ (500 seeds m^{-2}) were sown in September 2012. The spring wheat varieties ‘Manu’ and ‘Uffo’ (600 seeds m^{-2}), the barley varieties ‘Grace’ and ‘Maali’ (500 seeds m^{-2}), and the oat varieties ‘Ivory’ and ‘Kalle’ (500 seeds m^{-2}) were sown in May 2013. All the cereal varieties were sown after each legume species. The barley variety ‘Maali’ and the oat variety ‘Ivory’ were sown in May 2014 after each previous cereal species.

Germination of legumes was uniform and the development of herbage was satisfactory, despite of high temperatures and shortage of precipitation in 2011 (Table 1). Higher than average precipitation and mean average temperature were favourable for the growth of legumes in 2012. Small, but regular, amounts of precipitation resulted in a relatively high yield level of cereals in 2013. A high rate of precipitation, combined with cooler than average temperature in June, prolonged the first part of plant development, resulting in a high yield level of cereals in 2014.

Above- and below-ground biomass of legumes were measured in July 2012 (before winter cereals) and at the end of the vegetation period in October 2012. The above-ground biomass of legumes was harvested by a forage plot harvester (Hegel 212). Approximately 1 kg of fresh biomass from each plot was taken and weighed. Then, samples were oven-dried at 105°C to a constant weight and dry matter yield (DMY) was calculated. The monoliths (15 × 30 × 5 cm, up to 25 cm in depth) were taken, in order to determine the below-ground and stubble biomass. The roots were washed, then oven-dried as described above and weighed. Chemical analyses from above- and below-ground biomass were determined as follows: nitrogen and carbon by the TUMAS ISO/TC 16634-2:2009 method, phosphorus and potassium by inductively coupled plasma optical emission spectrometry after pressure digestion.

Cereal plots were harvested with a combine harvester (Hegel 140). Plot yields were dried and cleaned. Grain yield (kg ha^{-1}) was recorded and adjusted for 14% of moisture content. Metabolizable energy (ME) content was calculated by multiplying grain yield in dry matter with the ME content per kg of respective cereal species (Sikk 2004).

In order to test the reliability of the first- and second-year after-effect of leguminous pre-crops on cereal grain yield, we performed analysis of variance. Least significant differences were calculated in order to evaluate the statistical significance of differences between measured characteristics. The data of cereals were expressed as the average of two varieties. Correlations between DMY, C, N, P and K content of all the legumes were calculated. Correlations between grain yield and the above-mentioned factors were calculated separately for spring and winter cereals. All statistical analyses were performed by Agrobase Generation II SQL version 37.2.4.

Results and discussion

DMY and nutrient content of legumes

Before the sowing of winter cereals (July 2012), the average DMY of perennial and biennial legumes was significantly higher compared to the control species (timothy) (Table 2). DMY of red, alsike and sweet clover was comparably high (up to 14.9 t ha^{-1}),

Table 2. DMY (t ha^{-1}) and included carbon (C, kg ha^{-1}), nitrogen (N, kg ha^{-1}), carbon/nitrogen ratio (C/N), phosphorus (P, kg ha^{-1}), potassium (K, kg ha^{-1}) of biomass (green mass + roots) of pre-crops sampled in July 2012 before winter cereals.

Pre-crop	DMY	C	N	C/N	P	K
Red clover[a]	14.7*	6233*	319.0*	20*	35.3*	236.1*
Alsike clover[a]	13.8*	5882*	245.9*	24*	34.2*	240.4*
Lupine[a]	10.3*	3975*	158.5*	25*	24.1*	164.3*
Sweet clover[b]	14.9*	6503*	326.8*	20*	47.9*	279.7*
Alexandria clover[c]	6.3	2591*	124.9*	21*	17.1*	126.8*
Crimson clover[c]	6.4	2666*	111.2*	24*	16.5*	123.5*
Control (timothy)	5.5	1828	38.3	48	5.4	25.7
$LSD_{0.05}$	1.0	485	39.5	13	3.3	33.0

Note: LSD: least significant difference.
[a]Perennial.
[b]Biennial.
[c]Annual.
*Means within columns are significantly different from control at $p < .05$ (Fisher's LSD test).

Table 3. DMY (t ha^{-1}) and included carbon (C, kg ha^{-1}), nitrogen (N, kg ha^{-1}), carbon/nitrogen ratio (C/N), phosphorus (P, kg ha^{-1}), potassium (K, kg ha^{-1}) of biomass (green mass + roots) of pre-crops sampled in October 2012 before spring cereals.

Pre-crop	DMY	C	N	C/N	P	K
Red clover[a]	13.9*	6474*	321.8*	20*	41.3*	279.6*
Alsike clover[a]	13.4*	5993*	322.7*	19*	42.0*	296.0*
Lupine[a]	12.0*	4871*	268.0*	18*	30.6*	178.2*
Sweet clover[b]	11.8*	5302*	275.4*	19*	33.2*	263.7*
Alexandria clover[c]	10.6*	3336*	160.9*	21*	12.4*	99.0*
Crimson clover[c]	4.6	2004*	87.2*	23*	6.7	76.7*
Control (timothy)	5.4	1667	38.0	44	6.2	32.6
$LSD_{0.05}$	0.8	374	22.5	17	2.8	21.4

Note: LSD: least significant difference.
[a]Perennial.
[b]Biennial.
[c]Annual.
*Means within columns are significantly different from control at $p < .05$ (Fisher's LSD test).

however, DMY of lupine was lower (10.3 t ha^{-1}). In contrast, DMY of annual legumes did not differ from the control and remained, on average, 53% lower than that of other legumes. In the study of Fraser et al. (2004), DMY of crimson clover remained even lower compared to our results. The content of C, N, P and K of all the tested legumes was significantly higher (being on average up to 55% higher) than that of the control, for perennial and biennial legumes compared to annuals. Red and sweet clover contained the highest amounts of nitrogen (319.0 and 326.8 kg ha^{-1}, respectively), whereas the lowest rate of N was fixed by crimson clover (111.2 kg ha^{-1}). Similar levels of nitrogen uptake in red and sweet clover have been previously reported by Groya and Sheaffer (1985) and Deprez et al. (2004). However, considerably higher N uptake (178 kg ha^{-1}) of crimson clover compared to our results was measured in central Germany (Karpenstein-Machan & Stuelpnagel 2000).

The C/N ratio of all the tested legumes was favourable (20–25 depending on the species), being comparable to previously detected C/N ratios (Nykänen et al. 2008; Skuodiene et al. 2012; Talgre et al. 2012). The smaller the ratio and the greater the nitrogen content in biomass, the more nitrogen is mineralized into soil (Chaves et al. 2004). In this case, microorganisms are not using soil nitrogen for rebuilding their cells during degradation of organic matter (Janssen 1996).

At the end of the growing season (October 2012) DMY and nutrient content of red and alsike clover remained the highest among tested legumes as in July 2012, due to the good regrowth ability of these species (Table 3). However, DMY, and the content of C, N, P and K of sweet clover had significantly decreased, which may be explained by the lower regrowth ability of sweet clover compared to perennial legumes. Similarly as in July 2012, DMY and nutrient content of annual clovers remained significantly lower than that for other legumes, although the measured characteristics of Alexandria clover were considerably higher in October compared to July. The nitrogen uptake of red and alsike clover was 321.8 and 322.7 kg ha^{-1}, respectively. Late autumn total biological N fixation of red clover reached up to 218 kg ha^{-1} in the Finnish trial series (Känkänen et al. 1998). Lower N uptake in this study might have been caused by the colder climate and the shorter vegetation period. N uptake of lupine remained slightly lower than for perennial clovers, although it was found to be higher than (Lauringson et al. 2013), and equal to, red clover (Bender 2012). N uptake of Alexandria clover was almost twice as high as crimson clover, being comparable to N fixation found in vetch (Tarui et al. 2013). One reason for the low N content of crimson clover could be in the weaker and more fibrous root system compared to perennials, which could have been already partially decomposed by October (Bender & Tamm 2014). The C/N ratio of all the tested leguminous species was between 18 and 23, being slightly lower than that measured in July.

In conclusion, it can be summarized that the highest DMY, C, N, P and K content of this trial was in sweet, red and alsike clover, followed by lupine. We found high significant positive correlations between DMY, C N, P and K content of legumes ($r = 0.88$ -0.99; $p < .05$). Similar high correlations between the above-mentioned characteristics were also found by Skuodiene and Nekrosiene (2012).

The first-year after-effect of legumes (year 1)

All cereal species produced significantly higher grain yields in the subsequent year (year 1) after the pre-crop of legumes, compared to the control (Table 4). Spring and winter cereals were influenced differently by perennial, biennial and annual legume species. The yields of spring barley and wheat increased the most after red and alsike clover (115–132%), compared to timothy. In the recent study of Feiziene et al. (2016) there was found to be a considerably lower effect of leguminous pre-crop species (yellow lupine) on grain yield of spring wheat, which could be explained by the poor establishment of the legume stands. Contrary to other spring cereals, oat benefited less from legume pre-crops and produced quite uniform extra yields (46–58%), independently of preceding legume species. This can be explained by oat being less demanding on soil N and other nutrients (Forsberg & Reeves 1995). However, previous results from an organic trial have shown a higher extra yield of oat following red clover (63–70%) (Løes et al. 2011). The positive effect of pure sowings of leguminous pre-crops, as implemented in our study, has been shown to be considerably higher compared to the effect of legumes as catch crops (Känkänen et al. 2001; Olesen et al. 2007; Løes et al. 2011). In addition, the grain yield of spring cereals had a strongly significant correlation with DMY ($r = 0.72$; $p < .001$), C ($r = 0.76$; $p < .001$) and N content ($r = 0.80$; $p < .001$) of legume pre-crops in our trial.

In contrast to spring cereals, winter cereals produced the highest extra yields, following lupine and sweet clover as well as both annual clovers. Grain yield of rye increased by up to 529% following legumes compared to the low yield of control. The effect of a leguminous pre-crop on grain yield of winter wheat reached up to 252%. The lowest extra yield of winter wheat and rye were produced after red and alsike clover, which could be explained by poor overwintering. The high nitrogen level produced by red and alsike clover promoted lush growth of cereals, causing insufficient hardening of plants. Therefore, winter cereals were susceptible to snow mould and other types of winter injury, causing a decrease in yield. Snow mould may attack dormant plants in northern regions with prolonged snow cover (Matsumoto 2009). In winter of year 1, snow fell on unfrozen soil and lasted longer than average (140 days, average 98 days) causing damage by snow mould. However, the influence of sweet clover was different, as its coarse stems and roots decayed more slowly, leaving less nutrients in the soil for the autumn growth of winter cereals (Sweetclover 2014). In addition, we found weak but significant correlations between the grain yield of winter cereals and nutrient elements C ($r = 0.20$; $p < .05$) and N ($r = 0.27$; $p < .05$). The correlation between grain yield of winter cereals and DMY of legumes was not significant.

The ME content of all cereals increased significantly following the pre-crops of all the legumes, compared to the control (Table 5). The amount of ME increased by up to 132% for barley, 119% for spring wheat, 48% for oat, 429% for rye and 152% for winter wheat. The ME content of spring cereals increased significantly more after perennial and biannual pre-crops compared to annuals. Contrary to this, ME of rye increased the most after Alexandria and sweet clover, whereas ME of winter wheat increased the most after crimson and sweet clover. Compared to our study, the positive influence of perennial leguminous pre-crops on the ME content of barley and winter triticale remained

Table 4. The first-year after-effect of legumes on grain yield of cereals, kg ha^{-1}.

Pre-crop	Barley	Spring wheat	Oat	Rye	Winter wheat
Red clover[a]	5850*	5530*	4580*	3600*	3490*
Alsike clover[a]	5790*	5630*	4320*	3820*	4360*
Lupine[a]	5710*	4750*	4450*	4020*	5710*
Sweet clover[b]	5430*	4420*	4360*	4380*	6140*
Alexandria clover[c]	4900*	4120*	4210*	4870*	5700*
Crimson clover[c]	4130*	4430*	4270*	4120*	6220*
Control (timothy)	2520	2570	2890	920	2470
$LSD_{0.05}$	180	350	220	500	340

Note: LSD: least significant difference.
[a]Perennial.
[b]Biennial.
[c]Annual.
*Means within columns are significantly different from control at $p < .05$ (Fisher's LSD test).

Table 5. The effect of preceding crops on the amount of ME of cereals grain yield in year 1, GJ ha^{-1}.

Pre-crop	Barley	Spring wheat	Oat	Rye	Winter wheat
Red clover[a]	65.40*	65.63*	46.87*	42.11*	41.42*
Alsike clover[a]	64.73*	66.82*	44.21*	44.68*	51.74*
Lupine[a]	63.84*	56.37*	45.54*	47.02*	67.77*
Sweet clover[b]	60.71*	52.46*	44.62*	51.23*	72.87*
Alexandria clover[c]	54.78*	48.90*	43.09*	56.96*	67.65*
Crimson clover[c]	46.17*	52.58*	43.70*	48.19*	73.82*
Control (timothy)	28.17	30.50	29.58	10.76	29.31
$LSD_{0.05}$	2.01	4.15	2.25	5.85	4.04

Note: LSD: least significant difference.
[a]Perennial.
[b]Biennial.
[c]Annual.
*Means within columns are significantly different from control at $p < .05$ (Fisher's LSD test).

considerably lower in the study undertaken by Skuodiene and Nekrosiene (2012).

The second-year after-effect of legumes (year 2)

Grain yield of barley and oat sown after control (timothy) in year 2 was considerably higher (3600 and 3460 kg ha^{-1}, respectively) than that in year 1 (2520 and 2890 kg ha^{-1}, respectively) (Table 6). Higher yields of barley and oat after control in year 2 can be explained by especially favourable weather conditions, whereas these cereals suffered from a shortage of available nutrients in the top soil caused by an early drought in year 1. Barley and oat produced extra yields also in the second year after all the legume species compared to the control, although they remained lower than that in year 1. The highest extra yields of barley were harvested after red and alsike clover (28% and 26%, respectively). Extra yields of oat were comparatively equal after perennial and biennial legume species (up to 28%). The second-year significant positive after-effect of pure sowings of leguminous crops on cereal yield has also been found previously (Bullied et al. 2002; Talgre et al. 2009; Løes et al. 2011; Bender & Tamm 2014).

