Eesti Maaülikool

Weeds in different cropping systems

Umbrohtumus erinevates viljelussüsteemides

Helena Madsen

Doctoral Thesis in Agriculture
Doktoritöö põllumajanduses

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Institute of Agricultural and Environmental Sciences
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LIST OF ORIGINAL PUBLICATIONS

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II. **Madsen, H.**, Talgre, L., Kuht, J., Alaru, M., Eremeev, V., Mäeorg, E., Loit, E., Luik, A. 2020. Organic cropping systems do not increase weed seed numbers but do increase weed diversity. Agricultural Research & Technology Open Access Journal, 23 (4). DOI: 10.19080/ARTOAJ.2020.23.556244.

III. **Madsen, H.**, Talgre, L., Eremeev, V., Alaru, M., Kauer, K., Luik, A. 2016. Do green manures as winter cover crops impact the weediness and crop yield in an organic crop rotation? Biological Agriculture & Horticulture, 32 (3), 182–191. DOI: 10.1080/01448765.2016.1138141

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Paper	**I**	**II**	**III**	**IV**
Idea and study design	AL; JK, LT	AL, JK, LT	AL, LT	AL, LT
Data collection	HM, JK, EM, VE	HM, JK, EM, VE	HM, LT	HM, LT
Data analyses and interpretation	HM, JK, LT, VE	HM, JK, LT, VE	HM, LT, VE	HM, LT, VE
Manuscript preparation	EM, JK, LT	All	All	All

HM – Helena Madsen; AL – Anne Luik; EL – Evelin Loit; EM – Erkki Mäeorg; JK – Jaan Kuht; KK – Karin Kauer; LT – Liina Talgre; MA – Maarika Alaru; MT – Merili Toom; VE – Viacheslav Eremeev; All – all authors of the paper

ABBREVIATIONS

ANOVA	Analysis of variance
C	Carbon
Ca	Calcium
cv.	cultivar
Fe	Iron
ha	hectare
K	Potassium
Mg	Magnesium
N	Nitrogen
P	Phosphorus
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
S-W	Shannon-Wiener
us.	undersown

1. INTRODUCTION

The two of the most fundamental resources for mankind are land and water, which are essential for the production of food (Schneider *et al*. 2011). But since it has been projected that the human population will exceed 9 billion by 2050 (Murphy *et al*. 2007; Connor 2013; Garg and Balodi 2014), these resources are under pressure by environmental stress (climate change) and economic development (Schneider *et al*. 2011; Garg and Balodi 2014). Agriculture is considered to contribute up to 24% of the global greenhouse gas CO_2 and N_2O emissions from the soil (Trewavas 2001; Vermulen *et al*. 2012; Armengot *et al*. 2015; FAO 2021) and a threat for the decline of worldwide biodiversity (Tilman *et al*. 2001; Hole *et al*. 2005; Garg and Balodi 2014). In fact, homogenization of the landscapes (Benton *et al*. 2003; Puech *et al*. 2014) and monoculture agrosystems are claimed to be unsustainable (Trewavas 2001) due to their high dependence on external inputs and unfavourable to many species for the lack of diverse habitats (Schneider *et al*. 2011; Forster *et al*. 2013).

Organic cropping methods have been suggested to be a realistic approach for sustainable agriculture (Oerke 2006; Garg and Balodi 2014; Blanco-Canqui *et al*. 2017; Mahedi *et al*. 2025). Its main difference compared to conventional farming is the exclusion of the use of synthetic chemical pesticides, mineral N, P and K fertilizers and genetically engineered crop species (IFOAM 2005; Garg and Balodi 2014; Blanco-Canqui *et al*. 2017). By limiting fertilization and avoiding pesticides, organic agriculture can influence various environmental factors including water availability and quality (protection of groundwater and surface water); soil fertility; biodiversity (higher number of species); climate protection (reduced nitrogen losses and enhanced carbon sequestration); climate adaption (erosion prevention and flood protection) and resource efficiency (lower nitrate leaching risk and energy inputs) (Leifeld 2012; Argyropoulos *et al*. 2013; Cavigelli *et al*., 2013; Reganold and Wachter 2016; Blanco-Canqui *et al*. 2017; Sanders and Heß 2019; Çakmakçı and Çakmakçı 2023). Nutrient management in organic farming relies on the use of animal manures, crop residues and legumes for nitrogen fixation, as well as practices like planting cover crops, intercrops and using rotations for the diversification of plant species in time and space (Forster *et al*. 2013; Valenzuela 2023). Organic agriculture is considered to be sustainable and an environmentally friendlier way of farming (Bengtsson *et al*. 2005; Gomiero *et al*. 2011; Gattinger *et al*. 2012; Tuck *et al*. 2014; Barbieri *et al*. 2023), but in light of increasing global population and the organic crop yields being 20–25% lower than for conventionally grown crops (De Ponti *et al*. 2012;

Seufert *et al*. 2012; Ponisio *et al*. 2015; Barbieri *et al*. 2023) there are concerns that it may not produce enough food. Reduced yields are the result of restricted nutrient availability and weed infestation (Bilibio *et al*. 2023; Karlsson *et al*. 2025), though weeds could be managed in organic cropping by using different techniques.

Although synthetic herbicides are considered to be the most effective method for weed management, it will probably not be possible to rely only on them (Fischer and Connor 2018). Herbicides affect the dynamics of species diversity by reducing the more susceptible and promoting the more resistant weed species (Bàrberi *et al*. 1998; Rotchés-Ribalta *et al*. 2017; Ehrampoosh *et al*. 2025). Organic farming standards do not permit the use of synthetic chemical pesticides for crop protection and weeds are a yield limiting factor due to their strong competition with crop plants for water and nutrients (Armengot *et al*. 2013; Rotchés-Ribalta *et al*. 2023; Mahedi *et al*. 2025) and need to be managed. In organic farming, weeds competition can be reduced by mechanic weed control and management practices that improve crop competitiveness such as appropriate rotations, cover cropping, mulching, row spacing, seeding rates and the use of resistant crops (Garg and Balodi 2014; Restuccia and Scavo 2023). The diversification of crop rotation can improve the storage of soil organic carbon (SOC) (Blanco-Canqui *et al*. 2017) and limit the extent of diseases (Puech *et al*. 2014). Rotations that include cover crops also help to reduce soil disturbance which can result in higher soil C content and aggregate stability, improved soil structure and soil biodiversity, as well as lower weed competition through soil surface coverage (Peigne *et al*. 2015). Including crops with allelopathic properties could also contribute to weed suppression (Litterick *et al*. 2002).

There is evidence that biodiversity significantly affects nutrients dynamics, productivity and stability of agroecosystems (Tilman *et al*. 2014; Karlsson *et al*. 2025), and that at decline of weed species diversity affects the agroecosystems through impacts on organisms higher up the food chain. Although weeds reduce the productivity of crops to a significant extent, they are also thought to provide some ecological services. The beneficial role of weeds should not be neglected: they offer food, a mating place and shelter for many pollinators, natural enemies of crop pest, antagonists of crop diseases and birds (Marshall *et al*. 2006; Bretagnolle and Gaba 2015; Eraud *et al*. 2015; Rollin *et al*. 2016; Schumacher *et al*. 2020). Weeds can also play an important role in soil functions, as many weed species are symbiotic with fungi (mycorrhizae) and bacteria. According to a recent meta-analysis (Trinchera and Raffa 2023), a growing body of literature is highlighting how weeds, if well managed, could be considered as "service crops" which are able to foster arbuscular mycorrhizae

(AM) colonization across the elements of the agroecosystem and potentially improve the final performance of the main crop. Also, Litterick *et al.* (2002) have speculated that healthy soils and balanced crop nutrition result in thriving crop plants and minimal pest problem.

Successful organic farming is very site-specific. For the development of sustainable ecological weed management solutions, it is therefore also important to investigate the influence of crop rotations, cover crops and organic fertilizers on weed competition. However, there is limited information on the effect of these agronomic factors in Northern-European climates.

To address this knowledge gap the research presented here focused on monitoring weed density, biomass and diversity in a long-term five-field crop rotation. The aim was to provide a better understanding on the effect of weeds on crops and agronomically important ecosystem services.

2. REVIEW OF THE LITERATURE

Since the beginning of agriculture farmers have been combating with different harmful organisms – animal pests (insects, nematodes, rodents, birds), plant pathogens (viruses, bacteria, fungi) and weeds (competitive plants, which are not grown intentionally), also known as spontaneous species (Merfield 2022; Guo *et al*. 2025) – collectively called pests (Oerke 2006). Weeds have been considered to be a limitation of crop production in agricultural systems throughout history, as they compete with crop plants for nutrients, water, sunlight and space (Armengot *et al*. 2013; Robačer *et al*. 2015; Rotchés-Ribalta *et al*. 2023; Hassan *et al*. 2025). Weeds reduce the water availability for crops and their nutrient absorbing ability is usually greater than that of the crops (Robačer *et al*. 2015). Weeds are considered as the most important pest group affecting crop productivity mainly through competition for inorganic nutrients. The crop yield losses may be a result of reduced production and/or loss of content in valuable nutrients, leading to lower quality products (Oerke 2006). However, weed control often has a greater effect on reducing crop yields than the control of animal pests and diseases, as the weeds/unwanted plants can be controlled manually, by mechanical weeding or by using herbicides (Oerke 2006; Fischer and Connor 2018).

Agricultural intensification is increasingly recognized to have resulted in a significant loss of biodiversity, and this is partially due to the efficient control of weeds by modern herbicides (José-María and Sans 2011). While weeds are competing with crop plants they can also be "ecosystem service crops" themselves, by forming the basis of food chains within agroecosystems (Armengot *et al*. 2013). Specifically, weeds provide habitat and food source for field macrofauna such as earthworms, arthropods, birds and mammals, and have a conservational effect for many species (Clergue *et al*. 2005). Also, a diverse weed community in space and time can be a source of several ecosystem services to crop plants including increasing populations of natural enemies of plant pests and pollinators (Forster *et al*. 2013). Increased weed biodiversity is an improvement within high-input agroecosystems (Moonen and Bàrberi, 2008; Postma-Blaauw *et al.* 2012; Forster *et al*. 2013). Furthermore, maintaining a certain level of weed density/biodiversity may also increase the content of soil organic matter (SOM) by enhancing the soil biodiversity and thus improving the physical, chemical and biological processes in the soil (Blanco-Canqui et al. 2017). The non-crop/weed plant diversity in agricultural ecosystem is known to be reduced by external input of chemical fertilizers and pesticides, improved efficiency in seed-cleaning before sowing and simplified rotations. The impact of these agricultural practices on weed density and biodiversity

was also reported to reduce ecosystem services (José-María and Sans 2011), food chain interactions and multiple ecological functions (Armengot *et al*. 2013; Rotchés-Ribalta *et al*. 2023).

2.1 Pesticides in weed control

Weed management has in the past mainly been based on a combination of physical (e.g. ploughing, manual or mechanical weeding, mulching), rotation design, and to a lesser extent crop breeding and biological control (Oerke 2006). The introduction of herbicides in agriculture made it possible to replace laborious and time-consuming weed control and increase the crop yields. As weed control with tillage requires several trips with heavy equipment for adequate result, pesticide application saves fuel and reduces negative side effects of tillage on soil structure (Hossain 2015). Pesticide application made it also possible to replace fallowing, as this weed control method is related to water loss and nutrient leaching (Holm and Johnson, 2010). As pesticides reduced the competitive advantage of weeds in favour to crops, nutrient uptake from soil and thus yields improved (Hossain 2015). It has been shown that removing perennial weeds with pesticides could increase crop yields considerably. Also, higher moisture content in the soil can be preserved due to minimized tillage (Wylie 2008; Ehrampoosh *et al.* 2025), when pesticides are applied.

Although the introduction of herbicides has had a great impact on the crop production, increasing herbicide-resistance within weed populations in conventional farming has become alarming in many regions (Bàrberi *et al*. 1998; Rotchés-Ribalta *et al*. 2017). Properties of pesticides (activity and persistence in the soil) are of vital importance. If the activity of compounds is short-term or somehow decreased, extra work and multiple applications will be needed and soil health may also be compromised for a long time (Hassall 1966). Though herbicide resistance in plants may occur naturally, the continuous exposure to pesticides could also induce genetic mutations for developing resistance (Hossain 2015). Greater risk for developing pesticide resistant weed species in the field is related to repeated use of a particular pesticide, no tillage practices and not using crop rotations (Merotto *et al*. 2022). Therefore, as a result of using chemical pesticides several negative changes in the environment have been noticed: pollution of water and soil; loss of natural habitats; genetic erosion of the weed species; diminished richness and diversity of species; deteriorated food quality and potential negative health impacts of herbicide exposure on farmers and consumers (Reddy 2010; Armengot *et al*. 2013).

Since it is hard to predict the persistence of different pesticide residues in soil, as well as the sensitivity of the cultivars and ensure the optimal application rates of pesticides, herbicides may also have negative effects on the growth of crop plants (Hossain 2015). Furthermore, plants close to the field that could be unintentionally affected by low dosages of pesticides (Rotchés-Ribalta *et al*. 2015b), may experience delayed flowering or abnormal fruiting, potentially reducing the seed production (Strandberg *et al*. 2012; Rotchés-Ribalta *et al*. 2015a). Also, exposure to sub-lethal doses of pesticides can lead to more resistant and new dominant weed species (Boutin *et al*. 2010; Carpenter *et al*. 2013; Rotchés-Ribalta *et al*. 2015a). Consequently, the structure of the surrounding habitats becomes affected and altered (Hossain 2015).

Chemical runoff from spayed areas was demonstrated by a study conducted by Estonian Environmental research Centre (EKUK) in Central Estonia in 2018 and 2019. The study found traces of pesticides in the nitrate-sensitive areas, rivers and groundwater. Also, a study conducted by Centre of Estonian Rural Research and Knowledge (METK) in 2023 showed traces of active ingredients of pesticides in all soil samples taken across Estonian agricultural lands. Results from the long-term study indicated that the total concentration of active substances of pesticides has decreased in soils, whilst the total number of identified active substances has remained at the same level. The presence of pesticide residues in the water, soil and in plant tissue may pose a threat to biota within a field and neighbouring areas, as well as have a potential risk for human consumption (Hassall 1966; Kumari *et al*. 2025).

The potentially harmful effects of pesticides have been recognized by the European Union in their latest Regulation (European Commission 2020). Furthermore, several goals have been set for the environment, human and animal health protection via reducing the usage of chemical pesticides. For these purposes the European Commission announced a target of 50% pesticide reduction by 2030 as a part of Farm to Fork Strategy. For comparison, according to Statistics Estonia, in 2023 there were about 700 000 kg of active ingredient of pesticides sold, 70% of which were herbicides, and glyphosate accounted for 60% of all herbicides sold. The agricultural area in Estonia has remained approximately at the same level with 22% of the total land surface for the past 10 years (http://andmed.stat.ee), but the usage of pesticides has almost doubled during the same period (Lillak *et al*. 2021).