Extra yields of both cereal species remained the lowest, after annual legumes, being still significantly higher than the control. This can be due to the lower amount of nutrients left in the soil by Alexandria clover and crimson clover. Our results differ from those of Bender (2012), who found no positive effect of crimson clover on the yield of the preceding cereal crop. In year 2, no significant correlations between yield of cereals and DMY, C and N of legume pre-crops were found.

Barley and oat also produced a significantly higher amount of ME in year 2 compared to the control (Table 7), but it remained considerably lower than that in year 1. The average amount of ME after legumes increased by up to 28% for barley and 25% for oat compared to the control. The effect of annual legumes on spring cereals remained lower, similar to the first-year after-effect. Oat produced a lower amount of ME, compared to barley, also in year 2.

In the case of cereals as pre-crops, the highest yields of both barley and oat were harvested after winter wheat and rye (4170–4610 kg ha^{-1}) (Table 8). Barley produced a somewhat higher yield after winter wheat and rye compared to oat, whereas grain yields of barley and oat were similar after spring cereals.

Extra yields of barley and oat in year 2, produced by the combined effects of legumes and cereals, remained between 80 and 1390 kg ha^{-1} and for oat between 70 and 1120 kg ha^{-1} (Table 9). The best combinations of pre-crops for barley were sweet clover + rye, red clover + rye and red clover + winter wheat, producing extra yields of 37%, 32% and 28%, respectively. The lowest extra yields of barley were obtained after combination of Alexandria clover + barley, crimson clover + spring wheat and crimson clover + oat, and the extra yields were not significant.

Table 6. The second-year after-effect of legumes on grain yield of barley and oat, kg ha^{-1}.

	Grain yield	
Pre-crop	Barley	Oat
Red clover[a]	4610*	4330*
Alsike clover[a]	4530*	4320*
Lupine[a]	4390*	4310*
Sweet clover[b]	4450*	4430*
Alexandria clover[c]	3980*	3820*
Crimson clover[c]	3940*	3790*
Control (timothy)	3600	3460
$LSD_{0.05}$	130	140

Note: LSD: least significant difference.
[a]Perennial.
[b]Biennial.
[c]Annual.
*Means within columns are significantly different from control at $p < .05$ (Fisher's LSD test).

Table 7. The effect of preceding crops on amount of ME of cereals grain yield in year 2, GJ ha^{-1}.

	Grain yield	
Pre-crop	Barley	Oat
Red clover[a]	51.54*	44.31*
Alsike clover[a]	50.65*	44.21*
Lupine[a]	49.08*	44.11*
Sweet clover[b]	49.75*	45.34*
Alexandria clover[c]	44.50*	39.09*
Crimson clover[c]	44.05*	38.79*
Control (timothy)	40.25	35.41
$LSD_{0.05}$	1.45	1.43

Note: LSD: least significant difference.
[a]Perennial.
[b]Biennial.
[c]Annual.
*Means within columns are significantly different from control at $p < .05$ (Fisher's LSD test).

Table 8. The grain yield of barley and oat after cereals in year 2, kg ha^{-1}.

	Grain yield	
Cereal pre-crop	Barley	Oat
Barley	3960c	3940c
Oat	4110c	4020bc
Spring wheat	4030c	3920c
Winter wheat	4370b	4170ab
Rye	4610a	4280a
$LSD_{0.05}$	100	110

Notes: Means within each column followed by the same letter are not significantly different according to Fisher's LSD test. LSD: least significant difference; year 2: the second year after legumes.

Table 9. Combined effects of leguminous and cereal pre-crops on yield of barley and oat in year 2, kg ha^{-1}.

Leguminous pre-crop	Cereal pre-crop	Grain yield Barley	Grain yield Oat
Red clover[a]	Barley	4300*	4130*
	Oat	4600*	4430*
	Spring wheat	4310*	4140*
	Winter wheat	4860*	4590*
	Rye	4990*	4370*
Alsike clover[a]	Barley	4230*	4360*
	Oat	4620*	4280*
	Spring wheat	4610*	4230*
	Winter wheat	4370*	4280*
	Rye	4840*	4430*
Lupine[a]	Barley	4180*	4090*
	Oat	4050*	4160*
	Spring wheat	4230*	4100*
	Winter wheat	4680*	4490*
	Rye	4780*	4730*
Sweet clover[b]	Barley	4030*	4200*
	Oat	4240*	4450*
	Spring wheat	4110*	4220*
	Winter wheat	4690*	4560*
	Rye	5180*	4700*
Alexandria clover[c]	Barley	3720	3540
	Oat	3950*	3780*
	Spring wheat	3800	3860*
	Winter wheat	4160*	3880*
	Rye	4270*	4030*
Crimson clover[d]	Barley	3790	3900*
	Oat	3700	3600
	Spring wheat	3610	3470
	Winter wheat	4200*	3900*
	Rye	4380*	4090*
Control (timothy)	Barley	3500	3370
	Oat	3580	3440
	Spring wheat	3530	3400
	Winter wheat	3600	3470
	Rye	3790	3620
	$LSD_{0.05}$	300	310

Note: LSD: least significant difference.
[a]Perennial.
[b]Biennial.
[c]Annual.
*Means within columns are significantly different from control at $p < .05$ (Fisher's LSD test).

The best combinations for oat were red clover + winter wheat, lupine + rye and sweet clover + winter wheat (extra yields 32%, 31% and 31%, respectively). The lowest extra yields of oat obtained after combinations of Alexandria clover + barley, crimson clover + spring wheat and crimson clover + oat, which were not significant.

The highest grain yields were gained by combinations of biennial or perennial legume + winter cereal; the lowest yields were gained by the combination of annual legume + spring cereal.

Overall, we found that pure sowings of legumes as pre-crops had a positive influence on the yield of consecutive cereals in an organic trial setting. All the cereal species produced significant extra yields in the first and the second consecutive years following leguminous pre-crops. The largest amount of organic matter and nutrients was left in soil by biennial and perennial legumes, whereas annual legumes had a relatively lower ability to fix N. The best pre-crops for spring cereal species were red and alsike clover followed by lupine. In contrast, the best pre-crops for winter cereals were sweet clover and annual clover species.

High-quality green manure produced by leguminous species is an important component of crop rotation in organic farming, in order to maintain high cereal productivity and to improve soil quality for future cropping systems. There is a large number of legume species available, but there is a need to find out which are better suitable for variable climate conditions and farming practices. Increasing the number of species used in organic crop rotations enables to utilize specific advantages of the less-used and novel leguminous pre-crops and to support sustainable yield of cereals over the longer term. Because of expanding organic production, there is a need for the growing of locally adapted legumes worldwide. According to the results of our study, the proper selection of green manure species enables to increase the yield of subsequent crops and thereby improve efficiency of organic crop rotation. This study provides useful recommendations for selecting appropriate leguminous pre-crop species for organic farmers and advisors.

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References

Bender A. 2012. Varase punase ristiku (*Trifolium pratense* L.), hulgilehise lupiini (*Lupinus polyphyllus* Lindl.) ja inkarnaatristiku (*Trifolium incarnatum* L.) väetusväärtus haljasväetiskultuurina kasvatamisel [Fertilization value of early red clover (*Trifolium pratense* L), Washington lupin (*Lupinus polyphyllus* Lindl.) and crimson clover (*Trifolium incarnatum* L.) as green manure crops]. J Agri Sci. 1:3–11. In Estonian with English summary.

Bender A, Tamm S. 2014. Fertilization value of early red clover, Washington lupin and crimson clover as green manure crops. Research for Rural Development 2014. Annual

20th International Scientific Conference Proceedings. 1:84–88.
Billings P, Brian K, Mellor M, Morgan C. 2010. Managing clover for Better Returns. Beef and Sheep BRP Manual. 4:1–16.
Brink GE. 1990. Seasonal dry matter, nitrogen and dinitrogen fixation patterns of crimson clover and subterranean clovers. Crop Sci. 30:1115–1118.
Bullied WJ, Entz MH, Smith SR, Bamford KC. 2002. Grain yield and N benefits to sequential wheat and barley crops from single-year alfalfa, berseem and red clover, chickling vetch and lentil. Can J Plant Sci. 82:53–65.
Chaves B, DeNeve S, Hofman G, Boeckx P, Van Cleemput O. 2004. Nitrogen mineralization of vegetable root residues and green manures as related to their (bio)chemical composition. Eur J Agron. 21:161–170.
Deprez B, Lambert R, Decamps C, Peeters A. 2004. Nitrogen fixation by red clover (*Trifolium pratense*) and lucerne (*Medicago sativa*) in Belgium leys. In: Lüscher A, Jeangros B, Kessler W, Huguenin O, Lobsiger M, Millar N, Suter D, editors. Land use systems in grassland dominated regions. Book of abstracts. Proc 20th Eur Grassl. Luzern; 87 p.
Döring T. 2013. Manifold green manures. Part IV: large Birdsfoot Trefoil, Meadow Pea and White Sweet Clover. Org Grow. 25:26–27.
Döring T, Boufartigue C. 2013. Manifold green manures. Part 2: alsike and crimson clovers. Org Grow. 23:28–29.
Estonian weather service [Internet]. [cited 2016 May 9] Available from: http://www.ilmateenistus.ee/kliima/kliimanormid/sademed/?lang=en
Fairey DT. 1986. Alsike clover. Agric Can Public. 1264/E. Ottawa: Agriculture Canada; 18 p.
Feiziene D, Feiza V, Povilaitis V, Putramentaite A, Janusauskaite D, Seibutis V, Slepetys J. 2016. Soil sustainability changes in organic crop rotations with diverse crop species and the share of legumes. Acta Agric Scand, Sect B. 66:36–51.
Forsberg RA, Reeves DL. 1995. Agronomy of oats. In: Welch W, editor. The oat crop. Production and utilization. London: Chapman & Hall; p. 224–251.
Fraser J, McCartney D, Najda H, Mir Z. 2004. Yield potential and forage quality of annual forage legumes in southern Alberta and northeast Saskatchewan. Can J Plant Sci. 84:143–155.
Graves WL, Williams WA, Thomsen CD. 1996. Berseem clover: A winter annual forage for California agriculture. University of California, Division of Agriculture and Natural Resources, Publ. No. 21536; 12 p.
Groya FL, Sheaffer CC. 1985. Nitrogen from forage legumes: harvest and tillage effects. Agron J. 77:105–109.
Hannaway DB, Larson C. 2004. Berseem Clover (*Trifolium alexandrinum* L.) [Internet]. [cited 2015 Dec 8]. Available from: http://forages.oregonstate.edu/php/fact_sheet_print_legume.php?SpecID=196&use=Forage
[IUSS] Working Group WRB. 2015. World reference base for soil resources 2014, update 2015 international soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome.
Janssen BH. 1996. Nitrogen mineralization in relation to C:N ratio and decomposability of organic materials. Plant Soil. 181:39–45.
Kadziulene Z. 2004. Lucerne, white clover and red clover in leys for efficient N use. In: Lüscher A, Jeangros B, Kessler W, Huguenin O, Lobsiger M, Millar N, Suter D, editors. Land use systems in grassland dominated regions. Proceedings of the 20th European Grassland Federation, Luzern. Grassl Sci Eur. 9:492–494.
Känkänen H, Kangas A, Mela T, Nikunen U, Tuuri H, Vuorinen M. 1998. Timing incorporation of different green manure crops to minimize the risk of nitrogen leaching. Agric Food Sci Finland. 7:553–567.
Känkänen H, Eriksson C, Räkköläinen M, Vuorinen M. 2001. Effect of annually repeated undersowing on cereal grain yields. Agric Food Sci Finland. 10:197–208.
Karpenstein-Machan M, Stuelpnagel R. 2000. Biomass and nitrogen fixation of legumes monocropped and intercropped with rye and rotation effects on subsequent maize crop. Plant Soil. 218:215–232.
Knight WE. 1985. Miscellaneous annual clovers. In: Taylor NL, editor. Clover science and technology. Madison (WI): American Society of Agronomy, Inc.; p. 547–562.
Kurlovich B, Stoddard FL, Earnshaw P. 2008. Potential and problems of *Lupinus polyphyllus* Lindl. Domestigation. In: Palta JA, Berger JD, editors. Lupins for health and wealth. Proceedings of the 12th International lupin conference Sept 14–18; Fremantle (WA): International Lupin Association; p. 304–307.
Lambers H, Clements JC, Nelson MN. 2013. How a phosphorus-acquisition strategy based on carboxylate exudation powers the success and agronomic potential of lupines (*Lupinus, Fabaceae*). Am J Bot. 100:263–288.
Lauringson E, Talgre L, Makke A. 2013. Large-leaved lupin (*Lupinus polyphyllus* Lindl.) and early red clover (*Trifolium pratense* L.) as green manure crops. Proceeding Latvian Acad Sci Sect B. 67:242–246.
Lloveras J, Iglesias I. 2001. Morphological development and forage quality changes in crimson clover (*Trifolium incarnatum* L.). Grass Forage Sci. 56:395–404.
Løes AK, Henriksen TM, Eltun R, Sjursen H. 2011. Repeated use of green-manure catch crops in organic cereal production – grain yields and nitrogen supply. Acta Agric Scand, Sect B. 61:164–175.
Matsumoto N. 2009. Snow molds: a group of fungi that prevail under snow. Microbes Environ. 24:14–20.
Neumann G, Massonneau A, Martinoia E, Römheld V. 1999. Physiological adaptation to phosphorus deficiency during proteoid root development in white lupin. Planta. 208:373–382.
Nykänen A, Granstedt A, Jauhiainen L, Laine A. 2008. Residual effect of clover-rich leys on soil nitrogen and successive grain crops. Agric Food Sci. 17:73–87.
Olesen JE, Hansen EM, Askegaard M, Rasmussen I. 2007. The value of catch crops and organic manures for spring barley in organic arable farming. Field Crops Res. 100: 168–178.
Riesinger P, Herzon I. 2010. Symbiotic nitrogen fixation in organically managed red clover-grass leys under farming conditions. Acta Agric Scand Sect B. 60:517–528.
Rice WA. 1980. Seasonal patterns of nitrogen fixation and dry matter production by clovers grown in the Peace River region. Can J Plant Sci. 60:847–858.
Ross SM, King JR, Izaurralde RC, O'Donovan JT. 2009. The green manure value of seven clover species grown as annual crops on low and high fertility temperate soils. Can J Plant Sci. 89:469–476.

Sikk V. 2004. Söötade keemilise koostise ja toiteväärtuse tabelid [Chemical composition and nutritive value of feeds]. ETartu: EPMÜ Loomakasvatusinstituut; 122 p. Estonian.

Skuodiene R, Nekrosiene R. 2012. The effects of perennials as green manure on cereal productivity and disease incidence. Span J Agric Res. 10:44–45.

Skuodiene R, Nekrošiene R, Repšiene R. 2012. Residual effects of perennial grasses as green manure on soil agrochemical properties and spring barley. Agriculture. 99:237–246.

Sweetclover Production in Western Canada. 2014. [Internet]. [cited 2015 Dec 21]. Available from: http://www1.foragebeef.ca/$Foragebeef/frgebeef.nsf/all/aafc51

Sweetclovers. 2007. Managing cover crops profitably. 3rd ed. [Internet]. [cited 2015 Dec 12]. Available from: http://www.mccc.msu.edu/documents/ManagingCCProfitably.pdf

Talgre L, Lauringson E, Roostalu H, Astover A, Eremeev V, Selge A. 2009. The effects of pure and undersowing green manures on yields of succeeding spring cereals. Acta Agric Scand Sect B. 59:70–76.

Talgre L, Lauringson E, Roostalu H, Astover A, Makke A. 2012. Green manure as a nutrient source for succeeding crops. Plant Soil Environ. 58:275–281.

Tarui A, Matsushima A, Asakura S, Yamawaki K, Hattori R, Daimon H. 2013. Enhancement of nitrogen uptake in oat by cutting hairy vetch grown as an associated crop. Plant Root. 7:83–91.

Viil P, Võsa T. 2005. Liblikõielised haljasväetised [Leguminous green manures]. EMVI infoleht nr 148, 16 p. Estonian.

Wyngaarden SL, Gaudin AC, Deen W, Martin RC. 2015. Expanding Red Clover (*Trifolium pratense*) usage in the corn-soy-wheat rotation. Sustainability. 7:15487–15509.

III

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The characteristics of spring cereals in changing weather in Estonia

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Abstract. The objective of this investigation was finding out the impact of weather on yield, length of growing period, plant height, lodging resistance and protein content of spring cereals over 19 years (1991–2009). Two varieties per each crop were selected for testing. Historical weather and crop yield data from the Jõgeva Plant Breeding Institute were analyzed by the linear correlation analysis. To estimate the variation of grain yield, the minimum and maximum values, averages and coefficients of variation were calculated.

It can be stated that the both stress conditions – drought and excess precipitation caused decrease of yield and quality of all the crops. The highest yields developed in 180–250 mm precipitation range from sowing to maturity. Oat requires more moisture than wheat and barley. Significant positive correlation between the amount of precipitation and oat yield was found when three years of severe lodging were eliminated. Positive correlation between yield and plant height was found. In the years of severe lodging there was remarkable yield decrease of oat. Yield of oat and barley had negative correlation with sunshine hours in June. The same correlation for wheat was not significant. Extra-low protein content for all the cereals, especially for wheat, formed in a cool year with the lowest sum of sunshine hours during the whole growing period (2009). For oat and barley positive correlation between sunshine hours in June and protein content was found. For formation of higher protein content, warm and dry weather conditions are required. Protein content was inversely associated with yield.

Key words: spring wheat, barley, oat, precipitation, temperature, yield, quality

INTRODUCTION

In fluctuating weather conditions variation of yield and other characteristics may increase. Heavy rains and drought periods influence yield, quality and the length of growing period. In selecting crops and varieties for a particular climatic environment a farmer or a breeder must make a choice between high yield potential or stability of yield. Under ideal growing conditions certain varieties produce high yields, but they may be sensitive to stress conditions. Since crops are grown under varying environmental conditions, the ability to adapt quickly to stress is important (Fox & Rosielle 1982; Gusta & Chen, 1987). The response of a plant to a stress depends on its genetic potential to adapt, the duration of exposure, and stage of growth (Gusta & Chen, 1987).

Water deficits affect every aspect of plant growth from germination to seed set and final yield. Water stress at certain stages of growth is more injurious than at other stages. In cereals, the critical period is usually just before reproductive organ formation and right after pollination (Kramer, 1980; Forsberg & Reeves, 1995; Araus, 2002; Kutchera et al., 2010).

Ensuring the stability of crop varieties across years is a critical breeding goal when dealing with the uncertainty of climate change. Many researchers believe that higher temperature, drought and rainfall excess caused by climate change will depress on crop yield in the nearest future (Márton, 2005; Watts, 2005; Márton et al., 2007; Tammets, 2007; Márton, 2008a; 2008b). There are several agricultural investigations focused on understanding the relation between mean climate change and crop production (Karing et al., 1999; Rosenzweig & Iglesias, 2003; Márton, 2005; Watts, 2005).

The extent and yield of agriculture in high latitude regions is largely determined by thermal parameters (Carter, 1996). Estonia belongs to the Atlantic continental region of the temperate zone. Summers are moderately warm. The climate is humid because precipitation exceeds evapotranspiration. Nevertheless, there are often droughts during the summer period. A drought is a complex phenomenon that is difficult to describe accurately. In this paper, we focus only on the agricultural drought. The uncertainty about weather conditions is one of the key risk factors associated with crop production. In the last years, extreme dry as well as extreme wet periods have occurred in Estonia (Tammets, 2007).

The objective of this investigation was finding out the impact of weather on yield, length of growing period, plant height, lodging resistance and protein content of spring cereals over 19 years.

MATERIALS AND METHODS

In this paper the effect of weather on yield and quality characteristics was evaluated from several experiments in Estonia during the years of 1991–2009. The field trials were conducted at the Jõgeva Plant Breeding Institute, on soddy-podzolic soil. Fertilizer level $N_{70}P_{16}K_{29}$ was used for oat and $N_{90}P_{20}K_{38}$ for barley and wheat. Chemical control of weeds was carried out every year and insects were controlled only in the years of severe attacks. Seeding rate of 500 (barley) and 600 (wheat, oat) germinating seeds per m² was used. The plot size was 10 m² in 3 replicates. The trials were organised by randomised complete block design. Three different cereal crops were included – spring wheat, barley and oats. Two varieties per each crop – the Estonian barley varieties Anni, Elo, the oat varieties Villu and Jaak and the foreign varieties Satu (Sweden) and Munk (Germany) were selected.

Data collected included: yield, plant height, the incidence of lodging (1–9 points scale where 1 – severe lodging, 9 – no lodging), protein content, the days from sowing to heading, from heading to maturity.

Weather data for this experiment – precipitation and sum of effective temperatures (over +5°C) for these growth phases, and the sum of sunshine hours by months from May to August were available from the meteorological station of the Jõgeva Plant Breeding Institute (Fig. 1, 2). The years with exceptionally low total rainfall were 1992, 1999, 2002 and 2006. In 2007 there was an early drought before heading when especially wheat and oat were sensitive. The exceptionally high rainfall was in 1998. The years of higher than average rainfall (>300 mm) were also in 1991, 2000, 2001, 2003, 2004 but its distribution during the vegetation period was different.

The experiment years were characterized by frequent extremes of weather. Six years had an over rainfall and four years had drought. Nine years had closer to average rainfall that was more evenly distribution during the growth. The unfavorable effects of weather anomalies (drought, over-abundance of water) on yield and quality were registered.

Historical weather and crop yield data from the Jõgeva Plant Breeding Institute were analyzed with linear correlation analysis. Data were analyzed by factorial analysis of variance using the Agrobase II statistics software. To estimate the variation of grain yield, the minimum and maximum values, averages (*avg*) and coefficients of variation (*CV*) were calculated.

RESULTS AND DISCUSSION

The actual final yield and quality of a crop is determined by many factors: weather, crop variety, fertiliser supply, soil conditions, occurrence of pests and diseases. When the crop is sufficiently supplied with nutrients, yield and quality variation depends mostly on weather conditions. In our investigation all the spring crops reacted somewhat differently to weather conditions.

The increase of the annual number of extreme wet and dry days together indicates to the rising trend of the extreme precipitation events in Estonia in 1957–2006 (Tammets, 2007). In July 2006, the precipitation was only about 22% of the average level, which caused big harm to crops; the heavy precipitation in summer 2004 caused flooding in the fields of many districts all over Estonia (Tammets, 2007). A recent wave of higher than average temperature was experienced throughout Central Europe during 2000, 2001 and 2003 (Trnka et al., 2007). In Estonia we experienced during 2000–2003 the highest sum of effective temperatures within the tested 19 years. It was found by Karing et al., (1999) that the degree-days above 0 and 5°C have had a noticeably positive trend (about 1 degree-day per year) for almost 2 centuries in Estonia, and from this follows an important conclusion that heat accumulation has increased in early spring in the Estonian area. During our trial period we have also noticed the shift to earlier sowing time. High values of precipitation in Estonia are mainly of two different kinds. Firstly, heavy rainfall lasting for a few hours and secondly, multi-day wet spells, which are connected with the cyclones bringing heavy precipitation (Scientific Handbook…, 1990).

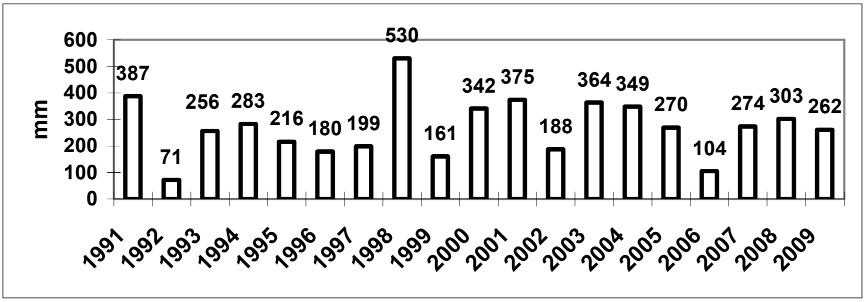

Figure 1. Precipitation of the growing period of spring cereals in 1991–2009.

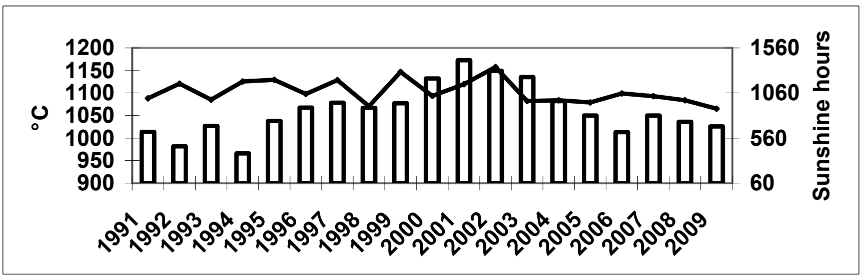

Figure 2. Sum of effective temperatures (> +5°C) and sunshine hours of growing period in 1991–2009.

Yield. The unfavorable effects of weather anomalies (drought, over-abundance of water) on the yield formation, quantity and quality depended on the time of vegetation when they were experienced and the period for which they lasted.

Variation in yield was high during the years (Fig. 3). Yield variation depended mostly on the year (52%) (Table 1) but crop x year interaction was also important (27%). Crop had minor influence to the yield variation (12%). The yields differed over three times for oat and barley and over two times for wheat (Table 2). The years of high yield capacity for all the spring cereals were 1993, 1995, 1996, 1997 and 2000. Higher yield was produced mostly in the years without extremely low or high amount of precipitation.

All the crops are sensitive to drought for any significant period especially at stem elongation, heading and flowering when the leaves are exposed to high temperatures, photosynthesis slows down and plant respiration increases (Forsberg & Reeves, 1995; Araus, 2002; Kutchera et al., 2010). The result is a loss of yield. The yields of all the crops in our trials were low in the years of drought (1992, 1999, 2006) and in early drought in June (2007). In Czech Republic only extremely dry seasons lead to a significant reduction of the spring barley yields. Forty years (1961–2000) data showed the tendency for more intensive droughts at the majority of the analyzed stations (Trnka, 2007).

The biggest yield loss for oat occurred when there was severe lodging or serious drought. Therefore the yield of oat was the most unstable (*CV* = 29%). The yields of barley and wheat varied less (CV = 22%). Oat was the most sensitive to the lack of water from sowing to heading. Oat requires more moisture to produce a given unit of dry matter than any other cereal except rice (Forsberg & Reeves, 1995). Significant positive correlation between the amount of precipitation and oat yield was found when the years of severe lodging (1998, 2001 and 2003) were eliminated: from sowing to heading (R = 0.73**), two weeks before heading (R = 0.52*) and the whole period from sowing to maturity (R = 0.55*). The same relationship between rainfall quantity during the vegetation period and yield was also found in Canada (Kutchera, 2010). Scientists from Czech Republic found that the seasonal water balance (April–June) significantly influences the spring barley production. Coefficients of correlation varied in individual districts from 0.19 to 0.70 (Trnka et al., 2007).

The yield of oat and barley had negative correlation with sunshine hours in June (oat R = –0.60**, barley R = –0.58*). The same correlation for wheat was not significant. Unsuitable for formation of high yield were also the years of excess precipitation (1998 especially for wheat and oat), 2003 and 2001 (oat and barley). All mentioned years moderate to severe lodging was estimated. Yield drop in Hungary (Márton, 2008b) in the very wet year was 43%, in our trial period 22% drop for oat and wheat was estimated in 1998.

High yield of all the crops formed in the years of moderate precipitation and temperature (1993, 1997). All the cereals reached the yield maximum in these years exceeding 7 t ha^{-1}. In the most unfavourable years the yields of oat and barley were close to 2,5 t ha^{-1} and wheat 3,3 t ha^{-1}.

Although the spring crops reacted somewhat differently still there were found significant positive correlations between the grain yields of the three crops over the years 0,65**–0,75** (Table 3).