Although mainly pesticides are used for crop protection in conventional cropping systems, crop rotations, cover crops, intercropping and mechanical weed management are still used widely.

2.2 Organic cropping

The increasing dependency on high agrochemical inputs to maintain current yield levels has led to consumer concerns about the negative environmental, biodiversity and public health impacts, and long-term sustainability of conventional farming (Krauss *et al*. 2020). Organic systems are defined by sustainable cropping with no synthetic fertilizers, chemical pesticides nor the use of genetically modified organisms (Rigby and Caceres 2001; Mahedi *et al*. 2025). There is also evidence that organic cropping has the potential to improve soil organic matter, biodiversity, soil biological activity and enhance soil fertility (IFOAM 2005; Forster *et al*. 2013; Blanco-Canqui *et al*. 2017; Fischer and Connor 2018; Bilibio *et al*. 2023; Çakmakçı and Çakmakçı 2023). A recent review concluded that long-term organic farming affects significantly the biological and chemical properties of soil and has an overall positive effect on soil quality and microbial diversity (Çakmakçı and Çakmakçı 2023).

However, organic systems produce lower yields and this is often due to lower N-availability and less efficient weed control which are thought to be major explanatory factors for the lower yields of organic compared with conventional crops (Bilibio *et al*. 2023). Thus, for the same amount of production as in a conventional system, larger land areas are required (Muller *et al*. 2017). Although the production costs for organic farmers can be lower due to fewer inputs needed via fertilizers and pesticides (Reddy 2010), thoughtfully planned inputs are still necessary as chemical-free organic cropping does not always mean sustainability (Rigby and Caceres 2001).

Soil fertility building is a key factor for successful organic cropping and it's closely related to and affected by weed management. Some methods for soil improvement include regular inputs of animal manure or organic waste-based compost; soil cultivation (e.g. for weed control and to incorporate manure and fertility building crops); planting cover crops; diversification of crop rotations and growing intercrops (Valenzuela 2023; Mishchenko *et al.* 2025). Since the soil is the basis for all production in agriculture, as it has to support biological productivity and offer other ecosystem services (Doran and Zeiss 2000; Babu *et al*. 2023), all management practices should be targeted to improving the soil quality (Fine *et al*. 2017; Nunes *et al*. 2020; Babu *et al*. 2023).

2.2.1 Mechanical weed management

For weed management a wider range of different agronomic practices both in organic and conventional cropping could be used: increasing the density and varying the sowing patterns of crops (Weiner *et al*. 2001; Kristensen *et*

al. 2008; Eyre *et al*. 2011), altering the sowing times and tillage methods (Eyre *et al*. 2011; Robačer *et al*. 2015; Xuan *et al*. 2025). Also, ploughing controls the weediness by burying freshly shed weed seeds deeper into the soil, hindering their germination. This method is energy-consuming and may lead to long-term problems, because the buried seeds usually stay viable in the soil seedbank until they are returned to the surface by subsequent cultivations (Melander and Rasmussen 2000; Bond and Grundy 2001; Bilibio *et al*. 2023). Weed harrowing, on the other hand, tills the soil whilst also uprooting and/or covering weed seedlings with soil. Harrowing is most effective when done at earlier growth stages of weeds (Armengot *et al*. 2013). Since the soil seedbank in organic cropping tends to increase more with time, compared to conventional cropping systems, weed management should focus on preventive methods (Bàrberi 2002; Armengot *et al*. 2013; Kumari *et al*. 2025).

2.2.2 Crop rotation and intercropping

Crop rotations are an essential tool for improving soil fertility and nitrogen availability by generating temporal diversification of vegetation within a field (Olesen *et al*. 1999; Watson *et al*. 2002; Shah *et al*. 2017; Valenzuela 2023; Mishchenko *et al.* 2025). In addition to improving nitrogen availability, especially when legumes are included into rotation, rotational cropping can also (i) improve soil health via generating more diverse microbial communities, (ii) reduce weed pressure and (iii) result in lower pest and disease incidence by distrupting the life-cycles of pests and diseases (Watson *et al*. 2002; Liu *et al*. 2022; Bilibio *et al*. 2023). Diversified crop rotations may also significantly increase the crop yields, compared to monocultures (Wang *et al*. 2022; Valenzuela 2023). The establishment of legumes in the rotation supports the subsequent non-legume crops with the accumulated nitrogen. For further effectiveness legumes must be incorporated into the soil before the seed set, since harvest removes most of the benefits of fixed nitrogen (Salvagiotti *et al*. 2008; Fischer and Connor 2018). Nitrogen could be provided through pre-crop, for example by using grass-clover mixture previously in the crop rotation (Olesen *et al*. 2009; Shah *et al*. 2017).

Each rotation may have a different influence on weed flora (Simic *et al*. 2016; Mishchenko *et al.* 2025), the effectiveness of reducing weeds depends on the specific crops used in the rotation. Longer rotations with more phenologically diverse crops could have a considerable effect on reducing the populations and abundance of weeds in the soil seed bank (Teasdale *et al*. 2004). Studies in Lithuania (Butkevičienė *et al*. 2021) have demonstrated the reduction of weeds in the field and in the seedbank in a diverse long-term crop rotations. In a meta-analysis of 54 studies conducted by Weisberger *et al*. (2019), it was

found that diversification of crop rotations can significantly reduce the weed density (by 49%), whereas various environmental conditions and different crop production systems did not have such a major effect. Cropping sequence that is alternated between resource competition, soil disturbance, allelopathic effects and mechanical damage limit the proliferation and dominance of any specific weed species (Liebman and Davis 2000; Bond and Grundy 2001).

Diversification of rotations by intercropping and use of cover crops can also improve the soil fertility and contribute to weed management (Kanatas 2020). Intercropping – growing two or more crop species during the same cultivation period – can stabilize the yield and reduce weed problems. Undersowing – the combination of main crop and undersown intercrop – is a way of diversification of the agroecosystem as well as intercropping (Theunissen 1997). Intercropping contributes to sustainable agriculture, but requires thoughtful management and production methods (Charles 1958). Intercropping with legumes can result in significant nitrogen fixation, soil erosion control, and improvement of the soil structure and organic matter content (Liebman and Staver 2001). In many countries barley and oat are often mixed with field pea and other legumes to increase the protein content of the harvested feed crop with no negative effect on total forage yield. Other benefits of these mixtures include greater use of light, higher absorption of water and nutrients and improved weed suppression (Kanatas 2020).

2.2.3 Cover crops

Cover crops are grown for their ecosystem services such as nitrogen uptake and supply, weed control, reduction of soil erosion and nutrient leaching, aggregate stability improvement and to increase the soil fertility (Lu *et al.* 2000; Bond and Grundy 2001; Hartwig and Ammon 2002; Robačer *et al.* 2015; Pearsons *et al.* 2023) but usually not for harvesting. Furthermore, winter cover crops reduce nitrogen leaching and provide green manure for the subsequent crops (Toom *et al.* 2019). Cover crops are incorporated into the soil by tillage or cut and left as a mulch on the soil surface before planting the main crop (Robačer *et al.* 2015). Since tillage stimulates the germination of weed seeds and cover crop residues on the soil surface can reduce weed emergence and competition. Weed suppression by cover crops is a result of competition for resources and allelopathic abilities – release of phytotoxins from root exudates and decomposing residues of crops, which minimize the seed germination of weeds (Bond and Grundy 2001; Fageria *et al.* 2005). Thus, biomass produced by cover crops is an important factor for weed control (Robačer *et al.* 2015), as larger amounts of dry matter produced by cover crops suppresses the weeds more efficiently (Fracchiolla *et al.* 2020). A well-designed rotation with

cover crops can successfully reduce the cost of weed control and reduce the weediness, especially before a less competitive crop in the rotation (Anderson *et al*. 2001). It has been shown (Moonen and Barberi 2004) that even short-term cover cropping can lower the weed biomass, despite the initially larger soil seedbank, compared to the systems without cover crops, whilst long-term cover crop systems may reduce weed seedbank.

Thus, the influence of cover crops on weeds and soil properties depends on the specific plant species and their mixtures. Grass species are desirable for their ability to provide substantial soil cover and protection against rain and wind erosion (Robačer *et al*. 2015). Broadleaf species are used for their quick decomposition and release of nutrients into the soil. The leguminous species are known for their ability to fix atmospheric nitrogen (Bond and Grundy 2001). Mixture of different cover crop species could also assure a better C:N ratio for its decomposition, larger biomass and improved weed suppression ability. Cover crops may enhance the accumulation of organic C and N in the soil as well as the increase in availability of P, K, Ca, Fe and Mg in some soil types and climatic conditions. Additional benefits of using cover crops include improved soil aggregate stability, water infiltration and hydraulic conductivity. Furthermore, cover crops may provide better conditions for microbial abundance, diversity and activity (Koudahe *et al*. 2022) and contribute to the increase the collonization of roots by arbuscular mycorrhizal fungi in subsequent crop (Njeru *et al*. 2014). Consequently, diversification of crop rotations with cover crops may improve soil quality and contribute to weed management in organic and conventional cropping systems.

For optimized nutrient management cover crops may be utilized in combination with manure application (Thilakarathna *et al*. 2015). It was confirmed by Schwalb *et al*. (2023) that manure compost is a source of bacterial and fungal biomass, which promotes the decomposition of weed seeds. Soil fertility, fauna and microbial activity are stimulated by application of organic matter (Omotayo and Chukwuka 2009; Forster *et al*. 2013; Garg and Balodi 2014; Valenzuela 2023). Active and diverse soil life improves the transformation of organic compounds into plant-available mineral nutrients.

2.2.4 Crop yield

Crop yields are strongly affected by weed density, as it reduces yields through competition for water, nutrients and sunlight. In organic cropping systems, the prevention of potential weed problems is crucial (since herbicides cannot be used as tratments) and cover crops have the potential to affect the weed population and crop yields in the long term (Robačer *et al*. 2015). Since the

formation of the yield requires sufficient amount of N-availability in the soil, the influence of cover crops on the soil fertility and organic matter and thus the impact on yields has been recognized (Toom *et al*. 2019; Fracchiolla *et al*. 2020). Besides the potential of yield improvement, the effect of cover crops can be detected in the crop grown immediately after and subsequent crops (Reumaux *et al*. 2023). Deciding on crop choice and sequence in organic crop rotations is important, because it will determine the nitrogen availability and thus the crop yield. For example, using legume species in the rotation can increase the yield stability of subsequent crops (Frankow-Lindberg *et al*. 2009; Reumaux *et al*. 2023). The presence of slowly mineralizing organic N can have weed biomass and density enchanting effect (Semmartin *et al*. 2023).

Optimizing sowing dates and seed rates was also shown to have the potential to support high and stable yields in sustainable cropping systems (Li *et al*. 2023; Semmartin *et al*. 2023).

Agronomic managements have a long-term impact on agro- as well as on natural environment. Also, the effect on crop wellbeing and yielding-capacity of various cropping systems becomes evident in rather decades than years. Thus, ongoing observations and research will be required for better assessment and understanding.

3. AIM AND HYPOTHESIS OF THE STUDY

The aim of the study was to identify and explain differences in weed density and diversity in three organic and two conventional crop production systems of five-field crop rotation in a long-term experiment. Organic systems were diversified by winter cover crops and manure to determine their role on weeds. The purpose was to use the data collected to support the development of more environmentally sustainable weed management approaches.

The specific objectives of the study were as follows:

1. Study soil weed seedbank in the first rotation cycle (**I**) and in the second rotation cycle (**II**) in the five different cropping systems.

   Hypotheses: The number and diversity of weed seeds in the seedbank is dependent on cropping system and crop species. Cover crops in organic cropping system decrease the number and diversity of weed seeds in the seedbank.

2. Study weed abundance, biomass and diversity of different cropping systems in the second rotation cycle (**III, IV**).

   Hypotheses: Weed density, weed biomass and weed species diversity is dependent on cropping system and crop. Cover crops reduce density, diversity and biomass of weeds.

3. Study crop yields in organic cropping systems at the end of the first rotation cycle (**III**).

   Hypothesis: Cover crops increase crop yields.

4. MATERIAL AND METHODS

4.1 Study area and experimental design

The field trial was carried out in the Estonian University of Life Sciences experimental fields located near Tartu. The experiment area's soil type was sandy loam Stagnic Luvisol, based on the World Reference Base classification (FAO 2014), the humus layer reached to about 20-30 cm (Reintam and Köster 2006). The characterization of humus layer: C_{org} 1.1–1.2%, N_{tot} 0.10–0.12%, P 110–120 mg kg^{-1}, K 253–260 mg kg^{-1}, pH_{KCl} 5.9 and soil bulk density 1.45–1.50 g cm^{-3}.

The five-field crop rotation experiment with three organic and two conventional systems was initially set up in 2008. The results described include the overview of the soil seedbank in the first rotation (2011; **I**) and in the second rotation (2015; **II**); evaluation of aboveground density, biomass and diversity of weed and the yield of crops at the end of the first rotation (2012 and 2013; **III**); description of changes in weed flora during the second rotation (2013–2017; **IV**). Each plot area (60 m^2) was established in four replications placed in a systematic block design. To prevent contamination of organic plots with synthetic pesticides and mineral fertilizers, the organic and conventional plots were separated with 18 m long division of mixed grasses.

The crops grown were common in Northern European agriculture and the rotational sequence was as follows: winter wheat (*Triticum aestivum* L.) cv. Fredis, pea (*Pisum sativum* L.) cv. Tudor, potato (*Solanum tuberosum* L.) cv. Maret, barley (*Hordeum vulgare* L.) cv. Anni undersown with red clover (*Trifolium pratense* L.) cv. Varte and red clover. Crop management differed among the fields – no synthetic fertilizers were used in the organic systems, but green manure and composted cattle manure was used in combination. System Org 0 performed as control, following the initial rotation. In Systems Org I and Org II, winter cover crops, later used as green manure, were grown as follows: ryegrass (*Lolium perenne* L.) before pea, winter oilseed rape (*Brassica napus L.,* var. *oleifera*, subvar. *biennis*) before potato and winter rye (*Secale cereale* L.) before barley us. with red clover (**I**; **III**). Since weed aboveground density was very high in ryegrass, which was grown as a winter cover crop in 2008–2012, it was replaced with more suppressive mixture of winter rye and oilseed rape in autumn 2012, winter oilseed turnip (*Brassica rapa* L. var. *oleifera*) since 2014. Thus, winter rye was cultivated before barley undersown with red clover; mixture of rye and winter oilseed rape (oilseed turnip since 2014) before pea and winter oilseed rape (**II**; **III**; **IV**) (oilseed turnip since

2014 (**II**; **IV**)) preceded potato. In addition to cover crops used as green manure, composted cattle manure was applied in System Org II (20 t ha^{-1} for potato and 10 t ha^{-1} for winter wheat and barley). All cover crops, were sown immediately after harvest of the main, and were incorporated into the soil prior to sowing of the subsequent crop. Conventional systems did not have winter cover crops, but both systems Conv 0/I and Conv II were treated with herbicides, fungicides and pesticides as needed. Conv 0/I acted as control without fertilizers and system Conv II received mineral fertilizers: P 25 kg ha^{-1} and K 95 kg ha^{-1} for all crops, N 20 kg ha^{-1} for pea, N 120 kg ha^{-1} for barley undersown with red clover and N 150 kg ha^{-1} for winter wheat and potato. Red clover plots did not receive chemical pesticides nor mineral fertilizers in either of the conventional system. More detailed description of the setup of conventional systems can be found in Talgre *et al*. 2023.