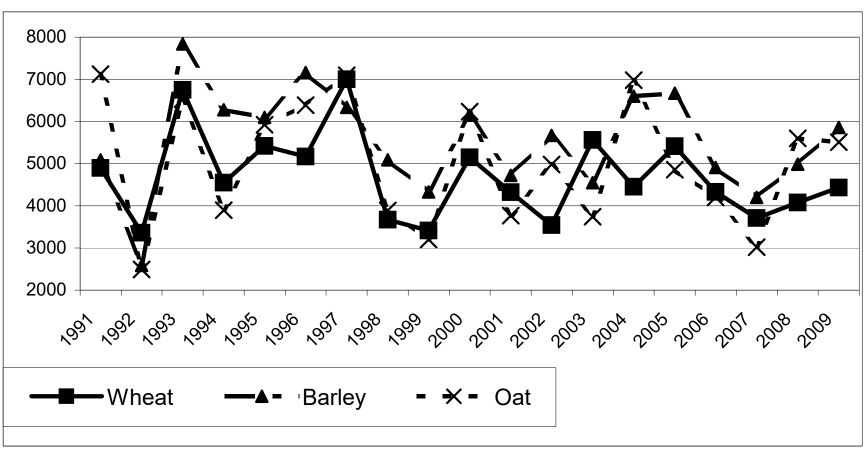

Figure 3. The average grain yield of spring cereals in 1991–2009.

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Lodging. It has been estimated that lodging can reduce yields up to 40% depending on its severity and time of occurrence (Fischer & Quail, 1990). Weather conditions explained 38% of the variation of lodging and co-effect of year x crop was 37%. All the crops lodged in unfavourable years, mainly the years of excess precipitation or heavy thunderstorms. Negative correlation between lodging and the amount of precipitation from sowing to heading was found (R = –0.54* wheat, R = –0.53* oat, R = –0.51* barley). Moderate lodging (6–7 points) had no considerable effect to yield of all the crops. As average of the years oat lodged the most. In two years (1998, 2003) out of 19, oat had severe lodging (1.7 and 2.2 points respectively). No lodging of barley and wheat over 5 points occurred. Despite the considerable differences in the lodging of the crops during the years there were positive correlations between the lodging of all the cereals (R = 0.52*–0.60**).

Plant height. From environmental conditions plant height foremost is affected by nutrients, water, temperature and sunshine (Coffman & Frey, 1961). Drought conditions, especially early drought, decreased plant height. In our trials there was positive correlation between plant height and grain yield (R = 0.67** wheat, R = 0.62** oat, R = 0.43* barley). But when plant height increases the situation may change, as longer plants are more prone to lodging. Plant height was the most depending on the weather of the year (43%) and crop (38%). The oat plants had the highest straw length. The difference between maximum and minimum plant height for oat was 67 cm, barley 41 cm and wheat 35 cm. Plant height of oat varied the most (CV = 20%). There was similar reaction of plant height of all the cereals to weather conditions. Strong positive correlation between the crops was found (R = 0.83***–0.88***). Plants grew taller in the years of higher precipitation and less sunshine hours. Positive correlations between amounts of precipitation from sowing to heading were found (R = 0.48* wheat, R = 0.82*** barley, R = 0.66** oat).

Growing period from sowing to heading. There was similar length of the period from sowing to heading of all the cereals (59–60 days) (Table 4). In the drought years the period was 51–52 days and in cooler and more rainy years it extended up to 65–68 days. Strong positive correlation between the crops was found (R = 0.84***–0.93***). This period was mainly depending on the weather of the year (77%). Sunny weather in June decreased the period from sowing to heading. There was negative correlation between the length of this period and sunshine hours in June for all the cereals (R = –0.58* wheat, R = –0.60* oat, R = –0.73*** barley).

Growing period from heading to maturity. This period of wheat was longer than that of barley and oat (respectively 46, 36 and 39 days). It extended in cooler and rainier years. The longest period from heading to maturity of all the cereals was in 2008 (53–60 days) exceeding the crops average by 11–21 days. Difference in length of the period from heading to maturity in maximum was even more than 3–4 weeks. Compared to the period from sowing to heading, it varied more – CV = 13% for wheat, 17% for barley, and even 22% for oat. This period was depending not only on the weather of the year (51%) but also on the crop (25%).

Growing period from sowing to maturity. Spring wheat had the longest period from sowing to maturity in most of the years. The spring crops length of growing period differed in maximum of 28–40 days. Cool and wet weather increased the length of total growing period. There was positive correlation between the length of the whole growing period and the sum of precipitation from sowing to maturity (R = 0.49* wheat, *R* = 0.46* oat, *R* = 0.40* barley). The shortest growing period was in the years of drought. This period depended on the weather of the year (61%) but also from the crop (21%). The length of growing period varied similarly. The correlation coefficients of this trait between the crops were high (*R* = 0.76***–0.90***).

Protein content. The variation of protein content was depending from weather of the year (39%), crop (35%) and their co-effect (12%). The protein was higher in the dryer years when the yield was lower (1992, 1999, 2002, 2006 and 2007 – early drought). Protein content was inversely associated with yield (*R* = –0.45* wheat and oat, *R* = –0.46* barley). Positive correlation between sunshine hours in June and protein content (oat *R* = 0.54*, barley *R* = 0.59*) was found. Average protein content of wheat was over 2% higher than that of barley and oat. Variation coefficients of the crops were similar (10–12%). Exceptionally low protein content, especially for wheat, was measured in 2009. This was a cool year and the number of accumulated sunshine hours during the whole growing period was the lowest in the tested 19 years. The crops reacted to the weather conditions by rather similar pattern. There were positive correlations between the crops (*R* = 0.65*–0.67**).

Table 1. The share of factors in the total variation %.

Source of the variation	Grain yield	Lodging resistance	Plant height	Growing time: Sowing to heading	Growing time: Heading to maturity	Growing time: Sowing to maturity	Protein content
Year	52	38	43	77	51	61	39
Crop	12	5	38	1	25	21	35
Crop by year	27	37	11	15	11	15	12
Variety	1	1	2	3	ns	1	5
Total	93	80	84	96	87	98	91

Table 2. Variation of yield, lodging, plant height and protein content of spring cereals during 1991–2009.

	Grain yield kg ha^{-1}			Lodging resistance, 1–9 points			Plant height Cm			Protein content %		
	Wheat	Barley	Oat	Wheat	Barley	Oat	Wheat	Barley	Oat	Wheat	Barley	Oat
Avg	4,695	5,533	5,009	8.2	8.4	7.6	87	69	98	14.2	12.0	11.6
Min	3,360	2,590	2,490	5.8	5.8	1.7	64	44	60	10.6	9.5	9.3
Max	7,000	7,840	7,100	9.0	9.0	9.0	99	85	127	16.7	14.5	14.3
CV	22	22	29	11	12	31	13	17	20	11	10	12

Table 3. The correlation coefficients (*R*) between the characteristics of spring cereals during 1991–2009.

	Grain yield	Lodging resistance	Plant height	Growing period: Sowing to heading	Growing period: Heading to Maturity	Growing period: Sowing to maturity	Protein content
Wheat/barley	0.67**	0.54**	0.86***	0.84***	0.68**	0.76***	0.65**
Wheat/oat	0.65**	0.60**	0.88***	0.93***	0.89***	0.87***	0.67**
Barley/oat	0.75**	0.52*	0.83***	0.89***	0.74***	0.90***	0.65**

* significance at $p< 0.05$; ** significance at $p<0.01$; *** significance at $p<0.001$; ns – non-significant

Table 4. The variation of growing period of spring cereals during 1991–2009.

	Sowing to heading, days			Heading to maturity, days			Sowing to maturity, days		
	Wheat	Barley	Oat	Wheat	Barley	Oat	Wheat	Barley	Oat
Avg	60	59	60	46	35	39	106	94	99
Min	52	51	52	34	28	28	90	83	80
Max	66	68	65	57	53	60	118	113	120
CV	7	7	6	13	17	22	7	8	11

CONCLUSIONS

Long-term experiments are ideal for evaluating the complex influences of weather to yield and other characteristics. It can be stated that biological yield potential is important but in the analysed test period the weather in Estonia was quite fluctuating, influencing both – the yield and agronomic potential. The both stress conditions – drought and excess precipitation caused decrease of yield and quality of all the crops. The highest yields formed in 180–250 mm precipitation range from sowing to maturity. Above and below this range of rainfall yields mostly decreased. Yield of oat and barley had negative correlation with sunshine hours in June (oat R = –0.6**, barley R = –0.58*). The same correlation for wheat was not significant.

In the years, when weather conditions were not favorable for straw growth, yields tended to be lower. In our data series was found positive correlation between yield and plant height. But when plant height increases the situation may change, as longer plants are more prone to lodging. In the years of severe lodging there was remarkable yield decrease of oat.

The lowest protein content was formed in cool year with the lowest sum of sunshine hours during the whole growing period (2009). Therefore can be concluded that for formation of higher protein content warmer and dryer weather conditions are required. Protein content was inversely associated with yield (R = –0.45* wheat and oat, R = –0.46* barley). Positive correlation between sunshine hours in June and protein content (oat R = 0.54*, barley R = 0.59*) was found.

Summing up our findings can be concluded that the more the frequency of weather extremes increase, the more there appear variation in yield and other characteristics and the more adaptation ability in the current location is of major importance. One of the most important impacts of climate change in Estonia is the increase of extreme wet and extreme dry periods and challenge is the prolonging of the total growing season. As different spring crops reacted somewhat differently to weather conditions, cultivation of various crops can erase risks. Thus, farmers must take into consideration the changeability of climate to optimize their crop and variety selection and management in the nearest future.

REFERENCES

Araus, J.L. 2002. Physiological Basis of the Processes Determining Barley Yield Under Potential and Stress Conditions: Current Research Trends on Carbon Assimilation. In: Slafer, A., Molina-Cano, J.L., Savin, R., Araus, J.L. & Ramagosa, I. (eds.): *Barley Science: Recent Advances from Molecular Biology to Agronomy of Yield and Quality.* Food Products Press, USA, pp. 269–306.

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

Coffman, F.A. & Frey, K.J. 1961. Influence of climate and physiologic factors on growth in oats. In: Coffman, F.A. (ed.): *Oats and Oat Improvement.* Madison, USA, pp. 420–464.

Gusta, L.V. & Chen, T.H.H. 1987. The physiology of water and temperature stress. In: Heyne, E.G. (ed.). *Wheat and wheat improvement.* USA, pp. 115–150.

Fischer, R.A. & Quail, K.J. 1990. The effect of major dwarfing genes on yield potential in spring wheat. *Euphytica* **46**, 51–56.

Fox, P.N. & Rosielle, A.A. 1982. Reference sets of genotypes and selection for yield in unpredictable environments. *Crop Sci.* **22**, 1171–1174.

Forsberg, R.A. & Reeves, D.L. 1995. Agronomy of oats. In: Welch, W. (ed.). *The Oat Crop. Production and utilization.* Chapman and Hall, London, pp. 224–251.

Karing, P., Kallis, A. & Tooming, H. 1999. Adaptation principles of agriculture to climate change. *Climate Research* **12**, 175–183.

Kramer, P.J. 1980. Drougth, stress and the origin of adaptions. In: Turner, N.C. & Kramer, P.J. (eds.). *Adaption of Plants to water and High Temperature Stress.* John Wiley and Sons, New York, pp. 7–20.

Kutchera, H.R., Warlandb, J.S. & Brandtc, S.A. 2010. Temperature and precipitation effects on canola yields in Saskatchewan, Canada. *Agricultural and Forest Meteorology,* **150**(2), 161–165.

Márton, L. 2005. Disasters as drought-, and rainfall excess and artificial fertilization effects on crop yield. *Intern. Conf. on Energy, Environment and Disasters–INCEED2005 Charlotte, 24–30 July, 2005*. ISEG, Charlotte, pp. 49–50.

Márton, L., Pereda, M.P. & Mohinder, S.G. 2007. Long-term studies of crop yields with changing rainfall and fertilization. *Agricultural Engineering Research* **13,** 37–47.

Márton, L. 2008a. Impact of Rainfall, Liming, Nitrogen (N), Phosphorus (P2O5), Potassium (K2O), Calcium (CaO), Magnesium (MgO) Mineral Fertilization on Triticale (x*Triticosecale* Wittmack) Yield in a Monoculture in Hungary. *Cereal Research Communications* **36**(2)*,* 333–341.

Márton, L. 2008b. Effect of Precipitation and Fertilization on the Changes in Soil Organic Carbon (SOC). *Cereal Research Communications* ***36***(4), 611–622.

Rosenzweig, C. & Iglesias, A. 2003. Potential impact of climate change on world food supply. *Data sets from a major crop modeling study. Socioeconomic Data and Applications Center*. Columbia University, New York, USA, 28 pp.

Saini, H.S. & Aspinall, D. 1981. Effect of water deficit on sporogenesis in wheat (*Triticum aestivum* L). *Ann. Bot.* **48**, 623–644.
Scientific Handbook of the Climate of the USSR. 1990. Gidrometeoizdat, Leningrad, **3**, 1–6. (in Russian).
Tammets, T. 2007. Distribution of extreme wet and dry days in Estonia in last 50 years. *Proc. Estonian Acad. Sci.* **13(**3), 252–259.
Trnka, M., Hlavinka, P., Semerádová1, D., Dubrovský, M., Z. Žalud, Z. & Možný, M. 2007. Agricultural drought and spring barley yields in the Czech Republic. *Plant soil environ*. ***53***(7), 306–316.
Watts, L. 2005. *Impact of climate change on crops worse than previously thought.* Royal Society, London, United Kingdom, p.5.

IV

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Spring cereals performance in organic and conventional cultivation

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Abstract. The field trials were carried out at the Jõgeva Plant Breeding Institute to compare grain yield and quality characteristics of spring wheat, barley and oat in organic and conventional conditions. Thirteen varieties of each cereal crop were tested during the four trial years (2005–2008). By the results turned out that all the spring crops were able to produce comparatively high yields in organic conditions after a suitable precrop. Oat as the most unpretentious crop was the highest yielding in organic trial and had the best weeds suppressing ability among the spring cereals. The most widely spread weeds were (*Chenopodium album)* and (*Viola arvensis*). Among the quality traits protein content was the most influenced by the management regime having evident decrease in organic conditions. A yield gap between organic and conventional production depended on crop, precrop and growing conditions.

Key words: spring wheat, barley, oat, yield, quality, weeds, organic, conventional

INTRODUCTION

The lack of information on the relative performance of cereal crops and their modern varieties under organic conditions is a limitation for organic farmers. In Europe Vogt-Kaute (2001), Lammerts van Bueren (2003), and (Wolfe et al., 2008) have tested and summarized results of organic trials and drawn out several aspects of organic plant breeding and crop production. In the Estonian University of Life Sciences research on the effects of pure and undersowing green manures on yields of succeeding spring cereals was carried out by a group of scientists (Talgre et al., 2009). Concurrent comparison of spring cereals and their varieties in organic and conventional conditions was started in 2005 in Estonia. Preliminary results of our trials about yield and quality were published in 2007 (Tamm et al., 2007) and 2008 (Ingver et al., 2008). The trial was continued and 4 years results are summarised in the current publication.

MATERIALS AND METHODS

The trials were carried out during 2005–2008 at the Jõgeva Plant Breeding Institute. Thirteen varieties (Estonian Variety List of 2005) of each spring cereal crop, wheat, barley and oat, were tested in organic and conventional conditions. The trials were established on 5 m² plots in 4 replications by randomized complete block design on soddy-podzolic soil. The organic trial was organised in accordance of the principles of organic farming in Estonia. In the organic trial the contents of P and K in soil were fluctuating but no decrease was evaluated. The content of P remained on good and K on average level. The soil pH decreased from 6.4 to 6.2 in the trial period. Precrop in organic trial was red clover in 2005 and 2006 followed by buckwheat in 2007 and 2008. Mechanical weed control by repeated harrowing was carried out after germination and at the 3–4 leaves stage. Precrops in conventional trials were potato (2005, 2006) and rapeseed (2007, 2008). Fertilizer level $N_{70}P_{16}K_{29}$ was used for oat and $N_{90}P_{20}K_{38}$ for barley and wheat in the conventional trial. Chemical control of weeds (mixture of Lintur 120 g/ha and MCPA 500 ml/ha) and insects (Proteus 0,6 l/ha) was carried out every year. Seeding rate of 500 (barley) and 600 (wheat, oat) germinating seeds per m² was used. Yield, 1000 kernel weight, volume weight, protein content (Kjeldahl method), falling number (ICC/No. 107/1) for wheat and husk content for oat was measured after harvest. Significance of differences between the means was estimated using ANOVA of the statistical package Agrobase.

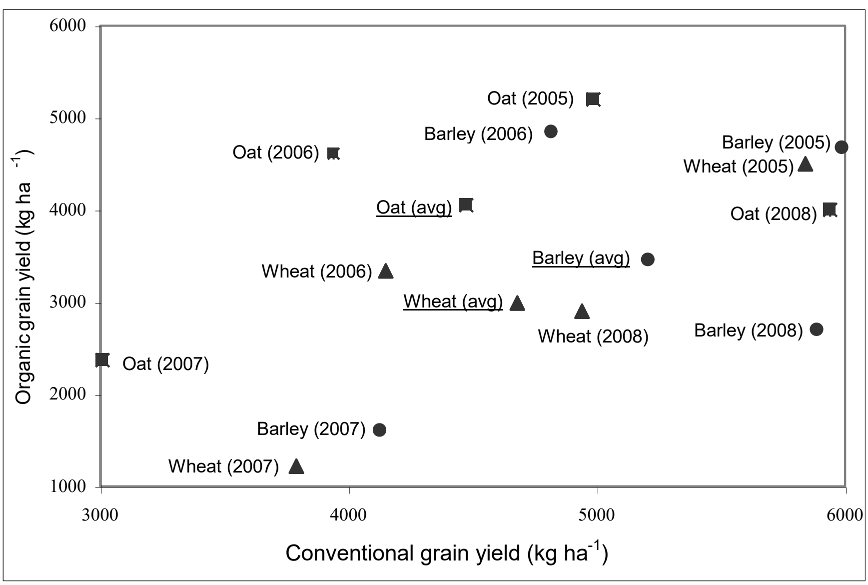
Weather conditions were the most favourable for spring cereals in 2005, when the first part of the vegetation period was cool and there was enough moisture in the soil for good root development and plant growth. Drought in July somewhat hindered plant development, but in spite of that weather conditions favoured high yield formation. In 2006 and 2007 all the cereals suffered because of drought. In 2008 very dry soil conditions in May and first half of June turned to continuous rains up to harvesting. This improved the yield potential but decreased the quality. Harvesting was carried out in extremely unfavourable conditions.

RESULTS AND DISCUSSION

Grain yield. Oat was the highest yielding (4050 kg ha^{-1}) in the organic conditions considering the four years average (Fig. 1). The yields of wheat and barley were significantly lower, 3450 and 2990 kg ha^{-1} respectively. It has also been common experience in Norway that oat generally performs better than wheat with lower nutrients availability (Loes et al., 2007). Oat is less demanding on soil nutrient content and able to produce comparatively high yields also in moderate soil fertility conditions (Forsberg & Reeves, 1995). The grain yield of oat turned up to be 35% higher compared to that of wheat in organic trial. Nutritional needs of wheat are the highest among the tested spring cereals. In conventional conditions barley was the highest yielding followed by wheat and oat. Oat was the less influenced by the two management systems and produced quite similar yields in both conditions. Organic oat gave a 10% lower yield than conventional oat. In organic conditions grain yield of barley constituted 66 and that of wheat 64% of the conventional yield. Yielding level of spring cereals in organic conditions was largely influenced by the precrop and weather conditions. In the first trial year after the favourable precrop (red clover) and favourable weather conditions all the cereals produced yields higher than 4500 kg ha^{-1}. Oat varieties average was even 5200 kg ha^{-1}. In 2006 oat and barley grain yields after red clover were high, 4600 and 4840 kg ha^{-1} respectively. The same year spring wheat suffered mostly from drought and average yield was 3340 kg ha^{-1}. In the last two years after buckwheat the yields of all the cereals were lower than after red clover. The lowest average yields were produced in 2007, caused by heavy soil crust during germination and early drought before heading. Spring wheat and barley yields were very low – 1220 and 1600 kg ha^{-1}. In the last year of the trial cycle (2008) after an unsuitable precrop (buckwheat) the yields were higher than in 2007 but lower than after the red clover (oat 4000, wheat 2900 and barley 2670 kg ha^{-1}). The varietal differences were characterised in our earlier publication (Ingver et al., 2008). Considerable differences in grain yield between the varieties were found and the majority of them ranked similarly in both growing conditions. The correlation coefficients between grain yields in organic and conventional trials were 0.71** for oat, 0.63* for barley and 0.71** for wheat (Table 1). In favourable conditions all the spring cereals were able to produce comparatively high yields also in organic cultivation. In unfavourable weather conditions and unsuitable precrop yield differences between the two cultivation regimes were higher.

Grain quality. *Spring wheat* quality characteristics are important for cultivation for food purposes. Weather conditions had the biggest influence on the grain quality.

The average 1000 kernel weight in the organic trial was even bigger (35.8 g) compared to the conventional one (34.2 g) (Table 2). Volume weight was somewhat lower in organic cultivation. The number of grains per head in organic conditions was smaller but grains grew bigger. In the organic trial significantly lower was the protein content, respectively 12.6% and 15.0%. The same tendency occurred in all the trial years. Previous studies have shown that yield and protein content of wheat produced under organic conditions are often 20–40% lower than those achieved in conventional conditions (Mäder et al., 2002; Taylor & Cormack, 2002).



■ – oat; ● – barley ▲ – wheat

Fig. 1. Grain yields of spring cereals in organic and conventional conditions in 2005–2008 (LSD$_{0.05}$ for 2005=212, 2006=186, 2007=159, 2008=128, average =132 kg ha^{-1}).

Table 1. Correlation coefficients (R) of grain yield and quality characteristics of spring cereals between conventional and organic trial.

Characteristic	Oat	Barley	Wheat
Grain yield	0.71**	0.63*	0.71**
1000 kernel weight	0.93**	0.95***	0.93***
Volume weight	0.78**	0.74**	0.78**
Protein content	0.85**	0.64*	0.85***

* – significant for $P < 0.05$; ** – significant for $P < 0.01$; *** – significant for $P < 0.001$

Table 2. Grain quality characteristics of spring cereals in conventional and organic conditions.

	Conventional conditions			Organic conditions			
	Oat	Barley	Wheat	Oat	Barley	Wheat	$LSD_{0.05}$
1000 kernel weight, g	35.0	45.3	34.2	36.0	44.8	35.8	1.0
Volume weight, g l^{-1}	498	674	783	472	675	767	23
Protein content, %	12.2	12.0	15.0	11.3	11.3	12.6	0.3

The gluten content of wheat in the organic trial was also lower (27.1 and 34.4% resp.) but its quality was better. Falling numbers were similar (285 and 268 sec) and more depending on weather conditions of the year than on the cultivation regime.

Barley grain quality characteristics during the years were more similar. 1000 kernel weight was 44.8 g in the organic and 45.3 g in the conventional trial. The same tendency was estimated in volume weight (675 and 674 g/l). Only the protein content in the organic trial was lower (11.3%) compared to the conventional one (12.0%).

Oat 1000 kernel weight was higher in the organic (36.0) compared to the conventional trial (35.0 g). Husk content was also comparable (25.8 and 25.5% respectively). Average volume weight was estimated lower in the organic management (472 g l^{-1}) compared to the conventional (498 g l^{-1}). Bigger differences occurred only in year 2007 (early drought), 420 in organic and 512 g l^{-1} in the conventional trial respectively. Lower protein contents were found in organic conditions (11.3 and 12.2%).

Grain quality of the same varieties was higher in both management conditions. There were high positive correlations between grain quality traits in organic and conventional conditions of all the crops.

Plant diseases. The most common diseases of the barley varieties were net blotch, spot blotch and to a small extent also scald. Average infection level was not exceeded during the tested years and differences between the two managements were not remarkable. Low infection by crown rust and leaf blotch of oat varieties was found in both trials. Spring wheat varieties were more infected by powdery mildew, septoria, brown rust, DTR and spot blotch. More favourable conditions for septoria, mildew and DTR appeared in 2007 and 2008 when above average level of infection was recorded. The infection level of most of the diseases in the two compared cultivation managements was quite similar. Some diseases decrease in importance in organic management systems since disease pressure is generally lower compared to the conventional management (Vogt-Kaute, 2001). The same situation of wheat powdery mildew occurred in some years in our trial (in 2005 and 2008). Diseases that are common in conventional farming due to high crop densities and frequent nitrogen applications, such as mildew in cereals, are rarely a problem in organic farming (Lammerts van Bueren et al*.*, 1998).

Weeds may be one of the primary problems in organic cultivation. Therefore cereals weed suppression ability is important. For estimations all the weeds from a 0.5 m^{-2} test area were counted and weighed in each plot. Totally 32 species of weeds were found during the trial years in the organic trial. The weed species distribution between the cereal crops was equal. The number of weed species was higher in the years of higher precipitation. The most dominating were common lamb's quarters (*Chenopodium album),* field pancy *(Viola arvensis)*, black bindweed *(Fallopia convolvulus)* and sun spurge *(Euphorbia helioscopia)* covering 2/3 of the total number of weeds. In spite of two harrowings the number of weeds per m^2 was quite high although their biomass under the cereals suppression was not high. A tendency for less weeds (100 plants per m^2) was found in the oat plots (Fig. 2). The number in barley and wheat plots was higher, 142 and 138 respectively. The number of weeds in the organic trial field had no increase during the four years. The highest number of weeds was in 2005 when there was enough moisture in the soil in the first half of the vegetation period. The less weeds were in 2008 when there was shortage of moisture in soil at the beginning of the vegetation period (May and first half of June). The smallest average weeds biomass (48 g) was in the oat plots (Fig. 3). The weeds biomass in barley and wheat plots was higher, 80 and 84 g respectively. The biggest weeds biomass was in 2008 when a droughty beginning of the vegetation period was followed by continous rains up to harvesting. The smallest biomass was in 2006 when droughty conditions extended for the whole growing season.

Oat suppressed weeds more successfully than wheat and barley. There was no significant difference in weed suppression ability of wheat and barley.

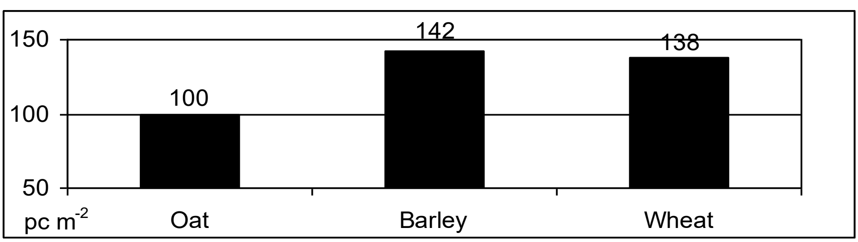


Fig. 2. Average number of weeds in the organic trial in 2005–2008 ($LSD_{0.05}$=8).

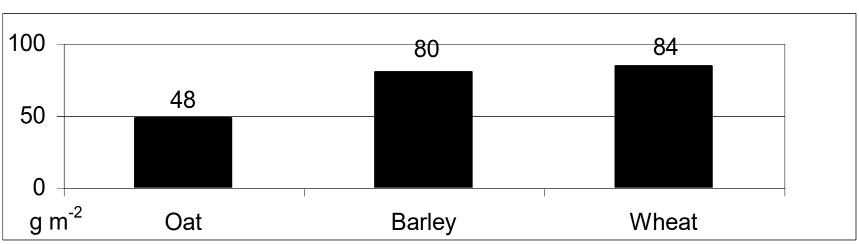


Fig. 3. Average biomass of weeds in the organic trial in 2005–2008 ($LSD_{0.05}$=6).

CONCLUSIONS

The results of the trials indicated that on fertile soil and after a suitable precrop (red clover) all the spring cereals produced comparatively high yields with good quality in organic conditions. Yielding potential decreased while cultivating the spring cereals after an unfavourable precrop (buckwheat). In organic conditions oat was the highest yielding among the spring cereals. Oat also had the best weeds suppression ability. Concerning the quality characteristics, protein content was the most influenced by the cultivation regime. It was lower in organic trial of all the cereals. The biggest decrease in protein content was found in the wheat trials. The other quality characteristics were less influenced by the management regime. Kernel weight of oat and wheat even increased under organic conditions. In cultivating spring wheat high soil fertility should be guaranteed to produce high yield with good quality. A yield gap between organic and conventional production depended on crop, precrop and growing conditions. Combining information from both organic and conventional cultivation is beneficial for low-input farmers.