Cover crops in organic systems were sown after the harvest of the main crop and ploughed into the soil in the beginning of May. Cereals and peas were harvested at the beginning of August; potato tubers were collected by hand during August–September. Red clover was cut twice during the vegetation period – in the middle of June and in the second half of July, then it was ploughed into the soil in all organic systems. Crop yields were measured only in organic systems in 2012–2013. Yield data was calculated per dry matter basis.

In paper IV, Conv 0 is used instead of the previously used Conv I for unfertilized conventional system treatment. Therefore, for better understanding, Conv 0/I will be used henceforth.

4.2 Weed seedbank analysis (I, II)

The weed seedbank samples were taken in 2011 (**I**) and in 2015 (**II**) with soil borers (15 mm diameter) before the autumn ploughing. 16 soil samples from 0–25 cm deep soil layer from each plot were mixed together in a bucket. The soil samples were then air-dried and 500 g of each sample was sifted through a 0.25 mm sieve. Weed seeds were extracted from the soil using potassium carbonate (K_2CO_3) aqueous solution, identified under the microscope and counted. The size of the seedbank was calculated to a plot area of 1 m^2 using formula:

$$N=(h*\rho*n*10)/Wd$$

where: N – number of viable seeds (n m^{-2}); h – depth of plough layer (cm); ρ – soil bulk density (g cm^{-3}); n – counted number of seeds in the soil sample; Wd – weight of dry soil sample (g).

Biodiversity was assessed by using the composition of weed seed communities and the number of seeds.

The Shannon-Wiener index was calculated as follows:

$$H' = -\sum_{i=1}^{s} pi \ln(pi)$$

The Margalef index was calculated as follows:

$$R = \frac{S-1}{\ln N}$$

Simpsons' index of species dominance (Simpson, 1949) was calculated as follows:

$$\lambda = \sum_{i=1}^{s} pi^2$$

The Equitability index (also Pielou evenness index) (Pielou 1966; Boyce 2005) was calculated as follows:

$$J' = \frac{H\prime}{H\prime max}$$

The *pi*'s are the proportion of all observations in the i^{th} species category; $H'max$ = ln(S); S – number of species (the total number of weed types in a single treatment); N – total number of individuals of all the species in the block.

4.3 Weed analysis (III, IV)

All weed samples were taken in four replicates per plot using a 0.25 cm^2 frame. Each assessment included the collection of aboveground biomass of weeds, identifying and counting of all weed species. The weed samples were then dried to a constant weight and weighted immediately. The collection of the weed samples from the fields was carried out two times during the vegetation period – before the ploughing of cover crops and 3 weeks before the harvest of rotation crops. Weed studies were conducted twice in red clover – before the first cutting (June) and before the aftermath incorporation into the soil (August). All data was collected in accordance with the TILMAN-ORG Handbook of Methods (Cooper *et al*. 2012).

4.4 Weather conditions

The experimental area is a part of the South Estonian upland agroclimatic region. The average annual sum of active air temperatures is 1700–1800 °C, the total precipitation is 550–650 mm. The vegetation period lasts usually 115 to 135 days (Tarand 2003). The meteorological data presented in Table 1 were recorded daily using a Eerika Meteorological Station located within the experimental area.

Table 1. Average weather conditions at the field site 2011–2017, compared with the long-term average (1964–2017).

Month	Mean temperature (°C)							
	2011	2012	2013	2014	2015	2016	2017	1964–2017
January	–4.7	–6.1	–7.2	–7.8	–1.9	–9.4	–3.5	–5.7
February	–11.2	–11.2	–3.6	–0.3	–0.8	0.3	–2.9	–5.7
March	–1.9	–0.4	–7.8	2.2	2.7	–0.1	1.4	–1.5
April	6.4	5.0	3.5	6.5	5.4	6.1	3.4	4.8
May	11	11.6	14.8	11.9	10.2	14.0	10.3	11.4
June	17.2	13.6	18.2	13.4	14.2	15.9	14.0	15.4
July	19.9	18.1	17.8	19.3	15.7	17.8	15.9	17.4
August	15.8	15.3	16.9	16.8	17.0	16.1	16.8	16.1
September	12.3	12.2	11.0	12.1	12.5	12.3	12.2	11.1
October	6.8	5.6	6.6	5.3	4.2	4.1	5.4	5.7
November	2.9	2.6	3.5	1.5	3.1	–1.0	2.4	0.5
December	1.0	–6.8	–6.6	1.0	–1.5	1.4	–0.4	–3.1

Month	Sum of precipitation (mm)							
	2011	2012	2013	2014	2015	2016	2017	1964–2017
January	19.0	30.2	11.4	25	29.6	34	27.4	28.6
February	9.4	18.6	14.4	12.4	8.4	55.8	22.4	22.6
March	5.8	39.4	15.6	9.0	12.0	23.3	17.0	22.5
April	11.2	42.0	16.8	13.4	69.0	51.6	51.5	31.2
May	58.4	81.6	61.2	83.8	62.0	1.6	15.5	52.9
June	35.2	100.6	52.4	103.4	39.4	124.6	94.3	70.9
July	48.2	75.0	62.6	71.4	61.4	81.6	60.7	69.2
August	54.6	87.4	75.6	113.0	41.2	42.0	106.2	81.1
September	80.0	59.8	37.6	22.2	59.0	15.4	83.4	59.3
October	47.8	45.2	44.6	35.8	10.8	33.2	75.3	56.3
November	34.4	50.2	69.8	10.4	53.8	45.5	26.1	44.7
December	52.6	9.2	47.0	41.6	41.6	30.6	51.8	36.6

Weather conditions varied considerably during the study period. In 2011 the mean temperatures were more or less consistent with the long-term average, but the vegetation period from May to August was very dry. Mean monthly temperatures in 2012 were similar to long-term average, but the total precipitation from March to June was 78 mm higher than usual. In 2013 May and June were warmer than usual, also June was noticeably drier compared to the long-term mean (Table 1).

Temperatures in 2014 were similar to the long-term average with an exception of July with above-average temperature by 1.8 °C. The precipitation on the other hand differed quite a lot from the usual with very dry March, April and September and very wet conditions in May, June and August. Winter in 2014/2015 was mild and snowy. Temperatures in 2015 did not differ a lot from the long-term average, but in terms of precipitation it was a very dry year. In 2016 the temperature in May was 2.6 °C higher, but the precipitation was highly variable, with only 2 mm of rainfall in May and June, whereas in July significantly above-average (by 61 mm) precipitation was recorded. 2017 was similar, as the temperatures were comparable to the long-term average, whilst the precipitation was the lowest in May and higher in June, August and September.

4.5 Data analyses

Statistical analyses were carried out using the Statistica software package version 13 (TIBCO Software Inc.). The statistical significance of cropping systems and their effects on summer and winter annual weed species, weed seedbank, cover crops, weed dry biomass and weed density were tested using full-factorial analysis of variance (ANOVA). Significant differences between individual means were tested using Fisher's (Tukey in **IV**) least significant difference test, where the statistical significance level was set at $p<0.05$ (unless indicated otherwise). Mean values were given with standard errors (±SE). Linear correlation coefficients between variables were calculated (**I**), and compared to significance of coefficients $p<0.01$, $p<0.05$.

5. RESULTS

5.1 Weed seedbank composition during the first (I) and second rotation (II)

The first seedbank study was carried out during the first rotation in 2011, in the soil of two organic and two conventional cropping systems.

The number of weed seeds depended on cropping systems and crop species. On average, the most seeds were found in the soils of conventional cropping systems, compared to organic ones (**I**, Table 1). In system Conv 0/I, where herbicides and no mineral fertilizers were used, the highest number of weed seeds was found. There were significantly less viable annual weed seeds in the conventional cropping system with mineral fertilizers and herbicides (Conv II) and in the organic system with winter cover crops and cattle manure (Org II), compared to other cultivation systems, by 3.1–6.1 and 2.5–5.6 thousand seeds m^{-2}, respectively (**I**, Table 1). As an average of all cropping systems the amount of weed seeds was the lowest in treatments of potato and barley undersown with clover and the highest in pea plots. Also, a clear negative relationship ($r=0.56$; $p<0.05$) was found between the dry matter yield of crops in 2011 and the number of weed seeds in Org II and Conv II systems (Fig. 1).

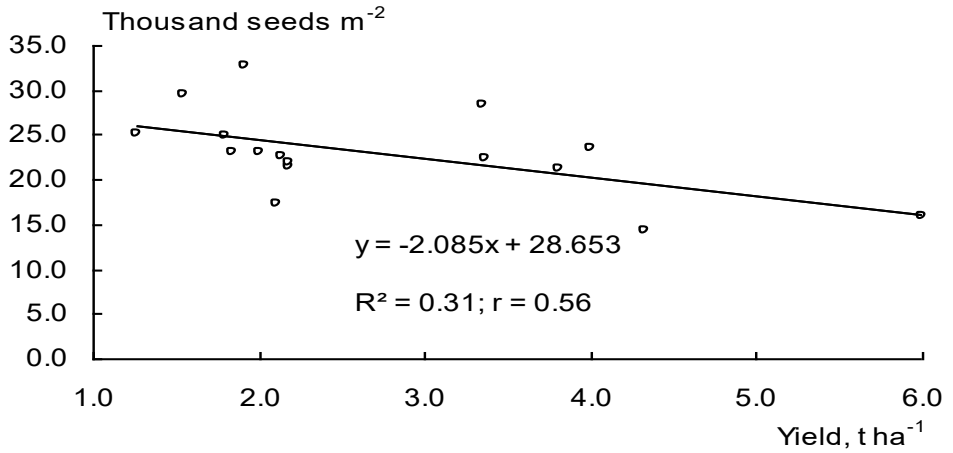

Figure 1. The correlation between total yield of the preceding crop (dry mass, t ha^{-1}) in 2010 and the number of weed seeds in the soil in 2011 (thousand seeds m^{-2}). Figure includes data from article I.

There were about 11 times more weed seeds of summer annual than winter annual species, dominated by the seeds of common lambsquarter (*Chenopodium album* L.) in 2011. System Org II soils had significantly less weed seeds of summer species. Among winter weeds the most dominant species was field pansy (*Viola arvensis* Murr) and as an average there was much less winter weed seeds in organic systems compared to the conventional plots (**I**, Table 1). The highest number of winter weed seeds was found in Conv II system.

In 2012, the control system Org 0 was added to the comparison of organic systems, and in Org 0 the same crop rotation was used without winter cover crops. Therefore, the second research of the seedbank in 2015 also included the system Org 0.

Compared to 2011, in 2015 the number of weed seeds (including summer and winter weeds) had increased in all cropping systems, although the smallest increase was recorded in system Conv I, (Fig. 2), (**II**; Table 1).

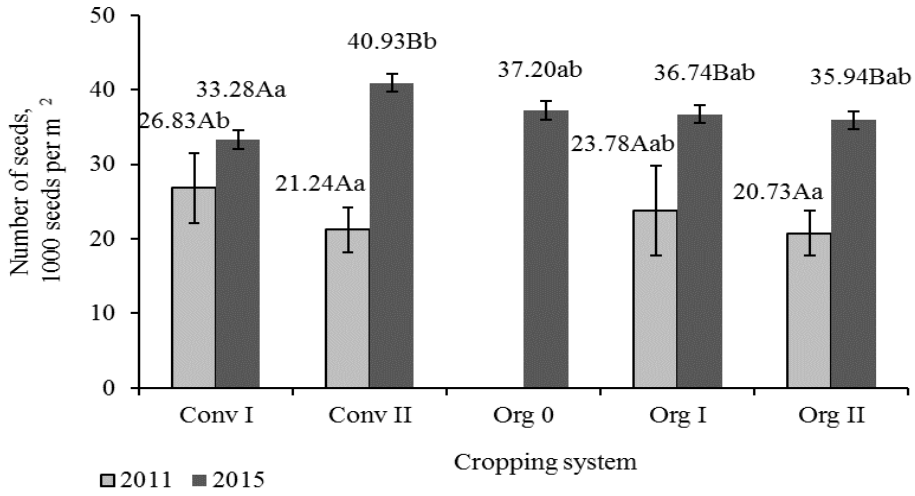

Figure 2. Total number of weed seeds, 1000 seeds per m^2 in the soil of crop rotation average of all crops in 2011 and 2015 (ANOVA, Fisher (LSD) test). Means followed by different capital letter within each bar indicate significant differences ($p<0.05$) between cropping years for the same cropping system; means followed by a different small letter within each bar indicate the significant differences ($p<0.05$) between cropping systems in the same year. Error bars denote the standard error of the means. Figure includes data from articles I and II.

The seed content almost doubled in system Conv II, where fertilizers were used. As an average of all cropping systems a tendency of higher seed number in system Conv II occurred (Fig. 2).

Although the number of weed seeds was more affected by cropping system, crop species also had influence. The tendency of higher number of weed seeds occurred in pea plots, although there were no significant differences between systems. The tendency of lowest content of weed seeds appeared in red clover plots in system Conv 0/I (**II**, Table 2).

Shannon-Wiener (S-W) diversity indexes (*H'*) were calculated to evaluate the weed seed composition in different systems. In 2015 the S-W diversity of weed species increased significantly in system Org II and decreased in system Conv 0/I in comparison to initial data gathered in 2011 (**II**, Fig. 2; **I**, Table 2). Also, the dominant weed species (C. album among summer annuals and V. arvensis among winter annuals) remained unchanged throughout the first and second study (I, Table 1; II, Table 1). Therefore, by the second rotation the greatest increase of seed numbers and unchanged species diversity of weed seeds occurred in system Conv II, whilst the lowest number of seeds and highest increase in species diversity appeared in system Org II.

5.2 Weed density and biomass in organic cropping systems at the end of the first rotation and at the beginning of the second rotation (III)

The density and biomass of weeds was measured before winter cover crop ploughing at the end of the first rotation in 2012 and at the beginning of the second rotation in 2013 (**III**).

In 2012, the density of weeds in system Org 0 was at the same level with winter oilseed rape plots, much higher than in ryegrass plots and the lowest in winter rye plots (Fig. 3). In 2013, the weed density in winter oilseed rape plots was significantly higher in systems Org I and Org II, when compared with system Org 0. Winter oilseed rape plots had the highest weed biomass in 2012 and 2013 (Fig. 4). The weed density of winter rye plots was the lowest in system Org II (Fig. 3). Weed biomass was also the lowest in winter rye plots during both years (2012 and 2013; Fig. 4). Therefore, winter rye was the best suppressor of weed dry biomass and weed density compared to other winter cover crops, whilst winter oilseed rape and its mixture with rye did not have such effect.