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REFERENCES

Forsberg, R.A. & Reeves, D.L. 1995. Agronomy of oats. In Welch, Ed. R.W (ed): *The Oat Crop. Production and utilization.* London, Chapman & Hall, pp. 221–251.

Ingver A., Tamm I. & Tamm Ü. 2008. Effect of organic and conventional production on yield and quality of spring cereals. *Latvian Journal of Agronomy* **11**, 61–67.

Lammerts van Bueren, E.T. 2003. *Challenging new concepts and strategies for organic plant breeding and propagation*. Available at http://www.leafyvegetables.nl/download/ 04_017-022_Lammerts.pd accessed on 7.01.2008

Lammerts van Bueren, E.T., Hulcher, M., Jongerden, J., Haring, M., Hoogendoorn, J.D., van Mansvelt, J.D. & Ruivenkamp, G.T.P. 1998. *Sustainable organic plant breeding.* http://www.ifgene.org/breed1.htm accessed on 8.01.2008.

Løes, A.-K., Henriksen, T.M. & Eltun, R. 2007. N supply in stockless organic cereal production under northern temperate conditions. Undersown legumes or whole season green manure? *3rd QLIF Congress: Improving Sustainability in Organic and Low Input Food Production Systems,* University of Hohenheim, Germany, March 20–23, 2007, pp. 230.

Mäder, P., Fliebach, A., Dubois, D., Gunst, L., Fried, P. & Niggli, U. 2002. Soil Fertility and Biodiversity in Organic Farming. *Science* **296**, 1694–1697.

Talgre, L., Lauringson, E., Roostalu, H., Astover, A., Eremeev, V. & Selge, A. 2009. The effects of pure and undersowing green manures on yields of succeeding spring cereals. *Acta Agriculturae Scandinavica,* Section B, Plant Soil Science **59**(1), 70 – 76.

Tamm, I., Tamm Ü. & Ingver, A. 2007. Comparison of grain yield and qualiy of spring cereals in organic and conventional conditions. *Agronomy 2007*, Saku, pp. 57–60 (in Estonian).

Taylor, B.R. & Cormack, W.F. 2002. Choices of species and varieties. In Younie, D., Taylor, B., Welch, J.P. & Wilkinson J.M (eds): *Organic cereals and Pulses.* Lincoln: Chalcombe Publications, 9–28.

Vogt-Kaute, W. 2001. *Crop breeding for organic agriculture.* Available at http://www.ncl.ac.uk/tcoa/files/cropbreeding_orgagr.pdf accessed on 10.01.2008

Wolfe, M.S., Baresel, J.P., Desclaux, D., Goldringer, I., Hoad, S., Kovacs, G., Löschenberger, F., Miedaner, T., Østergard, H. & Lammerts van Bueren, E.T. 2008. Developments in breeding cereals for organic agriculture. *Euphytica* **163**, 323–346.

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Ingver, A., Tamm, I., Tamm, Ü. 2008. EFFECT OF ORGANIC AND CONVENTIONAL PRODUCTION ON YIELD AND QUALITY OF SPRING CEREALS. Agronomijas Vestis, Latvian Journal of Agronomy, 11, 61–67.

EFFECT OF ORGANIC AND CONVENTIONAL PRODUCTION ON YIELD AND THE QUALITY OF SPRING CEREALS

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Abstract
The situation in the agricultural sector has changed during the last years. The need to increase sustainability and protect the environment has become more relevant. Also organic farming is increasing in Estonia. The field trials were carried out at the Jõgeva Plant Breeding Institute to compare the grain yield and quality characteristics of spring wheat, barley and oat in organic and conventional conditions. Thirteen varieties of each cereal crop were tested during a three year period (2005-2007). The trial results showed that all the spring crops were able to produce comparatively high yields in organic conditions. The highest yielding in the organic trial was obtained by oat followed by barley and wheat. The yield decrease in spring wheat was the biggest (34%) in organic conditions compared to conventional conditions. Yield reduction was mostly the result of the shortage of plant nutrients. Weather conditions were more favourable for cereals in 2005. Drought caused a decrease in grain yield and quality in 2006 and 2007. The grain quality of barley and oats was similar in both cropping systems; wheat produced bigger kernels in the organic trial. Protein content in organic conditions decreased, wheat having the largest decrease

Key words: spring wheat, barley, oat, yield, quality, organic, conventional condition

Introduction
Cereals cultivated in organic conditions should produce sufficient yields without the use of mineral fertilizers and plant protection chemicals (pesticides). At the same time organic cultivation is oriented to high quality production. Yield usually takes priority in non-organic cultivation but will often have a lower priority in organic farming, relative to quality. Also, organic farming management is complex. In contrast to conventional systems, organic farmers rely mostly on preventive and adaptive management.
In Europe, Lammerts van Bueren (2003), Wolfe (2002) and Vogt-Kaute (2001) have tested and summarized the results of organic trials - organic plant breeding and crop production yield and yield stability, the efficiency of nutrient uptake, adaptation to organic inputs, quality characteristics etc.
In Estonia the following topics have been discussed during recent years. Sepp and his colleagues (2006) have tested the influence of organic crop rotation on yield and the quality and weediness of wheat and barley. Changes in the earthworm community in experimental plots of conventional and organic trials have been studied by Ivask and her group (2007). The comparison of spring cereals and their varieties in conventional and organic systems have not been carried out in Estonian conditions. The preliminary results of our trials about the yield and quality of spring cereals were published in 2007 (Tamm *et al.*, 2007).
A series of field trials comparing organic and conventional systems of the production of spring wheat, barley and oats was established in 2005 at the Jõgeva Plant Breeding Institute in Estonia. The objective of the study was the assessment of the suitability of different spring cereal crops and their varieties to organic cultivation.

Materials and Methods
The trials were conducted from 2005 to 2007 and included 13 spring wheat, barley and oat varieties. The following barley varieties were included: Anni, Elo, Viire, Leeni (Estonia), Tocada, Danuta, Barke, Annabell (Germany), Wikingett, Mette (Sweden), Zazjorski 85 (Belorussia), Inari (Finland) and new the Estonian breed 3280.14.1.4. The oat varieties Jaak, Villu (Estonia), Hecht, Revisor, Nelson, Jumbo, Freddy, Aragon (Germany), Vendela, Belinda, Birgitta, Freja (Sweden) and Celsia (The Netherlands) were used. From the spring wheat varieties the folloning were

selected Helle, Meri, Mooni (Finnish-Estonian collaboration), Vinjett, Tjalve, Zebra, SW Estrad (Sweden), Munk, Triso, Monsun (Germany), Manu, Mahti (Finland) and Baldus (The Netherlands). The experimental design was a randomized complete block with 4 replications. The organic and conventional trials were established on soddy-podzolic soil. The average P content was good, the level of K average, the rganic matter content medium and the pH slightly acid. The precrop in the organic trial was red clover in 2005 and 2006 and was followed by buckwheat in 2007. Mechanical weed control by repeated harrowing was carried out after germination and in the 3-4 leaves stage. The precrops in the conventional trials were potato and rapeseed. The fertilizer level $N_{70}P_{16}K_{29}$ was used for oats and $N_{90}P_{20}K_{38}$ for barley and wheat in the conventional trial. Weeds were controlled by herbicides. A seeding rate of 500 (barley) and 600 (wheat, oat) germinating seeds per m² was used. The yield, 1000 kernel weight, volume weight, protein content, the falling number for wheat and the husk content for oats was measured after harvest. The falling number was determined by the ICC standard method 107/1, oat grains were dehulled by hand and the hulls and groats weighed separately.

Weather conditions in all of the tested years were drier than average (Figure 1). The most favourable for yield formation were the weather conditions in 2005. The first half of the vegetation period was cool and early season precipitation favoured plant growth and development. Drought in July had some effect on plant growth but the yielding level was above average. The driest was the vegetation period in 2006, but the distribution of precipitation caused only small yield decrease compared to the previous year. Severe drought (only 10 mm during the 2 weeks before heading) and a higher than average temperature in June of 2007 resulted in significantly shorter plants and fewer spikelets (Keppart, 2008). Yield decrease was remarkable. Because of drier than average vegetation periods in all of the 3 years there was almost no lodging and comparatively low disease incidence. Data was analysed using the Agrobase computer package (Agrobase gen.II^{TM}, 2004).

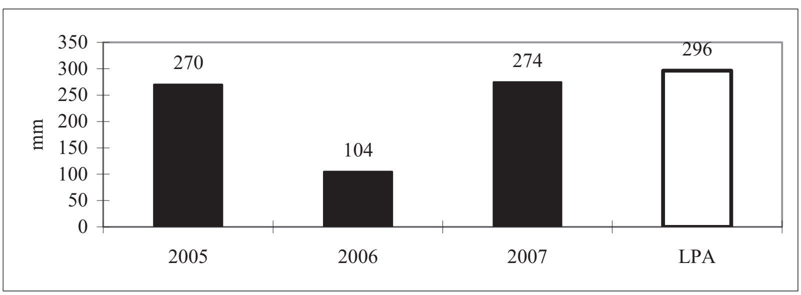


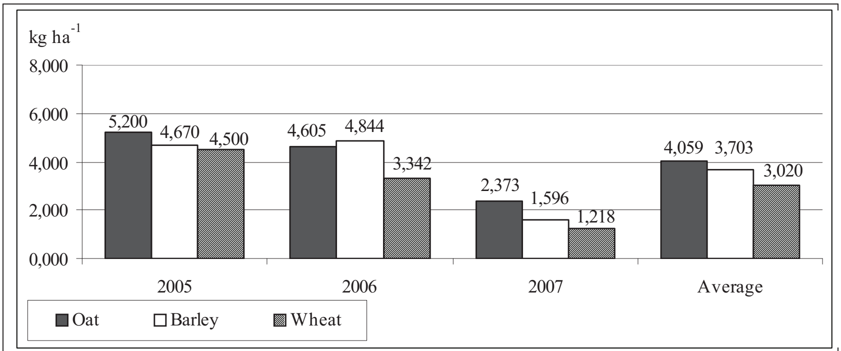
Figure 1. Precipitation (mm) of the vegetation period of 2005-2007 compared to LPA (long period average)

Results and Discussion

Grain yield. In the first trial year the yielding capacity of all the spring cereals in the organic trial was high extending to 4,500 kg ha^{-1} (Figure 2). Yields of oats and barley were despite the drought on average level also in 2006 respectively by 4,605 and 4,844 kg ha^{-1}. Spring wheat suffered the most, producing only 3,342 kg ha^{-1}. Heavy soil crust during germination, early drought before heading and an unsuitable precrop (buckwheat) in 2007 decreased the yields the most.

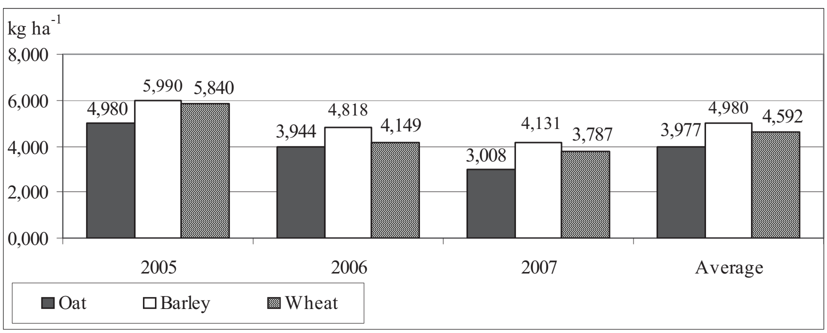
Similar to oganic trials in conventional conditions the yield were the highest in 2005 and the lowest in 2007 (Figure 3). The grain yield of the oat varieties in conventional trials was lower than that of barley and wheat during all the trial years.

In the conventional trial barely yield the highest average (4,980 kg ha^{-1}) followed by spring wheat (4,592 kg ha^{-1}) and oat (3,977 kg ha^{-1}). Oats were less influenced by the two management systems and there was no significant difference in the average yield of the organic and conventional trials. In organic conditions the grain yield of barley constituted 74 % and wheat 66 % of the conventional yield.



(LSD$_{0.05}$ for 2005= 155, 2006=162, 2007=113 and average= 97 kg ha^{-1})

Figure 2. The grain yields of spring cereals in organic conditions in 2005–2007



(LSD$_{0.05}$ for 2005=182, 2006=147, 2007=138 and average=97 kg ha^{-1})

Figure 3. The grain yields of spring cereals in conventional conditions in 2005–2007

The most of the varieties ranked similarly by grain yield in both growing conditions. The correlations between the grain yields of oat, barley and wheat varieties in organic and conventional trials were significant (Table 1).

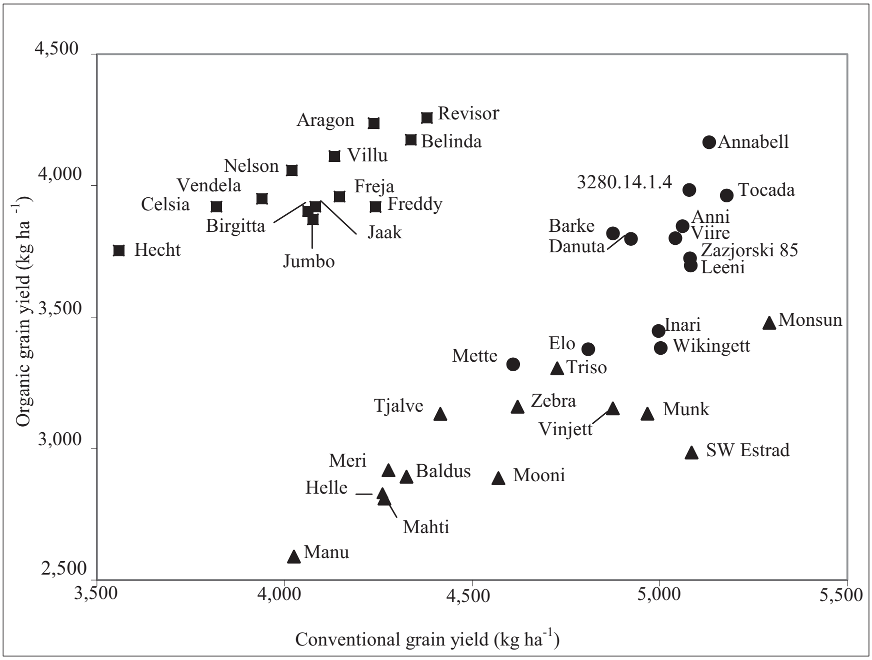
Table 1. The correlations between conventional and organic grain yield and quality characteristics of spring cereals

Characteristic	Oat	Barley	Wheat
Grain yield	0.76**	0.64*	0.80**
Thousand kernel weight	0.77**	0.93***	0.93***
Volume weight	0.85***	0.7*	0.71**
Protein content	0.76**	ns	0.88***
Husk content	0.81**	–	–
Falling number	–	–	0.7*

* – significant for P<0.05; ** – significant for P<0.01 *** – significant for P<0.001; ns – not significant

The highest yielding of the three years average in the organic trial were the oat varieties Belinda (4,336 kg ha^{-1}), Freddy (4,243 kg ha^{-1}), Aragon (4,238 kg ha^{-1}), Freja (4,147 kg ha^{-1}), Villu (4,133 kg ha^{-1}) and Jaak (4,082 kg ha^{-1}); the barley varieties Annabell (4,164 kg ha^{-1}), Tocada (3,942 kg ha^{-1}), Anni (3,845 kg ha^{-1}), Barke (3,818 kg ha^{-1}) and Viire (3,800 kg ha^{-1}) and the spring wheat varieties Monsun (3,479 kg ha^{-1}), Triso(3,305 kg ha^{-1}), Zebra (3,153 kg ha^{-1}), Vinjett (3,153 kg ha^{-1}) and Munk (3,133 kg ha^{-1}).

While comparing the yields of the two management systems the varieties of the different spring cereals formed quite clear groups (Figure 4).



■ – oat; ▲– wheat; ● – barley

Figure 4. Comparison of organic and conventional grain yields of spring cereals ($LSD_{0.05}$=402)

The grain yield of the oat varieties in conventional management was lower on the average yield than the rest of the conventional trial and the reaction in the organic trial was the opposite – all the varieties outyielded the trial average. Most of the barley varieties had higher than average trial yields in conventional conditions and close to average or even a little above in the organic trials. Several spring wheat varieties produced higher than average yields in the conventional trial but all were lower than average in the organic trial. Under both management conditions increased grain yield was associated with late maturity. The correlation coefficient between the yield and the length of the growing period of wheat was 0.73 ($P<0.01$) in the organic and 0.79 ($P<0.01$) in the conventional trial. No significant correlation between the yield and the length of growing period of oats and barley was found.

Grain quality was higher in the same varieties in both management conditions. Significant positive correlations of quality characteristics between both management conditions were found except for barley protein content. No significant correlations were found between most of the tested traits in both systems. The only significant correlation was between yield and protein content of spring wheat in the organic and conventional trials, respectively –0.53 ($P<0.05$) and –0.82 ($P<0.01$). For oat and barley the correlation was not significant.

When comparing the management the conditions the quality characteristics of barley differed less than the others. For three years the average 1000 kernel weight was 46.6 g in both conditions.

Barley produced big kernels in organic conditions also in the low-yielding year 2007. Protein content was also similar – respectively 116 g kg^{-1} in the organic and 120 g kg^{-1} in the conventional trial. The results of volume weight followed the situation respectively by 684 and 685 g l^{-1}.
In organic fertility management, oats also behaved similarly to barley – there were no significant differences. The tested years average 1000 kernel weight was 34.6 g in organic and 34.4 g in conventional trials and the same for every years. Husk content was also comparable by 262 and 265 g kg^{-1} respectively. Average volume weight was somewhat lower in organic management by 470 g l^{-1} compared to that of conventional management (503 g l^{-1}). During the first two years, volume weight in the both management systems was equal. Significant differences in volume weight occurred in 2007, a year with an early drought, respectively 420 g l^{-1} in organic and 512 g l^{-1} in conventional trials. The average protein content was 120 g kg^{-1} in organic and 129 g kg^{-1} in conventional conditions. In 2005 and 2006 the content of protein was similar, but in 2007 significant differences occurred 117 in organic and 135 g kg^{-1} in conventional trials.

Table 2. The grain quality characteristics of spring cereals in conventional and organic conditions

Characteristic	Conventional conditions				Organic conditions			
	Oat	Barley	Wheat	$LSD_{0.05}$	Oat	Barley	Wheat	$LSD_{0.05}$
Thousand kernel weight, g	34,4	46.6	34.2	1.8	34.6	46.6	36.5	1.9
Volume weight, g l^{-1}	503	685	808	29	470	684	788	32
Protein content, g kg^{-1}	129	120	151	10	120	116	127	10
Husk content, g kg^{-1}	265	–	–	–	262	–	–	–
Falling number, s	–	–	296	–	–	–	285	–

Spring wheat reaction to different management systems was the most sensitive one. Average 1000 kernel weight was significantly bigger (36.5 g) in the organic trial compared to the conventional trial (34.2 g). Significant difference in volume weight was not measured. The biggest dissimilarity was found in protein content. It was significantly lower in the organic trial in all the tested years, being 127 g kg^{-1} and 151 g kg^{-1} respectively as the average. Spring wheat turned out to be the most sensitive to the shortage of nitrogen in the soil for the production of protein. Falling number values were not much influenced by the particular management system - 285 s in organic and 296 s in conventional trial.
During a year average oats showed the highest level of grain yield in organic conditions (4,059 kg ha^{-1}), followed by barley (3,703 kg ha^{-1}) and spring wheat (3,020 kg ha^{-1}). It has also been a common experience in Norway that oats generally perform better than wheat with lower nutrient availability (Loes *et al.*, 2007). The grain yield of oat turned out to be 25% higher compared to that of wheat in organic trial. Nutrient requirements of oat are less than those of wheat (Forsberg and Reeves, 1995). Oats outyielded barley and wheat in organic trials in 2005 and 2007, but their yield was 5% lower than barley in 2006. This could be explained by the better tillering capacity of barley. The results of 3 years of trials show that some varieties were found to produce comparatively higher yields and better quality in organic conditions. To get the best possible yields on a given site, growers use varieties that are adapted to that particular environment and to nutrient levels, which fluctuate with the seasons (Lammerts van Bueren, 2003).
The decrease of the protein content of spring wheat by 16% was observed in organic trials compared to conventional trials. Previous studies have shown that the yield and protein content of wheat produced under organic conditions are often 20-40% lower than those achieved in conventional conditions (Taylor and Cormack, 2002; Mäder *et al.*, 2002). This may partially be due to on insufficient nitrogen supply during the later growth stages (Taylor and Cormarck, 2002). Cultivation of wheat in organic conditions is a challenge for a grower but has great value because of it can br utilized in multiple ways (Pedersen *et al.*, 2006).

Conclusion

The results of the trials indicate that on fertile soil and after a suitable precrop (red clover in our trial) all the spring cereals produced comparatively high yields with good quality in organic conditions. Unfavourable weather conditions and an unsuitable precrop caused a significant yield decrease. In terms of quality characteristics protein content and volume weight were the most influenced by the particular management system and the weather. In organic conditions the highest yielding was found in oats. In cultivating spring wheat high soil fertility is needed to produce a high yield with good quality.

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References

1. Agrobase generation II™ (2004) *User's manual.* Winnipeg, Manitoba, 250.
2. Løes A.-K., Henriksen T.M., Eltun R. (2007) N supply in stockless organic cereal production under northern temperate conditions. Undersown legumes, or whole season green manure? In: *3rd QLIF Congress: Improving Sustainability in Organic and Low Input Food Production Systems,* University of Hohenheim, Germany, March 20-23, 2007, 226-230.
3. Keppart L. (2008) Weather of growing seasons of 2006 and 2007 and influence to plant production. In: N*ew varieties of field crops, their characteristics and individuality of cultivation.* Jõgeva, 4-7. (In Estonian).
4. Mäder P., Fliebach A., Dubois D., Gunst L., Fried P., Niggli U. (2002) Soil Fertility and Biodiversity in Organic Farming. *Science 296*: 1694-1697.
5. Taylor B.R., Cormack W.F. (2002) Choices of species and varieties. In: *Organic cereals and Pulses.* Younie D., Taylor B., Welch J.P., Wilkinson J.M. (eds.) Lincoln: Chalcombe Publications, 9-28.
6. Forsberg R.A., Reeves D.L. (1995) Agronomy of oats. In: *The Oat Crop. Production and utilization*. Welch R.W. (ed.) London: Chapman & Hall, 221-251.
7. Lammerts van Bueren E.T., Hulcher M., Jongerden J., Haring M., Hoogendoorn J.D., van Mansvelt J.D., Ruivenkamp G.T.P. (1998) *Sustainable organic plant breeding:* http://www.ifgene.org/breed1.htm – accessed on 8.01.2008.
8. Ivask M., Sepp K., Kanger J. (2007) Changes of earthworm community in experimental plots of conventional and organic farming. *Agronomy 2007*, Kadaja J (ed.) Saku, 13-16. (In Estonian).
9. Pedersen L., Thorup-Kristensen K., Loges R. (2006) Wheat baking quality: The effect of catch crop strategies and species: http://orgprints.org/7575/01/Paper_forcongress2006LP.doc – accessed on 15.01.2008.
10. Sepp K., Kanger J., Pevzner J. (2006) Grain yield, quality and weediness of wheat and barley in organic crop rotation. *Agronomy 2006*, Nurmekivi H. (ed.), Jõgeva, 23-29 (in Estonian).
11. Tamm I., Tamm Ü., Ingver A. (2007) Comparison of grain yield and qualiy of spring cereals in organic and conventional conditions. *Agronomy 2007*, Kadaja J. (ed.) Saku, 57-60. (In Estonian).
12. Lammerts van Bueren E.T. (2003) Challenging new concepts and strategies for organic plant breeding and propagation*:* http://www.leafyvegetables.nl/download/04_017-022_Lammerts.pd – accessed on 7.01.2008.
13. Vogt-Kaute W. (2001) Crop breeding for organic agricultur*e:* http://www.ncl.ac.uk/tcoa/files/cropbreeding_orgagr.pdf – accessed on 10.01.2008
14. Wolfe M.S. (2002) Organic plant breeding. In: *Proceedings of the COR Conference.* Powell *et al*., (eds.), Aberystwyth, 303-305.

BIOLOĢISKĀS UN KONVENCIONĀLĀS AUDZĒŠANAS SISTĒMAS IETEKME UZ VASARĀJU GRAUDAUGU RAŽU UN KVALITĀTI

Ingver A., Tamm I., Tamm Ü.

Situācija lauksaimniecības sektorā pēdējo gadu laikā ir izmainījusies. Nozīmīgāka kļuvusi nepieciešamība palielināt ilgtspējību un aizsargāt vidi. Bioloģiskās lauksaimniecības platības Igaunijā palielinās.
Jogevas augu selekcijas institūtā tika iekārtoti lauka izmēģinājumi, lai salīdzinātu vasaras kviešu, miežu un auzu graudu ražu un kvalitātes pazīmes bioloģiskos un konvencionālos apstākļos. Katras graudaugu sugas 13 šķirnes tika pārbaudītas trīs gadu laikā (2005.-2007. g.). Izmēģinājumu rezultāti parādīja, ka visas vasarāju sugas bioloģiskos audzēšanas apstākļos spēja izveidot salīdzinoši augstas ražas. Ražīgākās bioloģiskajos izmēģinājumos bija auzas, tām sekoja mieži un kvieši. Lielākais ražas samazinājums (34%) bioloģiskos apstākļos salīdzinājumā ar konvencionālajiem apstākļiem bija vasaras kviešiem. Ražas samazinājums bija galvenokārt augu

barības vielu trūkuma dēļ. Laika apstākļi 2005. gadā bija graudaugiem labvēlīgāki. 2006. un 2007. gadā graudu ražas un kvalitātes samazināšanos izraisīja sausums. Miežu un auzu graudu kvalitāte abās audzēšanas sistēmās bija līdzīga; kviešiem bioloģiskos apstākļos veidojās lielāki graudi. Proteīna saturs bioloģiskos apstākļos samazinājās, lielākais samazinājums novērots kviešiem.

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2013	Spring wheat cultivar 'Hii'e, owner Estonian Crop Research Institute; authors Anne Ingver, Reine Koppel, Merlin Haljak; Priority number: 9/2013; Priority date: 7.03.2013
2013	Spring wheat cultivar 'Voore', owner Estonian Crop Research Institute; authors Anne Ingver, Reine Koppel, Merlin Haljak; Priority number: 10/2013; Priority date: 7.03.2013
2010	Winter wheat cultivar 'Kallas', owner Lithuanian Research Centre for Agriculture and Forestry, Estonian Crop Research Institute; authors Reine Koppel, Anne Ingver, Merlin Haljak, Vytautas Ruzgas; Priority number: 30/2010; Priority date: 12.07.2010
2010	Winter wheat cultivar 'Nemunas', owners Lithuanian Research Centre for Agriculture and Forestry, Estonian Crop Research Institute; authors Reine Koppel, Anne Ingver, Merlin Haljak, Vytautas Ruzgas; Priority number: 31/2010; Priority date: 12.07.2010
2007	Spring wheat cultivar 'Mooni', owners Boreal Plant Breeding, Estonian Crop Research Institute; authors Anne Ingver, Reine Koppel, Hans Küüts, Tapio Juuti; Priority number: 111/2007; Priority date: 20.12.2007
1999	Spring wheat cultivar 'Meri', owners Boreal Plant Breeding, Estonian Crop Research Institute;

authors Hans Küüts, Tapio Juuti, Anne Ingver, Reine Koppel, Mati Koppel; Priority number: 0030; Priority date: 1.06.1999

1999	Spring wheat cultivar 'Helle', owners Boreal Plant Breeding, Estonian Crop Research Institute; authors Hans Küüts, Tapio Juuti, Anne Ingver, Reine Koppel, Mati Koppel; Priority number: 0037; Priority date: 25.11.1999

ELULOOKIRJELDUS

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2005–...	Põhjamaade Põllumajandusteadlaste Organisatsiooni (NJF) liige
2005–2011	NJF-i taimekasvatuse sekstiooni Eesti koordinaator
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Osalemine uurimisprojektides:

2009–2019	„Varasema valmimisega, saagikate ja hea tera kvaliteediga, haigus- ja seisukindlate suvinisusortide aretus ja uute sortide säilitusaretus" (Project 3.4-23/ 155 1.2).
2013–2016	ERA–NET CORE ORGANIC ehk mahepõllumajanduse valdkonna 2013–2015 Euroopa Liidu teadusvõrgustiku II taotlusvoorust finantseeritav projekt „Mahesordiaretus geneetilise mitmekesisuse suurendamiseks" (Coordinating Organic plant Breeding Activities for diversity; COBRA).
2011–2014	Maaelu Arengukava meetme 1.7.1 raames teostatav rakendusuuring 1710011780024 „Mahetootmise efektiivsuse tõstmine, jätkusuutlikkuse suurendamine ja mahetingimustes toodetud toiduteravilja kvaliteedi parandamine".
2011–2014	Maaelu Arengukava meetme 1.7.1 raames teostatav rakendusuuring 1710011780017 „Toidu- ja tööstustarbelise teravilja sortimendi laiendamine ja sobivate kasvatustehnoloogiate täiustamine".