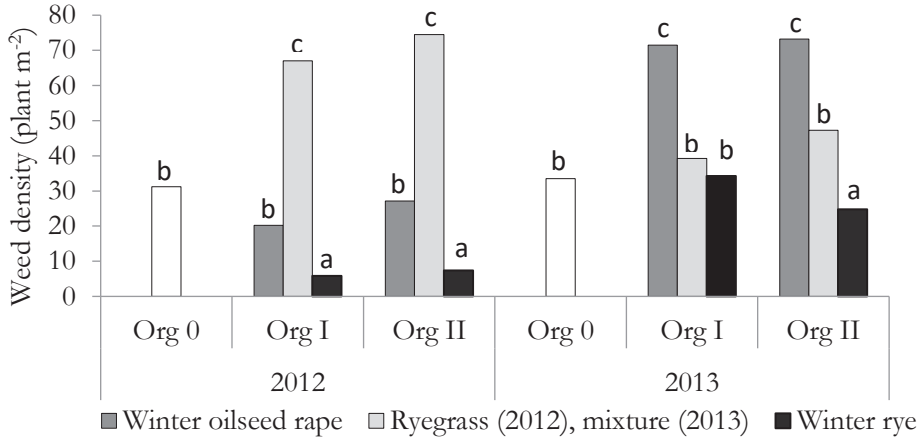

Figure 3. Weed density (plant m^{-2}) in green manures as winter cover crops before incorporation to soil in organic cropping systems in 2012 and 2013. Means followed by different letters indicate significant differences ($p<0.05$) between cropping systems in the same year (Fisher's test). Figure includes data from article III.

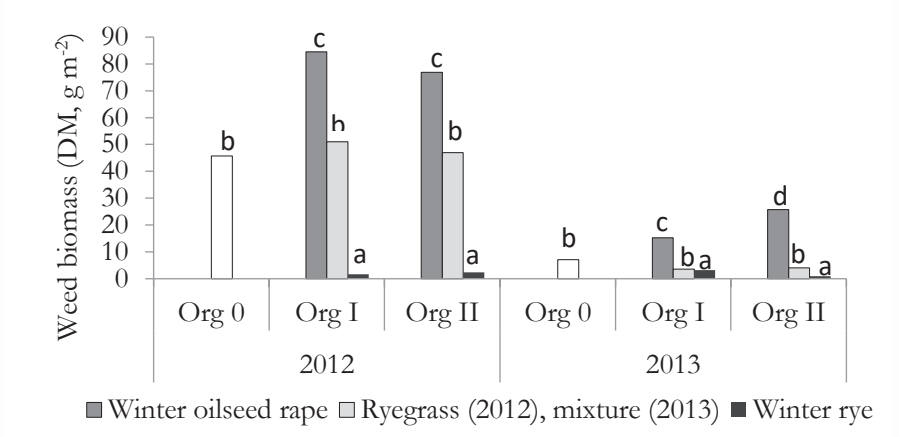

Figure 4. Weed dry biomass (g m^{-2}) in green manures as winter cover crops before incorporation to soil in organic cropping systems in 2012 and 2013. Means followed by different letters indicate significant differences ($p<0.05$) between cropping systems in the same year (Fisher's test). Figure includes data from article III.

Weed dry biomass in cover crops before their incorporation to soil indicated that weed biomass was significantly influenced by the interaction of year and cover crops ($p<0.001$) (**III**, Table 3). Therefore, the suppressive effect of winter cover crops depended on cropping system and growing year.

Weed infestation before main crop harvest at the end of the first rotation in 2012 did not find statistically significant differences between organic cropping systems, however several tendencies occurred. In control system Org 0 the highest weed biomass was measured in potato plots, mainly due to the dominance of *Equiseum arvense* L. (**III**, Fig. 3). Potato plots in systems Org

I and Org II also had high weed biomass. Significantly lower weed biomass, compared to potato plots was measured in barley (us. with clover) and winter wheat plots.

In 2013 high weed biomass occurred in pea plots – significantly high weed biomass was observed in system, where cover crops with manure was used (Org II). Weed biomasses were the lowest in barley (us. with red clover) and winter wheat plots (**III**, Fig. 3).

The overall weed density in 2013 in all crops was slightly higher than in 2012. Pea plots in system Org II had the highest weed density in 2012 and among all organic systems in 2013, whilst there were no significant differences between other crops (**III**, Fig. 4). Thus, the clear trend of cover crops and manure (Org II) increasing weed biomass and density in pea was observed. Weed dry biomass showed that weather (year) and cropping system interaction had a significant influence (**III**, Table 4).

5.3 The aboveground biomass, density and diversity of weeds in different cropping systems during the second rotation (IV)

During the second rotation the biomass and density of weeds were strongly affected by treatment and on average were significantly higher in organic systems (Fig. 5). However, there were no significant differences between the two conventional systems (Conv 0/I and Conv II) and the three organic systems (Org 0, Org I and Org II).

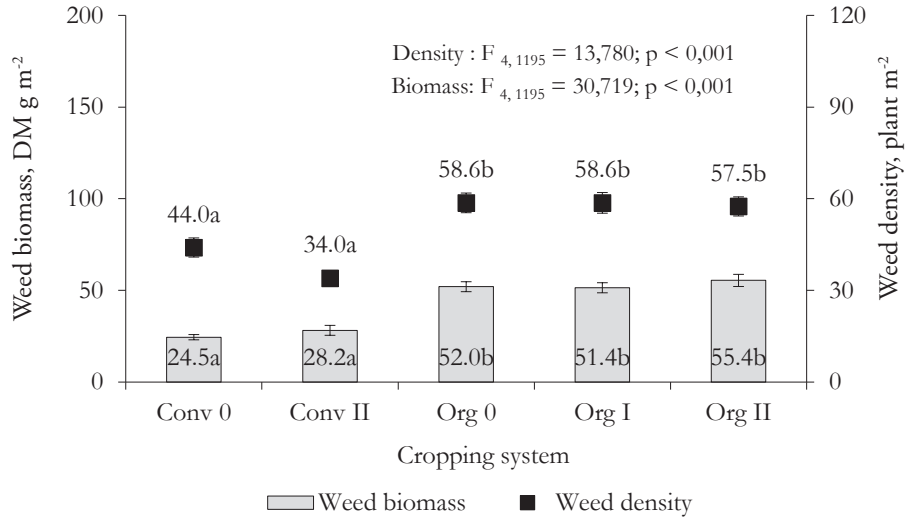

Figure 5. Weed biomass (DM, g m^{-2}) and weed density (plant m^{-2}) average of 5 crops in 2013–2017. Means followed by different letters indicate significant influence of crops (Tukey HSD post-hoc test, p<0.05). Error bars denote the standard error of the means, n=260. Figure includes data from article IV.

Differences in weed biomass and density depended significantly on crop species (**IV**, Fig. 1–5). The lowest weed biomass was measured in potato and barley plots, although they were about two times higher than in conventional system plots. Weed density in barley (us. with clover) plots was also significantly higher in organic systems, with a trend of being highest in systems Org I and Org II (**IV**, Fig. 1). Weed diversity increased in all systems during the rotation. There was a significant rise of weed diversity in barley plots in system Conv 0/I, although the weed biomass was the lowest there. The diversity in Conv 0/I reached to a comparable level with organic system treatments, whilst the highest S-W index value of all was found in system Org I (**IV**, Table 4).

Weed biomass was higher in red clover than in barley plots. The lowest weed biomass among red clover plots occurred in systems Conv 0/I and Org I, whilst the highest was in system Conv II. Also, there was a trend of higher weed densities found in systems with cover crops (Org I and Org II) (**IV**, Fig. 2). The species diversity remained at the same level in systems Conv 0/I and Org 0, but decreased significantly in system Conv II and increased in system Org I during the rotation (**IV**, Table 4).

In winter wheat plots the weed biomass and density were the highest in organic systems, but no differences among cropping system plots appeared (**IV**, Fig. 3). The highest weed diversity was measured in system Org 0 and it increased significantly in systems Conv 0/I and Org II during the rotation (**IV**, Table 4).

The highest values of weed biomass and density occurred in pea plots in all of the cropping systems in comparison with other crops. Similarly to other crops, the measures in pea plots were significantly higher in organic than in conventional system (**IV**, Fig. 4). There was a trend of lower weed density in systems, where cover crops were used (Org I, Org II), but the overall change in weed diversity during the rotation was small (**IV**, Table 4).

Although the weed biomass was at a similar level in both potato and barley plots, the weed density was much lower in former, compared to the latter in organic systems. Highest weed density occurred in system Conv 0/I, whilst in system Org II it was the highest among all organic system treatments (**IV**, Fig. 5). Weed diversity increased more in conventional systems, but also in system Org II during the rotation (**IV**, Table 4).

The Shannon–Wiener diversity index rose in all systems during the rotation from 2013 to 2017 (Fig. 6).

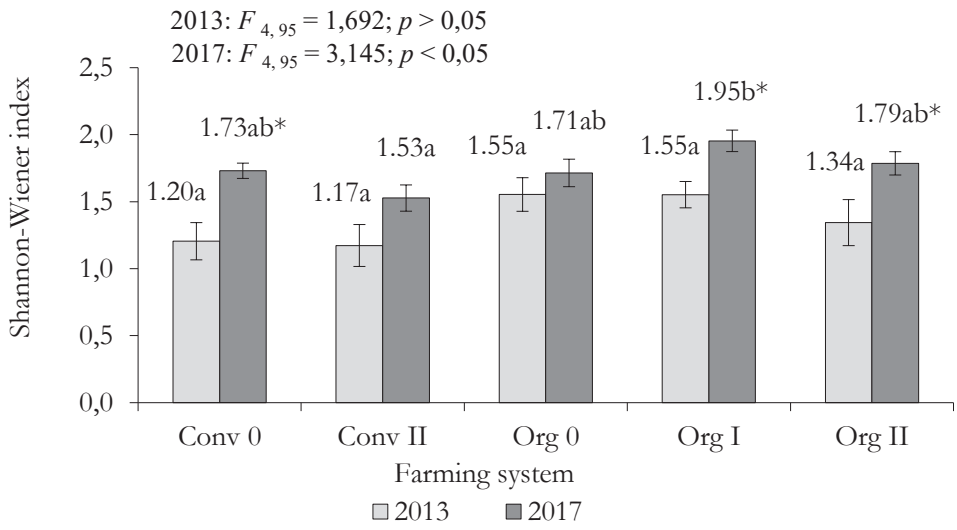

Figure 6. Shannon-Wiener index in 2013 (after the 1st crop rotation) and in 2017 (after the 2nd crop rotation) according to cropping systems. Means followed by a different letter(s) indicate significant influence of systems (Tukey HSD post-hoc test, p<0.05) Error bars denote the standard error of the means. Figure includes data from article IV.

At the beginning of the second rotation in 2013 the S-W indexes started to increase in favour of organic systems. After the second crop rotation in 2017 S-W index was higher in systems Org I and Org II compared to control system Org 0 and conventional system Conv II. By the end of the second rotation in 2017 S-W index rose in barley (us. with clover) (by 48.9 %), winter wheat (by 55.7%) and potato (by 52.6%) plots (**IV**, Table 4).

5.4 Crop yields during the second rotation (III)

Differences in the effect of winter cover crops on the yield of the following crops were dependent on crop and year (Table 2).

The yield of potato varied significantly among the systems through the years. In 2012 the yield was at an even level both in systems Org 0 and Org I, but almost 12% lower in system Org II. In 2013 the potato yield dropped remarkably compared to the previous year, as it was significantly low in system Org 0 (Table 2). Pea was one of the lowest yielding crops, as its yield was at the same level in all organic systems in 2012 (Table 2). The yield in total increased by 63% in 2013, with the lowest rates in system Org 0.

Table 2. Crop yield (t ha^{-1}) depending on the cropping system (CS) in 2012 and 2013. Table includes data from article III.

Crop CS	2012	2013	2012–2013
Barley			
Org 0	1.44a[1] ± 0.04[2]	2.65a ± 0.17	2.05a ± 0.24
Org I	1.34a ± 0.17	2.77a ± 0.12	2.06a ± 0.29
Org II	2.17b ± 0.29	3.41b ± 0.10	2.79a ± 0.27
Winter wheat			
Org 0	5.11a ± 0.28	3.62a ± 0.18	4.37a ± 0.32
Org I	5.86ab ± 0.29	3.94a ± 0.49	4.90a ± 0.45
Org II	6.58b ± 0.37	3.79a ± 0.15	5.19a ± 0.56
Potato			
Org 0	36.7a ± 2.5	18.2a ± 0.7	27.5a ± 3.7
Org I	35.8a ± 2.3	21.2b ± 0.4	28.5a ± 3.0
Org II	32.4a ± 1.4	21.3b ± 1.2	26.9a ± 2.3
Pea			
Org 0	2.11a ± 0.24	2.84a ± 0.13	2.48a ± 0.19
Org I	2.07a ± 1.10	3.46ab ± 0.20	2.77a ± 0.28
Org II	1.81a ± 0.08	3.16b ± 0.16	2.48a ± 0.27

[1]Means followed by a different letter within each column indicate significant influence ($p < 0.05$) of cropping systems;
[2]Standard error of the means.

Spring barley yield was at the lowest point in 2012, though it was significantly high in system Org II. The yield was also the highest in system Org II during 2013. Winter wheat had almost three times greater yield than barley in 2012 (Table 2). The yield in system Org II was the most prominent and the lowest in system Org 0. In 2013 the yield decreased to an equal rate, but the most eminent drop (44%) was evident in system Org II.

6. DISCUSSION

6.1 The effect of cropping system and crop species on diversity and number of the weed seedbank (I, II)

The five-field long-term crop rotation study with three organic and two conventional systems was performed. All five crops in the described experiments (barley us. with red clover – red clover – winter wheat – pea – potato) had significantly different effect on weed suppression. The detailed evaluation of the soil seedbank allows to study the influence of field management in the past and predict weed-related problems in the future.

High weediness and thus weed seed infestation in pea plots throughout all of the systems over the course of our experiment was the result of the poor choice of cultivar or weak competitiveness of the pea. Red clover, in contrary, was a strong competitor against weeds. Thus, undersowing barley with red clover had a decreasing effect on weed emergence. Albrecht (2005) also found that weed seedbank was reduced by 39% in treatments, where undersowing with clover was used. Clover was mowed twice before incorporation to the soil in all cropping systems of our experiment. As a result of mowing, the effect of clover on weed biomass and density was similar in all systems.

The first investigation of seedbank in two conventional and two organic systems showed differences depending on cropping systems and main crops. The yield of the preceding crop proved to be one of the main factors influencing the number of weed seeds. Negative correlation between dry matter yield of crops and the number of weed seeds was found in systems Org II and Conv II (Fig. 1). Higher biomass production of crops resulted in higher yields. In consequence, weeds had disadvantage in the competition for nutrients, sunlight and space and thus produced less seeds. Robačer *et al.* (2015) stated that competitiveness of crop is more dependent on the weed canopy density rather than biomass.

The number of weed seeds was also affected by winter cover crops – mostly by rye, which was sown as a winter cover crop before barley and ploughed into the soil in spring (**I**; Figure 2). Liebman and Dyck (1993) found that weed biomass was lower in cover crops as living mulch systems. Also, Miura and Watanabe (2002) found that living mulch is an effective tool for weed control. Cover crops appear to have an effect on the germination and sprouting of weed seeds by allelopathic interaction and by influencing the light conditions, soil temperature and soil moisture (Teasdale, 1996). Although the ability to suppress the number of weed seeds depended on the specific cover crop, rye

was the most effective species and ryegrass the least. Small reduction of weed seeds in red clover plots of Org II system was probably due to the fact that the cover crops were sown after the preceding pea and potato crops (**I**).

In our study cover crops have also greatly promoted ecosystem services such as natural regulation of weeds and pests; higher activity, density and diversity of polyphagous carabids – seed and pest predators (Kruus *et al.* 2014, Talgre *et al.* 2023). This may have been achieved by better overwintering and feeding conditions offered by cover crops (Kuht *et al.* 2016). Since no pesticide treatment affected carabids in the organic system, higher density and biomass of cover crops, as well as weeds (**IV**), promoted the diversity of carabids as seed predators in system Org II (Talgre *et al.* 2023), thus resulting in lowest number of weed seeds in the same system in 2011.

In the second rotation, the number of weed seeds increased and changes in diversity were observable in all systems (**II**). There have been similar changes described in other long-term experiments (De Cauwer *et al.* 2010; Butkeviciene *et al.* 2021). The largest increase of weed seeds since 2011 occurred in system Conv II, where mineral fertilizers with herbicides were used. The larger amounts of mineral fertilizers could have affected weed seed production in that system. On the other hand, the least amount of weed seeds, measured in system Conv 0/I with no fertilizers but with herbicides, could have been the result of long-time herbicide treatments in previous years. Some researchers have noticed that if herbicides were applied continuously, the total seedbank showed signs of declining (Ball and Miller 1990; Liebman and Dyck 1993).

The number of weed seeds in all organic systems was lower than in system Conv II, with the lowest number in system Org II, where cover crops with composted manure was used. System Org II also had the lowest number of seeds in 2011. Furthermore, the most diverse weed composition indicated by the highest Shannon-Wiener index was also observed in system Org II (**II**, Figure 2, 3). Therefore, it is possible to conclude that cover crops in combination with manure increased the diversity of weed species and consequently also promoted carabid diversity (Schumacher *et al.* 2020).

Although non-composted manure could be a source of weed seeds (Pleasant and Schlater 1994), it can also stimulate the activity of microorganisms and enzymes in the soil (Sánchez de Cima *et al.* 2015a). Data of soil investigation on the same site in 2013–2014 supported the former statement, as highest microbial activity and increased earthworm biomass was reported in system Org II (Madsen *et al.* 2015; Talgre *et al.* 2017). Many authors (Forster *et al.* 2013; Garg and Balodi 2014; Valenzuela 2023) have agreed that application

of organic residues like green manure and animal manure and using rotations with cover crops, intercrops and legumes stimulate microbial activity and increase soil fertility. Fertile soil, on the other hand, has a positive effect on crop yield and their competitive ability against weeds and diseases (Robačer *et al*. 2015).

The higher weed seed number trend in system Org 0 was probably caused by the lack of winter cover crops. Dorn *et al.* (2015) has stated that cover crops either growing or incorporated into the soil have an inhibitory effect on weeds. Cover crops, when incorporated in a cropping system, have numerous beneficial effects: better weed suppression, increased soil microbial activity and an abundance of seed predators, which can affect the abundance and distribution of weed seeds (Westerman *et al.* 2010; Sánchez de Cima *et al.* 2015a).

All in all, it seems that in organic systems where cover crops and cattle manure was used, the improved soil microbial activity and greater biodiversity of predators created a trend for better weed seed control, in opposite to conventional management, where herbicides did not have a comprehensible effect on the weed seedbank.

6.2 The influence of cover crops on weeds in organic cropping systems (III)

The ability of cover crops to suppress weeds was dependent on specific plant species and growing conditions. Accordingly, in winter rye plots the weed biomass and density were the lowest compared to winter oilseed rape and ryegrass plots. However, the influence of cover crops depended more on the year and not significantly on the cropping system.

In 2012, with more favourable growing conditions, the influence was stronger than in 2013, when overwintering conditions were less favourable. In addition, colder weather in April did not enhance the biomass formation. Accordingly, Linares *et al*. (2008) pointed out that the efficacy of a cover crop in suppressing weeds is affected by plant density and aboveground biomass. Further, Fageria *et al*. (2005) and Linares *et al*. (2008) found that winter rye as a winter cover crop can provide very effective weed control. Also, Barberi and Mazzoncini (2001) found that rye reduced weed biomass significantly, but the suppression depended on cover crop biomass. Also, it was found that in seasons with high crop yield, the weed biomass was reduced by up to 99%.

Rye promotes weed suppression through allelopathic compounds, which inhibit the germination of weed seeds (Kołota and Adamczewska-Sowińska 2013), and as a result light quality, soil surface temperature and competition for nutrients are reduced (Mirsky *et al*. 2013; Silva and Bagavathiannan 2023). Furthermore, a crop rotation study conducted by Valenzuela (2023) has shown that rye, when grown as cover crop and has produced sufficient amount of biomass, increases the soil organic matter content. Therefore, barley as the following crop may have had better soil conditions because of rye.

Weed biomass in barley (us. with red clover) plots was the lowest in all systems during the second rotation, possibly due to cover crop (winter rye) and the intercrop effect of red clover. Preceding crops often have a direct effect on the following crop by improving crop health and possible yield increase via nutrient availability (Angus *et al*. 2015; Reumaux *et al*. 2023; Gazoulis *et al*. 2025). Undersowing may offer multiple ecological advantages, including sustainable disease, pest and weed control and increasing nitrogen supply for the succeeding crops (Talgre *et al*. 2009; Blessing *et al*. 2022; Li *et al*. 2023; Landschoot *et al*. 2024).

Main crop species and weather conditions during the year influenced weed biomass significantly. In 2012 the weed biomass was the highest in potato plots and in 2013 it was higher in system with cover crops (Org I), compared to other systems. The reason could be in the preceding cover crop – oilseed rape – which was the weakest in weed density and biomass suppressing. Boydston and Hang (1995) found that incorporated residues of rapeseed can reduce weed density up to 85% in a subsequent crop. This effect of *Brassicacea*e did not appear in our study in either year.

In 2013, the largest weed biomass and density was measured in pea plots with the tendency to increase under the influence of cover crops in systems Org I and Org II. Weed biomass was probably affected by higher C content (Luik *et al*. 2014) in soil in Org I and II. Ryegrass (2011/2012) and mixture of winter oilseed rape and winter rye (2012/2013) did not form sufficient aboveground biomass for proper weed control in following pea plots. This led to increased weed seedbank size and thus higher weed pressure for pea. A study conducted in Lithuania (Deveikyte *et al*. 2009) found that pea had low competitiveness against annual weed species like *Chenopodium album* L., which was also the most abundant species in our trial in organic systems. Also, Lundkvist *et al*. (2008) noticed that pea had significantly higher weed biomass before harvest compared to winter wheat, for example. Lower infestation of winter wheat with weeds during the trial was explained by the strong competitor red clover as the preceding crop in the rotation.

6.3 The aboveground biomass, density and diversity of weeds in different cropping systems (IV)

During the second rotation weed biomass was noticeably lower in conventional systems, especially in system Conv I, where mineral fertilizers and herbicides were used. In his overview article, Hole *et al*. (2005) stated that many studies investigating field flora have concluded that as the major difference between conventional and organic cropping the number of weed species can be over two times lower under conventional farming. Reportedly, this phenomenon applied mostly on broad-leaved weed species (e.g., *Brassicaceae*, *Fabaceae*, *Polygonacea*), but it was also confirmed by our findings after the investigation of weeds (**IV**). According to our results, the weed density as well as diversity in conventional systems were similar to organic systems. This could be explained by the effect of herbicides on the more dominant weed species, which resulted in the opportunity for other species to occupy the vacated niche.

The average of weed biomass and density in different systems during the second rotation did not have any differences amongst organic systems. This could be an indication of the unsuitable cover crops used, as they could not prevent the larger extent of weeds in the main crops. Oilseed rape and mixture of oilseed rape with winter rye, which were the most weed infested cover crops (**III**), probably did not form sufficient biomass for adequate weed control during the main crop growth. According to Junod *et al*. (2024), the cover crops suppress weeds during their growing stage by limiting weed germination and access to resources and light. Although the selected cover crops in our field experiment may have had too weak ability to control weeds, decline in density, diversity and emergence of weeds after the cultivation of cover crops has been widely postulated in literature (Dorn *et al*. 2015; Masilionyte *et al*. 2017; Alonso-Ayuso *et al*. 2018; Büchi *et al*. 2020; Kadziene *et al*. 2020; Gazoulis *et al*. 2025). It has been noted that cover crop species with higher biomass potential have better weed control properties (Fracchiolla *et al*. 2020). In addition, the high amount of biomass is advantageous for improving the soil health and nutrition potential for following crops, and consequently has ecological benefits like promoting the growth of arbuscular mycorrhizae (Junod *et al*. 2024) and increasing the content of organic matter (Han *et al*. 2020).

There was a tendency for the higher weed species diversity in barley (us. with clover), red clover and potato plots under the cover crop influence. Tillage in potato plots had a negative effect on the amount and density of weeds in every system. It had an influence on the weed infestation of barley (us. with red clover) plots, since potato was the pre-crop (**IV**, Fig. 1). Also, Hole *et al*. (2005) noted that undersowing crops in organic crop rotation is a good

method to limit the weed cover. Weed biomass in barley (us. with clover) plots did not differ among organic systems, but higher density of weeds in systems with cover crops Org I and Org II was in correlation with higher diversity of weeds. Significantly high S-W diversity index at the end of the second rotation suggested that there were many different but small weed species in barley (us. with clover) plots. According to Rotchés-Ribalta *et al*. (2020) weed seed species diversity in the soil mimics the aboveground vegetation patterns in organic systems, thus ensuring a diverse species community in the system, as the number of weed seeds in barley (us. with clover) plots (41.09 seeds m^{-2}) was almost as high as in the most infested crop pea (42.07 seeds m^{-2}) (**II**).

The highest weed density in potato plots was measured in conventional system Conv 0/I, where no fertilizers but herbicides were used (Fig. 5; **IV**). The diversity index in potato plots increased in all systems by the end of the second rotation, with an almost threefold increase in system Conv 0/I (Table 4; **IV**). Rotchés-Ribalta *et al*. (2015b) have claimed that herbicides terminate the most sensitive weed species, thus meaning, that the remained species became more resistant to herbicides. Romero *et al*. (2008), on the other hand, pointed out that herbicide application may cause imbalances in weed community and affect the distribution of species. This may be implemented to our study as well, because at the beginning of the rotation there were no clear dominant weed species, but by the end of the rotation in 2017 the highest count of *Equisetum arvense* L. due to herbicide resistance and degraded soil properties was evident in system Conv 0/I potato plots.

In red clover plots, which followed the barley undersown with red clover in the rotation, the highest weed biomass occurred in system Conv II (Fig. 2; **IV**). Although undersowing cereals suppresses weeds mainly by providing a dense crop cover within the rotation (Bond and Grundy 2001; Hole *et al*. 2005; Eyre *et al*. 2011), the mineral fertilizers added to barley in the conventional system affected the freshly established clover. According to Bender (2015), N-fertilizer rate of 90 kg ha^{-1} had a negative effect on the growth and development of red clover. The much higher N-fertilizer rate of 120 kg ha^{-1} used for barley undersown with red clover in system Conv II in our study resulted in uneven crop cover in red clover plots, illustrated by gaps in the stand, which were consequently filled with diverse species of weeds. Among weed species there were numerous perennials like *Matricaria perforata* Merat, *Elymus repens* (L.) Gould, *Artemisia vulgaris* L. and *Taraxacum officinale* Weber in Wiggers s.l. On the contrary to conventional systems, the species diversity in organic systems was low at the beginning of the rotation, but increased by the end of the second rotation (Table 4; **IV**).

Overall weed density was almost twice as high in winter wheat compared to red clover plots, although weed biomass was lower in conventional systems (Figure 3; IV). Despite the higher density, the diversity was low in system Conv 0/I (Table 4; IV), which was an indication of a few dominant weed species. Melander *et al.* (2020) have noted that crop diversification during a crop rotation is the best way to disrupt the lifecycle of weeds. Furthermore, the decline of *Chenopodium album*, for example, from soil weed seedbank can be controlled through establishing winter crops in the autumn. Since *C. album* is a summer annual species, the seeds germinating during autumn will be terminated during winter. As the weed seedbank of our experimental area consisted mainly of *C. album* seeds (**I**; **II**), it may be relevant because of the significantly higher weed biomass and density in organic systems and low diversity in all systems. Also, weed biomass was affected by the abundance of perennial species *M. perforata* in the organic systems winter wheat plots, which was not susceptible to spring harrowing. However, as Melander *et al.* (2020) found, balance between different crops in the rotation prevents the accumulation of weed populations. Crop diversification by changing the seasonal establishment and crop composition stimulates the diversity and richness of weed species, whilst the general pressure reduces.

Pea had very weak weed control activity throughout all systems and during all rotations as the biomass, density and diversity of weeds in pea plots were the highest of all crops (Fig. 4, Table 4; **IV**). Weed biomass was higher in conventional system with fertilizers (Conv II) than in control system Conv 0/I, but the overall weed infestation was significantly lower than in organic systems. Although the low competitiveness of pea was already noticed by Lundkvist *et al.* (2008), Romanya *et al.* (2012) has shown that inclusion of legumes in organic crop rotation may produce about 0.53 kg m^{-2} increase of soil organic matter (about 1-1.5 kg C^{-2} per year). Furthermore, as stated by Shah *et al.* (2017), the main reason for using legume crops is the enhancement of nutrient supply for following crops. The increased C amount during pea growing season allowed weed biomass to proliferate, mostly at the expense of perennial weed species such as *Cirsium arvense* (L.) Scop. var. mite Wimm. et Grab. and *Equisetum arvense* in the organic systems. Still, tendency of the lower density and diversity of weeds occurred under the influence of cover crops and cover crops with composted manure in systems Org I and Org II. For better weed control, pea cultivars with fast initial development should be favoured. Also, optimal sowing time and seeding rate help to establish dense canopy, which has an advantage over weeds (Jõemaa 2017).