Erialane enesetäiendus:

9.01.2019	Koolitus „Efektiivsus igapäevajuhtimises", Äripäeva Akadeemia
26.10.12–13.12.2013	Statistika kursus, prof. Tanel Kaart, Maaülikool 18.05.2007 Täiendõppekursus „Ettevõttepraktika juhendamine", Eesti Maaülikool
22.11.–6.12. 2006	Täienduskoolitus „Lektori kutseoskuste arendamine", Tartu Ülikool
2006	Statistika kursus, dr. Märt Möls
2005	Akadeemiline kirjutamine inglise keeles, Carol Norris, Tartu
2003	Eetikakursus. Jaanus Noormägi, Tartu University
2002	Täiskasvanute koolitus. Jüri Ginter, EPMÜ
2002	Teadustöö metodoloogia. Jaanus Noormägi, Tartu Ülikool
2000	Tarkvara Agrobase kursus, Dieter Mulitze Agronomix Software Inc., Kanada, 1 nädal
2000	Biotehnoloogia kursus, kursus Sordiaretuse

	meetodid, Statistika kursus, Idy van Leeuven, Madalmaad
2000	„26. Põhja- ja Baltimaade kraadiõppe kursus sordiaretuses”. Iceland, 1 nädal
1996	Cochran Fellowship Program (USDA), nisuaretuse alane koolitus Oregoni Ülikool, 1 kuu
1995	„23. Põhja- ja Baltimaade kraadiõppe kursus sordiaretuses”. Eesti, 1 nädal
1994	Nisuaretuse alane koolitus Boreali aretuskeskuses, Soome, 2 kuud
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Patentsed leiutised:

2015	Talinisu sort 'Ruske', omanik Eesti Taimekasvatuse Instituut; autorid Reine Koppel, Anne Ingver, Merlin Haljak; Prioriteedi number: 68/2015; Prioriteedi kuupäev: 31.07.2015
2013	Suvinisu sort 'Hiie', omanik Eesti Taimekasvatuse Instituut; autorid Anne Ingver, Reine Koppel, Merlin Haljak; Prioriteedi number: 9/2013; Prioriteedi kuupäev: 7.03.2013
2013	Suvinisu sort 'Voore', omanik Eesti Taimekasvatuse Instituut; autorid Anne Ingver, Reine Koppel, Merlin Haljak; Prioriteedi number: 10/2013; Prioriteedi kuupäev: 7.03.2013
2010	Talinisu sort 'Kallas', omanik Leedu Põllumajanduse ja Metsanduse Teaduskeskus; autorid Reine Koppel, Anne Ingver, Merlin Haljak, Vytautas Ruzgas; Prioriteedi number: 30/2010; Prioriteedi kuupäev: 12.07.2010
2010	Talinisu sort 'Nemunas', omanik Leedu Põllumajanduse ja Metsanduse Teaduskeskus, autorid Reine Koppel, Anne Ingver, Merlin Haljak, Vytautas Ruzgas; Prioriteedi number: 31/2010; Prioriteedi kuupäev: 12.07.2010
2007	Suvinisu sort 'Mooni', omanik Boreali Aretuskeskus (Soome), Eesti Taimekasvatuse Instituut; autorid Anne Ingver, Reine Koppel, Hans Küüts, Tapio

	Juuti; Prioriteedi number: 111/2007; Prioriteedi kuupäev: 20.12.2007
1999	Suvinisu sort 'Meri', omanik Boreali Aretuskeskus (Soome), Eesti Taimekasvatuse Instituut; autorid Hans Küüts, Tapio Juuti, Anne Ingver, Reine Koppel; Prioriteedi number: 0030; Prioriteedi kuupäev: 1.06.1999
1999	Suvinisu sort 'Helle', omanik Boreali Aretuskeskus (Soome), Eesti Taimekasvatuse Instituut; autorid Hans Küüts, Tapio Juuti, Anne Ingver, Reine Koppel, Mati Koppel; Prioriteedi number: 0037; Prioriteedi kuupäev: 25.11.1999

LIST OF PUBLICATIONS

1.1. Articles indexed by Thomson Reuters Web of Science

Ingver, A., Tamm, Ü., Tamm, I., Tamm, S., Tupits, I., Bender, A., Koppel, R., Narits, L. & Koppel, M. 2019. Leguminous pre-crop improved quality of organic winter and spring cereals. Biological Agriculture & Horticulture, 35 (1), 46–60.

Chawade, A., Armoniené R., Berg G., Brazauskas G., Frostgård G., Geleta M., Tina Henriksson, T., Himanen, K., **Ingver, A**., Johansson, E., Nistrup Jørgensen, L., Koppel, M., Koppel, R., Makela, P., Ortiz, R., Podyma, W., Roitsch, T., Ronis, A, Svensson, J.T., Vallenback, P., Weih, M. 2018. A transnational and holistic breeding approach is needed for sustainable wheat production in the Baltic Sea region. Physiologia Plantarum, 164 (4), 442–451.

Tikhonova, M., **Ingver, A.,** Koppel, R. 2018. Identification of *Glu-A1* and *Glu-D1* high molecular weight glutenin subunits of common wheat (*Triticum aestivum* L.) using genetic markers. Proceedings of the Latvian Academy of Sciences, Section B: Natural, Exact, and Applied Sciences, 72 (6), 349–357.

Tamm, I., Tamm, Ü., **Ingver**, **A**., Koppel, R., Tupits, I., Bender, A., Tamm, S., Narits, L., Koppel, M. 2016. Different leguminous pre-crops increased yield of succeeding cereals in two consecutive years. Acta Agriculturae Scandinavica, Section B - Soil & Plant Science, 66 (7), 593–601.

Levandi, T., Püssa, T., Vaher, M., **Ingver, A**., Koppel, R., Kaljurand, M. 2014. Principal component analysis of HPLC-MS/MS patterns of wheat (*Triticum aestivum*) varieties extracts. Proceedings of the Estonian Academy of Sciences, 63 (1), 86–92.

Sooväli, P., Kangor, T., Koppel, R., **Ingver, A**., Tamm, I. 2013. Spring Wheat Disease and Yield Responses to Nitrogen Fertilization and Chemical Treatments Journal of Agricultural Science and Technology A, 3 (4), 290–296.

Peusha, H., Enno, T., Jakobson, I., Tsõmbalova, J., **Ingver, A**., Järve, K. 2008. Powdery mildew resistance of Nordic spring wheat

cultivars grown in Estonia. Acta Agriculturae Scandinavica, Section B - Plant Soil Science, 54(4), 289– 296.

1.2. Peer-reviewed articles in other International research journals with an ISSN code and International editorial board

Ingver, A., Tamm, I., Tamm, Ü., Kangor, T., Koppel, R. 2010. The characteristics of spring cereals in changing weather in Estonia. Agronomy Research, 8 (3), 553–562.

Kangor, T., **Ingver, A.,** Tamm, Ü., Tamm, I. 2010. Effect of fertilization and conditions of year on some characteristics of spring wheat and barley. Agronomy Research, 8 (3), 595–602.

Koppel, R., **Ingver, A**. 2010. Stability and predictability of baking quality of winter wheat. Agronomy Research, 8 (3), 637–644.

Tamm, I., Tamm, Ü., **Ingver, A.** 2009. Spring cereals performance in organic and conventional cultivation. Agronomy Research, 7 (1), 522–527.

Ingver, A., Tamm, I., Tamm, Ü. 2008. Effect of organic and conventional production on yield and quality of spring cereals. Agronomijas Vestis, Latvian Journal of Agronomy, 11, 61–67.

Haljak, M., Koppel, R., **Ingver, A**., Ruzgas, V. 2008. Variations in the morphological characteristics of winter wheat (*Triticum aestivum*). Agronomijas Vestis, Latvian Journal of Agronomy, 11, 54–60.

Koppel, R., **Ingver, A.** 2008. Comparision of yield and quality traits of winter and spring wheat. Agronomijas Vestis, Latvian Journal of Agronomy, 11, 83–89.

Kangor T., Tamm I., Tamm Ü., **Ingver A.** 2008. The agronomic and quality characteristics of spring cereals grown at different input levels of fertilizers and chemicals. Agronomijas Vestis, Latvian Journal of Agronomy, 11, 229–235.

3.2. Articles published by other publishers

Ingver, A., Koppel, R., Annamaa, K. 2016. The History of Wheat Breeding in Estonia. In: Alain P. Bonjean; William J. Angus;

Maarten van Ginkel Editors). The World Wheat Book. A History of Wheat Breeding. Volume 3, 157−191.

3.4. Articles published in conference proceedings not listed by Thomson Reuters or Scopus

Тихонова, М.А., **Ингвер, А.,** Коппель, Р. 2017. Молекулярно-Генетические Методы В Оценке Потенциала Качества Мягкой Пшеницы. Наука и молодежь:фундаментальные и прикладные проблемы в области селекции и генетики сельскохозяйственных культур. Материалы Международной школы-конференции молодых ученых, 7-10 ноября 2017 г. Россия, Зерноград, ФГБНУ «Аграрный научный центр «Донской», Отпечатано в АО «Книга», 102–108

Sooväli, P., Koppel, M., Koppel, R., **Ingver, A**. 2013. Fungitsiidi ja ilmastiku mõju tali- ja suvinisu saagile ja kvaliteedile 2011. ja 2012. a. Agronoomia 2013. Jõgeva Sordiaretuse Instituut, 132–137.

Haljak, M., **Ingver. A.,** Koppel, R. 2012. Suvinisu sortide ja aretiste glaukosiidsused ja saagikus aastatel 2008–2011. Toim. A. Astover, Agronoomia 2012, Rebellis, Tartu, 31–36.

Kangor, T., **Ingver, A**. 2012. Viljelusviiside mõju suvinisu küpsetuskvaliteedile. Agronoomia 2012. Toim. A. Astover, L. Metspalu, R. Viiralt, K. Karp, R. Lauk, V. Rehemaa. Tartu, 37–42.

Kangor, T., **Ingver, A.,** Tamm, I., Moks, M., Põldur, Ü., Soorm, Ü., Iisak, L., Kukk, J. 2011. Suvinisu agronoomilistest omadustest ja saagi kvaliteedist erinevates katsekohtades. Toim. Jüri Kadaja, Agronoomia, 2010/2011, Rebellis, Saku, 95–100.

Ingver, A., Tamm, I., Tamm, Ü. 2011. Viljelusviisi mõju suviteraviljade saagi komponentide ja kõrre omadustele. Toim. Jüri Kadaja, Agronoomia 2010/2011, Rebellis, Saku, 23–28.

3.5. Articles published in local conference proceedings

Ingver, A., Haljak, M., Koppel, R. 2017. Uued suvinisu sordid 'Hiie' ja 'Voore'. Taimekasvatuse alased uuringud Eestis 2017. Toimetajad I. Tupits, S. Tamm, Ü. Tamm, A. Toe. Jõgeva, AS Rebellis, Jõgeva, 60–67.

Tamm, Ü., Tamm, I., **Ingver, A.,** Tamm, S., Bender, A. 2017. Suviteraviljade terasaak ja kvaliteet erinevate liblikõieliste heintaimede järel. Taimekasvatuse alased uuringud Eestis 2017. Toimetajad I. Tupits, S. Tamm, Ü. Tamm, A. Toe. Jõgeva, AS Rebellis, Jõgeva, 93–98.

Ingver, A., Koppel, R., 2014. Nisusortide kvaliteedisüsteemi rakendamisest Eestis. Põllumajandusteaduselt tootjale. Aastaseminar 2014. Toimetajad I. Tupits, Ü. Tamm, S. Tamm. Jõgeva, 22−31.

Tamm, I., Koppel, R**., Ingver, A.**, Tamm, Ü., Tupits, I., Bender, A., Tamm, S., Narits, L. 2014. Liblikõieliste eelviljade mõju teraviljade saagikusele maheviljeluse tingimustes. Teaduselt mahepõllumajandusele. Konverentsi Eesti mahepõllumajandus täna ja tulevikus toimetised. Toimetajad L. Metspalu. A. Luik. Tartu, 98–101.

Ingver, A., Koppel, R. 2012 Eesti nisu kvaliteedi vastavus eksportturgude nõuetele. Põllukultuuride sordid ja nende kasutamine. Jõgeva, 20–27.

Tamm, I., Tamm, Ü., **Ingver, A.** 2012. Teraviljade saagikus ja kvaliteet mahetingimustes, maheviljelusse sobivamad sordid. Teaduselt mahepõllumajandusele. Konverentsi Mahepõllumajanduse arengusuunad – teadlaselt mahepõllumajandusele toimetised, 89−91.

Ingver, A., Koppel, R., Koppel, M. 2011. Nisu kvaliteet erinevates riikides. Efektiivne taimekasvatus, Jõgeva, 26–31.

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