6.4 The influence of cover crops on soil and crop yields (III)

The most distinguishing feature of conventional and organic soils, according to Aldebron *et al*. (2020), is the availability of soil organic matter (SOM). Soils enriched with composted animal manure, cover crops and green manures have a greater pool of SOM. Babu *et al*. (2023) described the soil as a substance of natural wealth that ensures various ecological functions like providing habitat, rainwater adjustment and carbon sequestration. A healthy ecosystem has many beneficial features for humans as well. However, soil is dependent on carbon input and microbial activity (Liang *et al*. 2020; Angst *et al*. 2021), but environmental stressors such as pesticides may inhibit the process of carbon sequestration. Sánchez de Cima *et al*. (2015b) published an article concerning the content of soil organic carbon (SOC) during the first rotation in 2010–2012 on the same site and it was already evident that the SOC pool in conventional systems lacked of organic fertilizers. Semmartin *et al*. (2023) acknowledged the need for the assessment of agronomic practices on carbon accumulation during long-term experiments, as although the changes in SOC stock are very slow, they are important for further knowledge on more sustainable cropping systems.

Organic systems where cover crops (Org I) or cover crops with manure were used (Org II) had a tendency of higher C accumulation, compared to the organic control system Org 0 (Madsen *et al.* 2015; Talgre *et al.* 2017). The diversification of crop species helps to store more soil organic matter in long-term than in simplified rotations, as was noted by Blanco-Canqui *et al*. (2017). Also, biomass from winter cover crops, cattle manure and weeds significantly increased microbial activity in organic systems (Madsen *et al.* 2015; Talgre *et al.* 2017).

A study conducted by Sánchez de Cima *et al*. (2015c) in the same field during the first rotation period in 2008–2012, noticed a trend of higher concentration of Ca and Mg in the soils of organic systems. Although there was an overall nutrient decline in all systems from the beginning of the first rotation, the soils in conventional systems had been gradually depleting whilst soils in organic systems remained stable until the end of the second rotation (Madsen et al. 2015; Talgre et al. 2017). Furthermore, Sánchez de Cima *et al*. (2015c) pointed out that since the soils of the whole experimental area were naturally acidic (pH_{KCl}<6), the availability of Ca and Mg was limited. However, the pH levels in organic systems have been increasing and consequently, the nutrient availability improved, compared to conventional systems with higher acidity. Although there were measurable benefits of cover crops and composted manure on the

soil health and nutrient composition, it did not affect the yields of the main crops as expected (Madsen et al. 2015).

Species richness of weeds in organic farming contributes to overall biodiversity in agroecosystems. An increased diversity of weeds leads to higher variety of pollinators and improved fruiting and yields in organic crop fields (Menalled *et al*. 2001; Morandin and Winston 2005; Roschewitz *et al*. 2005; Hyvönen *et al*. 2008). Our investigation of weed species confirmed that organic systems had larger diversity than conventional systems, particularly in system Org II plots (Talgre et al. 2017). According to study performed on the same plots during the third rotation by Talgre *et al*. (2023), organic plots held nearly two times more species than conventional plots. In addition, there was a strong correlation found between weed biodiversity and the abundance, diversity and community structure of carabid species. Findings by Mäder *et al*. (2002) support the higher activity-density of the carabids and spiders in organic plots.

In 2012, the cover crops did not have a significant effect on pea yield, but the yield of spring barley and winter wheat increased in the system with cover crops and composted manure (Org II) (**III**, Table 5). Gosling and Shepherd (2005) contrasted organic systems with conventional ones by claiming that higher yields in the latter systems are the result of larger SOM, due to larger amount of crop residues. Therefore, though it seemed that cover crops helped to increase the potato yield in system Org I, the largest yield obtained in control system Org 0 was due to the effect of higher weed biomass in that system (**III**, Figure 3), contributing to the SOM content.

In 2013, the yields of potato and winter wheat decreased dramatically during rough weather conditions. Control system Org 0 experienced the steepest drop in potato yield, whilst in winter wheat plots the decline was the largest in system Org II, although yields were at the same level in all organic systems. Le Campion *et al*. (2020) suggested that the main reason for lower yields in organic cropping is a consequence of the fertilization, as available nitrogen from organic sources mineralizes over twice as long as N from mineral fertilizers. Furthermore, organically managed crops experience different kinds of abiotic stress than conventional crops. Since the mineral N supply tends to be lower in organic soils, plants are more likely to use N fixed from atmosphere (Barbieri *et al*. 2023). For leguminous species like red clover and pea that derive nitrogen through root nodules from the air, there may have been a buffer against the harsh weather conditions in 2013. Furthermore, according to Valenzuela (2023), intercropping with legume species often improves the yield of the companion non-legume crop.

Crop yields of organic and conventional plots were measured by Alaru *et al*. (2014) during the first rotation (2008–2012) and it was found that the yields were lower by 25–35% in organic systems. The main findings confirmed that mineral fertilizers and pesticide treatment ensured larger yields, although yields of pea and red clover did not differ significantly between organic and conventional plots. Also, the winter wheat yield in conventional system was similar to organic systems Org I and Org II. According to another study by Keres *et al*. (2020) including two rotations on the same experimental site, it was noticed that average yields in organic systems were lower by 3–28% compared to conventional system and only Conv 0/I had similar yields to organic treatments. Although cover crops and cattle manure had improved the soil characteristics significantly (Madsen et al. 2015; Talgre et al. 2017), the main yield limiting factor in organic treatments was the slow mineralization rate of organic N in the soil. Some studies (Ponisio *et al*. 2015; Muller *et al*. 2017; Dash *et al*. 2023) have noted that with well combined management practices and thoughtful crop selection organic farming can produce yields close to that produced in conventional farming.

The aim of organic cropping is to achieve profitable yields, maintain soil fertility, keep environmental biodiversity and ensure animal and human health (Röös *et al*. 2018). Although organic cropping produces less yield, the benefits gained from more SOM and increased biodiversity have greater potential for the longevity and prosperity of the sustainable agrosystems in the future (Daugbjerg 2023; Marino 2023). Furthermore, as Çakmakçı and Çakmakçı (2023) have pointed out, organic agriculture has advantages over conventional farming in terms of greater soil aggregate and structural stability. Also, it was found that there is a higher concentration of nutrients in organically produced food.

Since crop yields are dependent on nutrient input, careful consideration of the crop and weed management via cover crops and/or manure could reduce the yield gap between organic and conventional cropping even more. All in all, further research adapted to local conditions may offer newer possibilities for yield increase in organic cropping systems as well.

CONCLUSION

The impact of weed seedbank, their aboveground biomass, density and diversity on crops yields were studied in a long-term crop rotation experiment with different cropping systems. The rotations consisted of two conventional systems – Conv 0/I and Conv II, and three organic systems – Org 0, Org I and Org II, of which Org I was diversified with winter cover crops and Org II with winter cover crops and composted cattle manure.

- Hypothesis: Seedbank is dependent on cropping system and crop species. Cover crops in organic cropping system suppress seedbank and its diversity.

Weed seedbank during the first rotation depended on cropping systems and crop species. The significantly high number of seeds was found in the soil of control system Conv 0/I. In organic system with winter cover crops and manure (Org II) a negative effect on the content of weed seeds in the soil was observed, there were less seeds compared to other systems.

During the second rotation the highest number of weed seeds was found in system Conv II. This was explained by the influence of mineral fertilizers on weed seed production. The highest increase in species diversity with the tendency of lower seed number appeared in system Org II. The degression in seed number was probably caused by increased soil microbial activity and stronger influence of seed predators. Both first and second rotation studies showed the decrease of weed seedbank in red clover plots and largest seedbank in pea plots. Thus, the hypothesis that weed seedbank is dependent on the cropping system and crop was supported by our data. The second part of the hypothesis that cover crops suppress seedbank and its diversity was partly confirmed because cover crops significantly suppressed the occurrence of weed seeds and increased the diversity of weeds only in combination with manure (Org II).

- Hypothesis: Weed density, weed biomass and weed species diversity depend on cropping system and crop. Cover crops suppress density, diversity and biomass of weeds.

During the second rotation aboveground biomass and density of weeds were significantly high in all organic, compared to conventional systems, with no significant differences within the systems. Weed diversity increased in all cropping systems, mostly in organic system with cover crops (Org I). The comparison with the first rotation showed that cover crops in system Org I had

increased the diversity of weed species in barley (us. with red clover), red clover and winter wheat plots. Weed density decreased due to cover crops and manure in systems Org I and Org II in winter wheat and pea plots. Nevertheless, compared to all rotational crops, pea plots had the highest density, biomass and diversity of weeds in all systems.

Weed density and biomass study at the end of the first rotation showed that among cover crops in organic systems winter rye suppressed weeds more effectively than winter oilseed rape and ryegrass or mixture of winter oilseed rape and winter rye. Still, their weed control ability was not sufficient and comparable to herbicides, probably due to their low biomass. Thus, hypothesis on the effect of cropping system and crop on the density, biomass and diversity of weeds was supported by our data. However, the suppression of weed diversity and biomass by cover crops was not found. Winter cover crops rather enhanced the weed growth due to improved soil conditions.

- Hypothesis: Cover crops improve the crop yields.

The study on crop yields at the end of the first rotation in organic cropping systems showed that the effect of winter cover crops on the yield was dependent on year and crop species. As an average of two years, the yield of barley and winter wheat was the highest in the system with winter cover crops and manure (Org II). In system Org I, with the effect of winter cover crops, the highest yields were obtained in pea and potato plots. The yield increase was probably influenced by the changes in the soil properties due to the cultivation of winter cover crops. Thus, hypothesis that cover crops improve crop yields was partly supported by our data.

In conclusion, winter cover crops had a declining influence on the size of the weed seedbank and increasing impact on the species diversity and crop yields. Although cover crops did not form sufficient biomass for effective weed suppression compared to herbicides, an increase in the diversity of weed species is highly beneficial for ecosystems services.

Suggestions for future studies

Cover crops are gaining importance as weed management and soil amendment means in both organic and conventional management. However, research on green manure as winter cover crops and their effect on biodiversity, soil properties and crop yield are still insufficient regarding long-term crop rotations and Nordic climatic conditions.

The main effects of cover crops on suppressing weeds are possible by producing sufficient biomass and diversifying the allelopathic relationships. Thus, further investigation of different cover crop species is needed for continuous improvement of soil health, adequate weed suppression as well as additional yield of main crops. Furthermore, as mixtures containing leguminous species have a potential to produce a larger biomass, the ongoing study will be needed.

Cost-efficiency analyses of using cover crops as weed control could be valuable information for both researchers and farmers.

Practical value of the thesis

The results of this work will help to promote the use of different sustainable approaches within a field in agriculture by encouragement to experiment with different cover crop mixtures and variability in crop rotations. Acknowledging the advantages of incorporating cover crops to crop rotations will help to mitigate the impact of climate change and soil fertility by additional C fixing, as well as increase in biodiversity and consequently crop yields. Also, it is important to acknowledge that all natural processes take time, thus field preparations should consider benefit gain in the long-term future. Although there is not much certainty in the ongoing climate change, it can be claimed that healthy and resilient ecosystems will be valued during all times.

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SUMMARY IN ESTONIAN

UMBROHTUMUS ERINEVATES VILJELUSSÜSTEEMIDES

Sissejuhatus

Maa ja vesi on kõige hädavajalikumad ressursid toidu tootmiseks (Schneider *et al*. 2011). Need ressursid on aga kliimamuutuste, majanduskasvu ja pidevalt kasvava rahvastiku tõttu maailmas surve all (Schneider *et al*. 2011; Garg and Balodi 2014).

Mahepõllumajandust peetakse jätkusuutlikuks, sest välistatud on pestitsiidide, mineraalväetiste ja geenitehnoloogia kasutamine (IFOAM, 2005; Garg and Balodi 2014; Blanco-Canqui *et al*. 2017). Paremini on tagatud ka keskkonnakaitse (põhja- ja pinnavee kaitse), mulla viljakus, bioloogiline mitmekesisus (liigirikkuse kasv), kliimakaitse (lämmastiku lendumise vähenemine ja tõhusam süsiniku sidumine), kohanemine kliimaga (erosiooni vähenemine, kaitse üleujutuste eest) ja sisendite tõhusam kasutamine (Leifeld 2012; Argyropoulos *et al*. 2013; Cavigelli *et al*., 2013; Reganold and Wachter 2016; Blanco-Canqui *et al*. 2017; Sanders and Heß 2019; Çakmakçı and Çakmakçı 2023). Toitainete tasakaal mahepõllumajanduses põhineb orgaaniliste väetiste ja põllukultuuride jäänuste kasutamisel, liblikõieliste kasvatamisel õhulämmastiku sidumiseks, vahekultuuride kasutamisel ja külvikordade mitmekesistamisel (Forster *et al*. 2013; Valenzuela 2023).

Umbrohutõrjeks mahepõllumajanduses parandatakse kultuurtaimede konkurentsivõimet sobiva külvikorra valimisega, multšimise, reavahede ja külvinormide reguleerimise ning vastupidavate taimesortide kasvatamisega (Garg and Balodi 2014; Restuccia and Scavo 2023). Külvikorra mitmekesistamine võib suurendada ka mulla orgaanilise süsiniku ladestumist (Blanco-Canqui *et al*. 2017) ja vähendada haiguste levikut (Puech *et al*. 2014).

Umbrohud kuuluvad bioloogilise mitmekesisuse hulka, seega on neil osatähtsus toidu, paaritumiskohtade ja elukoha tagamisel paljudele tolmeldajatele, taimekahjurite antagonistidele ja lindudele (Marshall *et al*. 2006; Bretagnolle and Gaba 2015; Eraud *et al*. 2015; Rollin *et al*. 2016; Schumacher *et al*. 2020). Paljud umbrohuliigid moodustavad ka sümbioosi arbuskulaarse mükoriisaga (AM), millel on tähtis rolli mulla aktiivsuses (Trinchera and Raffa 2023).

Edukas mahepõllumajandus on väga kohaspetsiifiline. Seetõttu on ökoloogiliselt jätkusuutlike umbrohutõrjemeetodite leidmiseks oluline

määratleda kasutatavate külvikordade, vahekultuuride ja orgaaniliste väetiste mõju Põhja-Euroopa tingimustes. Käesolevas töös uuriti umbrohtude arvukust, biomassi ja mitmekesisust pikaajalises külvikorras viie põllukultuuriga (oder punase ristiku allakülviga, punane ristik, talinisu, hernes, kartul) kolme mahe- ja kahe tavakülvikorra katses. Kahe mahesüsteemi külvikorda mitmekesistasid talvised vahekultuurid, millest ühte lisaks kompostitud veisesõnnik. Tavasüsteemid põhinesid külvikorras kasvatatavatel kultuuridel, mineraalväetistel ja herbitsiididel. Antud töö tulemus võib pakkuda paremat ülevaadet umbrohtude mõjust põllukultuuridele ning ökosüsteemile.

Doktoritöö eesmärgid ja hüpoteesid

Uurimuse eesmärgiks oli selgitada umbrohtude esinemine sõltuvalt kolmest mahe- ja kahest tavaviljelussüsteemist viieväljalises külvikorrakatses pikaajalise uurimuse jooksul. Mahekülvikorrad mitmekesistati talviste vahekultuuride ja sõnnikuga määramaks nende mõju umbrohtudele. Saadud andmed võivad pakkuda alternatiivset keskkonnasäästlikku lähenemisviisi umbrohutõrjele.

Uuringu eesmärgid olid järgmised:

1. Uurida umbrohtude mulla seemnevaru maheviljelusperioodi alguses esimese külvikorra rotatsiooni (I) ja teise rotatsiooni (II) järgselt erinevates viljelussüsteemides.

Hüpotees: Mulla seemnevaru sõltub viljelussüsteemist ja põllukultuuri liigist. Vahekultuurid mahekülvikorras pärsivad seemnevaru ja selle mitmekesisuse kujunemist.

2. Umbrohtude arvukuse, biomassi ja mitmekesisuse uurimine erinevates viljelussüsteemides teises külvikorra rotatsioonis (III, IV).

Hüpotees: Umbrohtude arvukus, biomass ja mitmekesisus sõltuvad viljelussüsteemist ja kultuurist. Vahekultuurid vähendavad umbrohtude arvukust, mitmekesisust ja biomassi.

3. Kultuuride saagikuse uurimine maheviljelussüsteemides esimese külvikorra rotatsiooni (III) lõpus.

Hüpotees: Vahekultuurid parandavad saagikust.

Metoodika

Põldkatse viidi läbi Tartu lähedal paiknenud Eesti Maaülikooli kasepõldudel. Viieväljaline külvikorra katse rajati 2008. aastal kolme maheviljelussüsteemiga (Org 0, Org I ja Org II) ning kahe tavaviljelussüsteemiga (Conv 0/I ja Conv

II). Kõikide süsteemide külvikorra kultuuride järjestus terve rotatsiooni jooksul oli järgmine: oder (*Hordeum vulgare* L.) 'Anni' punase ristiku (*Trifolium pratense* L.) 'Varte' allakülviga – punane ristik – talinisu (*Triticum aestivum* L.) 'Fredis'– hernes (*Pisum sativum* L.) 'Tudor' – kartul (*Solanum tuberosum* L.) 'Teele'. Mahesüsteemides Org I ja Org II külvati kohe pärast põhikultuuri koristamist järgmised vahekultuurid: talinisu järgselt (herne eelselt) raihein (*Lolium perenne* L.) (I, III) ning talirapsi (*Brassica napus L.,* var. *oleifera*, subvar. *biennis*) ja talirukki (*Secale cereale* L.) segu (II, IV), herne järgi (kartuli eelselt) taliraps ja kartuli järgi (odra eelselt) talirukis. Alates 2013. aastast kasutati talvise vahekultuuri taliraps asemel talirüpsi (*Brassica rapa* L. var. *oleifera*).

Mahesüsteemidest Org 0 oli kontrollsüsteem, mis järgis vaid külvikorda ning peale põhikultuuri koristust sellel katse osal sügisel mullaharimist ei toimunud. Mahesüsteemis Org II kasutati peale vahekultuuride ka kompostitud veisesõnnikut – kartulile 20 t ha^{-1} ja teraviljadele (talinisu ja oder) 10 t ha^{-1}. Talvel olid kõik Org I ja Org II väljad taimikuga kaetud. Tavaviljelussüsteemides Conv 0/I ja Conv II oli mahedaga sama külvikord ilma vahekultuurideta ning mõlemas süsteemis kasutati keemilisi taimekaitsevahendeid ja Conv II süsteemis ka mineraalväetisi. Tavasüsteem Conv 0/I oli kontrollsüsteem, kus mineraalväetisi ei kasutatud; Conv II süsteemis kasutati põhiväetisena mineraalväetisi 25 kg P ha^{-1} ja 95 kg K ha^{-1} ning lisaks lämmastikväetist olenevalt kultuurist: talinisule ja kartulile 150 kg ha^{-1} N, odrale ristiku allakülviga 120 kg N ha^{-1} ja hernele 20 kg N ha^{-1}. Kõik variandid rajati neljas korduses, iga katselapi pindala oli 60 m^2.

Umbrohuseemnete proovid võeti 2011. (I) ja 2015. aastal (II) mullapuuridega enne sügisest mullaharimist.

Umbrohtud koguti kõikidelt katselappidelt kolmes korduses 25 cm^2 raamiga.

Umbrohuproovide kogumine toimus vegetatsiooniperioodi jooksul kaks korda – enne vahekultuuride sissekündi ning kolm nädalat enne kultuuride koristamist. Peale kogutud umbrohtude liigilise koosseisu ning arvukuse määramist kuivatati need kuivkaaluni ning kaaluti.

Katseandmeid töödeldi statistiliselt dispersioonanalüüsi (ANOVA) meetodil, kasutati andmetöötlusprogrammi Statistica 13 (TIBCO Software Inc.).

Tulemused

Umbrohuseemnete varu mullas esimese rotatsiooni jooksul sõltus viljelussüsteemist ning kultuurist. Statistiliselt suurim arv seemneid

leiti tavakontrollsüsteemi Conv 0/I mullast. Mahesüsteemidest avaldas vahekultuuride ja sõnniku kasutamine Org II süsteemis pärssivat mõju umbrohuseemnete hulgale.

Teise rotatsiooni jooksul leiti suurim seemnete arv süsteemis Conv II, mis oli ilmselt põhjustatud mineraalväetiste mõjust umbrohuseemnete moodustumisele. Suurim mitmekesisus ja tendents väiksemale seemnete arvule leiti süsteemis Org II, kus seemnete arvu vähenemine võis tuleneda mulla mikroobse aktiivsuse kasvu ning suurenenud seemnesööjate putukate mõju tõttu. Nii esimese kui teise rotatsiooni uuringud näitasid suurimat umbrohuseemnete arvu herne katselappidel, samas kui punase ristikuga katselappidel seemnevaru vähenes. Seega, umbrohuseemnete varu sõltus küll viljelussüsteemist ja kultuurist, kuid talvised vahekultuurid vaid kombinatsioonis sõnnikuga surusid umbrohuseemnete esinemist alla ning suurendasid mitmekesisust.

Umbrohtude maapealne biomass ja tihedus teise rotatsiooni jooksul olid statistiliselt suuremad mahesüsteemides kui tavasüsteemides, sealjuures ei esinenud süsteemide sees erinevusi. Umbrohtude mitmekesisus kasvas kõigis viljelussüsteemides, kuid statistiliselt tõenäoliselt mahesüsteemis talviste vahekultuuridega (Org I). Võrdlus esimese rotatsiooniga näitas, et vahekultuuride kasutamine süsteemis Org I suurendas umbrohtude liigirikkust odra allakülvatud punase ristikuga, punase ristiku ja talinisu katselappidel. Samuti esines teatav umbrohtude tiheduse vähenemine vahekultuuride ja sõnniku mõjul süsteemides Org I ja Org II talinisu ja herne katselappidel. Sellegipoolest, kõigi kultuuride võrdluses esines herne katselappidel suurim umbrohtude biomass, tihedus ja mitmekesisus kõigis süsteemides.

Umbrohtude tiheduse ja biomassi uurimus esimese rotatsiooni lõpus näitas, et vahekultuuridest talirukis surus umbrohtumust alla efektiivsemalt kui taliraps ja raihein ning talirapsi ja talirukki segu. Siiski ei olnud vahekultuuride umbrohtusid tõrjuvad omadused võrreldavad herbitsiidide mõjuga peamiselt liialt vähese biomassi moodustamise tõttu. Seega, umbrohtude maapealne biomass, tihedus ning mitmekesisus sõltusid viljelussüsteemist ja kultuurist, kuid vahekultuurid pigem suurendasid umbrohtude tihedust ja biomassi paranenud mullatingimuste tõttu.

Mahesüsteemide kultuuride saagikus esimese rotatsiooni lõpus näitas, et talviste vahekultuuride mõju sõltus aastast ja konkreetsest kultuurist. Kahe aasta keskmine odra ja talinisu saak olid suurimad vahekultuuride ja sõnnikuga süsteemis Org II. Suurimad herne ja kartuli saagid saavutati vahekultuuride toimel süsteemis Org I.

Kokkuvõtteks, talviste vahekultuuride kasvatamine vähendas umbrohtude seemnepanka mullas, samas suurendades seemnete liigilist mitmekesisust. Vahekultuurid ei moodustanud piisavalt maapealset biomassi tõhusaks umbrohutõrjeks, mille peamiseks põhjuseks oli ilmselt liialt madala survetõrjega liikide valik. Sellegipoolest, katse jooksul saavutatud liigilise mitmekesisus kasv talviste vahekultuuride toel võib omada märkimisväärset tähtsust ökosüsteemide teenustena.

Edasist uurimist vajavad teemad

Uuringud talviste vahekultuuride mõjust umbrohtudele, saagikusele ja mullale pikaajaliste külvikordade raames on Põhjamaade klimaatilistes tingimustes veel ebapiisavad. Seega erinevate vahekultuuride täiendav uurimine selgitamaks piisava umbrohutõrjega kombinatsioonid on endiselt vajalik. Liblikõieliste liikide lisamine vahekultuuride segusse moodustab potentsiaalselt rohkem biomassi, mis omakorda võib oluliselt mõjutada ka kultuurtaimede saagikust.

Majanduslik tasuvus vahekultuuride kasvatamisel umbrohutõrje meetodina võib anda väärtuslikku teavet nii teadlastele kui põllupidajatele.

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I

ORIGINAL PUBLICATIONS

Kuht, J., Eremeev, V., Talgre, L., **Madsen, H.**, Toom, M., Mäeorg, E., Loit, E., Luik, A. 2017. The content of weed seeds in the soil based on the management. Agronomy Research, 15 (5), 1934–1943. https://doi.org/10.15159/AR.17.068

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The content of weed seeds in the soil based on the management system

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Abstract. In 2008 an experiment was set up on the field in Eerika experimental station (Estonian University of Life Sciences) as a 5-field crop rotation: barley (*Hordeum vulgare* L.) with undersown red clover, red clover (*Trifolium pratense* L.), winter wheat (*Triticum aestivum* L.), pea (*Pisum sativum* L.), potato (*Solanum tuberosum* L.). The objective of the study was to measure the content of weed seeds in the soil and to evaluate the diversity of the species at the beginning of the period of organic production in 2011. In conventional farming systems without fertilizer (Con I) and conventional farming with mineral fertilizer (Con II) herbicides were used for weed control. All the crops in Con II system received P 25 kg ha^{-1} and K 95 kg ha^{-1}, but the application rates of mineral nitrogen fertilizer differed. In organic systems (Org I – organic farming based on winter cover crop and Org II – organic farming based on winter cover crop and manure), the winter cover crops (ryegrass after winter wheat, winter oilseed rape after pea, winter rye after potato) were sown after the harvest and were ploughed into the soil as green manure in spring. Organic farming systems (Org II) had a negative effect on the content of weed seeds in the soil (2.0–22.7% less seeds than in other variants). The seeds of *Chenopodium album* were the most abundant among summer annual weeds and the seeds of *Viola arvensis* among winter weeds in the soil. Organic farming measures increased the domination of *Chenopodium album* – the dominance index *D'* was increased by 0.09–0.14 compared to conventional variants. The content of seeds of winter weed *Viola arvensis* in Org II variant was decreased by 82%. The index of species evenness *J'* and Shannon Wiener diversity index *H'* were lower in organic plots by 0.10–0.18 and 0.60–0.19, respectively. Org II variants showed the best results based on the decrease of soil weed seed bank and distribution of the weed species.

Key words: organic farming, winter cover crops, weed seeds, species diversity.

INTRODUCTION

The weed seed bank consists of many species, whereas some dominant species may comprise 70–90% of the total seed bank causing the most problems (Wilson, 1988). Plant protection practices without the use of herbicides has been pointed out as one of the main problems of successful organic cultivation system (Gianessi & Reigner, 2005). In organic farming weeds are the main crop yield decreasing factors. In ecologically friendly cultivation weeds can be controlled by tilling, crop rotation, harrowing,

mulching, growing legumes in rotation and cover crops (Watson et al., 2002; Thorup-Kristensen et al., 2003). Soil movement on no-tilled field may lead to much larger number of emerging weed seeds compared to tilled soils (Chauhan et al., 2006; Tamm et al., 2016). The increase of number of soil weed seeds has also been observed in reduced tillage system (Tørresen et al., 2003; Woźniak & Kwiatkowski, 2012). A vigorous cover crop can change the environment for weed seeds on and in the soil. Previous results indicate, that winter cover crops reduced the dry biomass and density of weeds compared to the conventional control system (Madsen et al., 2015).

The aim of the study is to investigate the influence of different winter cover crops and their combination with composted cattle manure on soil weed seed bank at the start of organic farming. The effect of the yield of winter cover crops and preceding crops on the number of weed seeds in the soil was studied in detail.

MATERIALS AND METHODS

The five-field crop experiment with three different organic systems was started in 2008 and was set up in test site of the Estonian University of Life Sciences in Eerika (58°22′ N, 26°40′ E). A 5-year crop rotation contains: red clover *RC* (*Trifolium pratense* L.), winter wheat (*Triticum aestivum* L.), pea (*Pisum sativum* L.), potato (*Solanum tuberosum* L.) and barley (*Hordeum vulgare* L.) undersown with red clover. First 5-year rotation ended in 2012. The experiment was established in four replications, each plot (60 m^2) situated in a systematic block design (80 plots). Organic and conventional plots were separated with an 18 m long section of mixed grasses to avoid contamination with synthetic pesticides, mineral fertilisers and winter cover crops. In systems Con I (conventional farming without fertilizers, as control) and Con II (conventional farming with mineral fertilizers) herbicides (Roundup 4 L ha^{-1} were used in last autumn). In conventional system Con II all the crops received phosphorous (P 25 kg ha^{-1}) and potassium (K 95 kg ha^{-1}). The amount of nitrogen (N) varied depending on the crop: for pea N 20 kg ha^{-1}, for barley undersown with red clover N 120 kg ha^{-1}, for winter wheat and potato N 150 kg ha^{-1}. Plots with red clover did not receive any mineral fertilizers and chemical pest control. Two organic farming systems (Org I and Org II) were investigated. In both systems winter cover crops as green manure were used. Cover crops were sown right after the harvest: ryegrass – *RG* (*Lolium perenne* L., sowing rate 25 kg ha^{-1}) after winter wheat, winter oilseed rape *WOR* (*Brassica napus* L., *var. oleifera, subvar. biennis*, 7.1 kg ha^{-1}) after pea and winter rye *WR* (*Secale cereale* L., 220 kg ha^{-1}) after potato. Before sowing the subsequent crop all cover crops were ploughed into the soil as green manure. The growth stage (according to BBCH) of cover crops before ploughing was determined (ryegrass 21–22, winter oilseed rape 24–26 and winter rye 23–26. In the organic system Org II fully composted cattle manure was added in the autumn 2010 and in spring 2011 at a total rate of 40 t ha^{-1} and ploughed into soil. The cover crops were sown with the Kongskilde sowing machine right after the harvesting of the main crop and in the beginning of May they were ploughed into the soil. Red clover was cut twice: middle of June and during the second half of July and ploughed into the soil in all organic systems. Cereals and peas were harvested at the beginning of August, using a Sampo Rosenlew experimental harvester. Potato tubers were hand-collected between August and September. Yield data were adjusted to dry matter content. Samples for measuring the weed seed bank were collected in September

2011, at the start of first year to full organic production. The weed seed bank samples were taken with soil borers (15 mm diameter) after crop harvest and before autumn ploughing. From each plot 16 soil samples were taken from the depth of 0–25 cm soil layer. Samples of each plot were mixed together in a bucket. The samples were air-dried and 500 g of each sample were sieved and washed through a 0.25 mm sieve. Weed seeds were separated from the soil by potassium carbonate (K_2CO_3) aqueous solution. For preparation of the solution 2.0 kg of potassium carbonate was dissolved in 1.8 L of water. The number of weed seeds in seed bank was calculated to an area of 1 m^2 of plot area using the formula Eq. 1 (Kuht et al., 2016) as shown below:

$$N = \frac{h \cdot \rho \cdot n \cdot 10}{W\mathrm{d}} \quad (1)$$

where N – number of viable seeds, n m^{-2}; h – depth of plough layer, cm; ρ – soil bulk density, g cm^{-3}; n – counted number of seeds in the soil sample; Wd – weight of dry soil sample, g.

The species composition of weed seed communities and the number of seeds of each species were used to assess the biodiversity.

The diversity indexes (Eq. 2) of weed seed species were calculated as Shannon-Wiener diversity index (Shannon, 1948; Shannon & Wiener, 1949) of weed seed species diversity *H'*:

$$H' = -\sum_{i=1}^{s} pi \ln(pi) \quad (2)$$

The community dominance was determined based on the Simpson index, Eq. 3. Simpsons' index of species dominance (Simpson, 1949) was calculated as follows:

$$\lambda = \sum_{i=1}^{s} pi^2 \quad (3)$$

The formula to calculate Pielou evenness index, Eq. 4 (Pielou, 1966; Boyce, 2005) is as follows:

$$J' = \frac{H'}{H'max} \quad (4)$$

The richness index, Eq. 5, was measured based on the Margalef index (Margalef, 1958) as shown below:

$$R = \frac{S - 1}{\ln N} \quad (5)$$

where the *pi*'s are the proportion of all observations in the i^{th} species category; $H'max = \ln(S)$; S – number of species (the total number of weed types in a single treatment); N – total number of individuals of all the species in the block.

The results were analysed by using STATISTICA 7.0: ANOVA, Fisher (LSD) test (Statsoft Inc, 2005). Correlation analysis was used to study the correlation between different number of weed seeds and some indicators of soil physical properties. Linear correlation coefficients between variables were calculated, the significance of coefficients being $P < 0.01$, $P < 0.05$.

RESULTS AND DISCUSSION

As an average, there were significantly less viable annual weed seeds in conventional variants with mineral fertilizers and herbicides (Con II) and organic variants with winter cover crops and cattle manure (Org II) compared to other cultivation methods by 3.1–6.1 and 2.5–5.6 (thousand seeds per 1 m^2) respectively (Table 1). In the soil of Org II variant, there were less seeds (as average) in the plots of potato and barley undersown with clover.

Table 1. Number of annual (summer, winter and total) weed seeds in the soil of different crops in 2011

Crop and preceding crops	Weed seeds	Number of seeds, 1,000 seeds per m^2			
		Con I	Con II	Org I	Org II
Red clover	Summer annual	24.22^{a}	20.58^{a}	28.42^{a}	21.00^{a}
	incl. *Chenopodium album*	19.04^{a}	18.20^{a}	27.16^{a}	19.88^{a}
1) barley, us. r. clover	Winter annual	0.98^{a}	0.70^{a}	1.12^{a}	2.10^{a}
2) potato	incl. *Viola arvensis*	0.14^{a}	0.56^{a}	0.14^{a}	0.28^{a}
3) pea	Total	25.20^{a}	21.28^{a}	29.54^{a}	23.10^{a}
Winter wheat	Summer annual	25.06^{b}	20.30^{a}	20.16^{a}	20.44^{a}
	incl. *Chenopodium album*	19.88^{a}	17.78^{a}	19.32^{a}	19.60^{a}
1) red clover	Winter annual	1.54^{a}	2.80^{ab}	1.82^{a}	3.78^{b}
2) barley, us. r. clover	incl. *Viola arvensis*	0.84^{a}	2.38^{b}	0.70^{a}	0.70^{a}
3) potato	Total	26.60^{b}	23.10^{a}	21.98^{a}	24.22^{ab}
Pea	Summer annual	27.72^{b}	20.02^{a}	20.30^{a}	23.24^{ab}
	incl. *Chenopodium album*	25.20^{a}	17.78^{a}	19.74^{a}	22.82^{a}
1) winter wheat	Winter annual	4.90^{b}	3.36^{ab}	1.68^{a}	1.54^{a}
2) red clover	incl. *Viola arvensis*	4.62^{a}	2.52^{a}	0.42^{a}	0.28^{a}
3) barley, us. r. clover	Total	32.62^{b}	23.38^{a}	21.98^{a}	24.78^{ab}
Potato	Summer annual	20.80^{a}	19.24^{a}	21.71^{a}	15.73^{a}
	incl. *Chenopodium album*	18.46^{a}	18.98^{a}	20.80^{a}	14.82^{a}
1) pea	Winter annual	0.52^{a}	3.38^{b}	1.30^{a}	1.56^{ab}
2) winter wheat	incl. *Viola arvensis*	0.52^{a}	2.47^{b}	0.65^{a}	0.26^{a}
3) red clover	Total	21.32^{a}	22.62^{a}	23.10^{a}	17.29^{a}
Barley, us. red clover	Summer annual	27.02^{c}	14.84^{a}	21.42^{b}	13.16^{a}
	incl. *Chenopodium album*	24.22^{b}	13.16^{a}	19.60^{b}	12.60^{a}
1) potato	Winter annual	1.40^{a}	0.98^{a}	0.98^{a}	1.12^{a}
2) pea	incl. *Viola arvensis*	0.70^{a}	0.56^{a}	0.14^{a}	0.00^{a}
3) winter wheat	Total	28.42^{c}	15.82^{ab}	22.40^{bc}	14.28^{a}
Average	Summer annual	24.96^{b}	19.00^{a}	22.40^{ab}	18.71^{a}
	incl. *Chenopodium album*	21.36^{b}	17.18^{a}	21.32^{b}	17.94^{ab}
	Winter annual	1.87^{a}	2.24^{a}	1.38^{a}	2.02^{a}
	incl. *Viola arvensis*	1.36^{ab}	1.70^{b}	0.41^{a}	0.30^{a}
	Total	26.83^{b}	21.24^{a}	23.78^{ab}	20.73^{a}

Note. Within the same row, values with different letters are significantly different (ANOVA, Fisher (LSD) test); 1) – preceding crops in 2010; 2) – preceding crops in 2009; 3) – preceding crops in 2008.

There were a lot more (11 times more as an average) weed seeds of summer annuals than winter weeds, dominated by the seeds of common lambsquarter (*Chenopodium album* L.). The domination of the seeds of common lambsquarter in various cultivation systems has been observed by many authors (Caroca et al., 2011). It was found that the proportion of the seeds of common lambsquarter among summer annuals was significantly higher in organic plots than in conventional variants. It was 95.2% in Org I, 95.9% in Org II and 85.6% and 90.4% in Con I and Con II systems (4.8–10.3% more in organic systems). Except the Con II variant with potato, the domination of the seeds of common lambsquarter was apparent in all the organic variants.

Among winter annual weeds the most dominant species was field pansy (*Viola arvensis* Murr) and as an average they were present in significantly smaller numbers in organic variants compared to the conventional plots (Table 1). On the contrary to the seeds of common lambsquarter which share among summer annuals was higher in organic variants, the proportion of field pansy seeds in summer annuals in Org I and Org II treatments was 0–50.0% in winter annuals (50.0–100% in conventional plots).

The yield of preceding crop proved to be one of the main factors influencing the number of weed seeds. Clear negative correlation ($r = 0.56$) between dry matter yield of crops (without the clover) and the number of weed seeds was observed in 2010 (Fig. 1). Moreover, very strong relationship ($r = 0.83$) between them was apparent in Org II and Con II systems. It was found that with higher dry matter yield of a preceding crop there were less weed seeds in the soil. For most of the crops studied, weed densities were lower when a crop was grown in rotation (Liebman & Dyck, 1993).

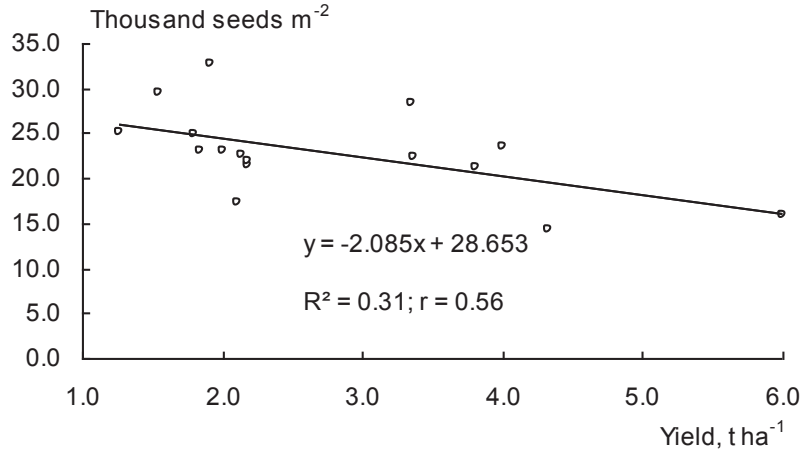

Figure 1. The correlation between total yield of the preceding crop (DM, t ha^{-1}) in 2010 and the number of weed seeds in the soil in 2011 (seeds per m^{-2}).

The correlation between dry matter yield of Org I variants and the number of weed seeds was $r = 64$, but there was no significant relationship with the yield of Con I system. In 2011, the correlation between yields and the number of weed seeds was $r = 0.32$. The number of weed seeds was mostly affected by winter rye (sown as green manure for barley preceding crop and ploughed into the soil in spring) and ryegrass (ploughed into

the soil before sowing the pea) the reduction in the number of weed seeds by 17.2% and 16.4% respectively (Fig. 2). Similar effect of reducing the density of weed plants was seen in the same plots where winter cover crops were used. Also, Miura & Watanabe (2002) found that living mulch is effective for weed control and Liebman & Dyck (1993) concluded that weed biomass was lower in the living mulch system. The use of cover crops has an effect on the germination and sprouting of weed seeds, by influencing the light conditions, soil temperature and soil moisture (Teasdale, 1996). Weed presence was strongly influenced by green manure crop, rye being the most suppressive one and ryegrass the least. This had a carry-over effect on weed density in the next pea crop (Barberi et al., 2014). Davis et al. (2005) observed that weed seed banks in the organic systems were positively correlated with weed biomass whereas seed banks in the conventional systems were less predictive. The small reduction (7.2%) of weed seeds in organic variants with red clover was probably due to the effect of the cover crops sown after the preceding pea and potato crops. The effect of growing potato and red clover on the weeds and their seeds was similar in conventional and organic systems.

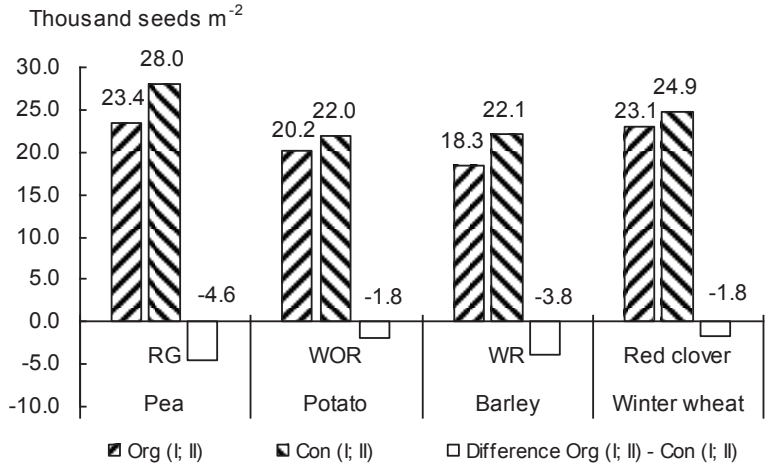

Figure 2. The number of weed seeds in the soil in 2011, depending on the winter cover crops or red clover sown in 2010. *Note*. RG – ryegrass; WOR – winter oilseed rape; WR – winter rye.

In potato plots it was because of the mechanical weeding and in clover plots it was due to the dense canopy that competed with annual weeds during the whole growing period. Also the red clover undersown to barley reduced the density of weeds. Albrecht (2005) also found that the soil weed seed bank was reduced by 39.0% when grasses undersown with clover were used.

Cover crops increase destruction of weed seed in fields. Additionally the increase in the activity of weed seed predator insects was observed. Our results showed that the increase in number of omnivorous predators was observed in areas where winter cover crops had been cultivated previously (Org I and Org II systems, Kuht et al., 2016). The dominant species was *Harpalus rufipes,* that was significantly more present on all organic plots compared to conventional ones. Previous studies have not revealed any significant changes in the number of seed beetles between crops. In our present

experiment the *Harpalus rufipes* was significantly more present in pea treatments compared to other crops. As an average of 2 year experiment, diversity index of seed beetles (species per area) was higher by (35%) in organic systems with winter cover crops, compared to the conventional treatments. This is partly due to the better wintering conditions for seed beetles offered by winter cover crops. Blubaugh et al. (2016) also indicated that the cultivation of cover crops increased the activity of weed seed eating insects (omnivorous predators) on the field by enabling their activity on the individual level.

As an average, the Shannon-Wiener diversity indexes (*H'*) were lower in organic variants than in conventional variants (by 0.06–0.19, Table 2), while the largest reduction (by 0.32–0.44) of species diversity was seen in weed seeds in the pea variant.

Simpson dominance indexes (λ) were higher in organic variants than in conventional variants (by 0.09–0.14), especially in the plots with pea. It was obvious that higher dominance index was due to the increase in the share of common lambsquarter seeds in the soil of organic systems.

Table 2. Species diversity index, dominance index and richness index of the weed seed bank in different crops in 2011

Crops	Shannon-Wiener diversity index, *H'*				Simpson's dominance index, λ				Margalef richness index, *R*			
	Con I	Con II	Org I	Org II	ConI	Con II	Org I	Org II	ConI	Con II	Org I	Org II
Barley	0.65	0.68	0.48	0.66	0.60	0.61	0.78	0.66	0.39	0.31	0.60	0.42
R. clover	0.67	0.49	0.30	0.60	0.61	0.74	0.85	0.74	0.39	0.30	0.39	0.70
W. wheat	0.49	0.56	0.56	0.47	0.73	0.70	0.77	0.78	0.20	0.30	0.40	0.40
Potato	0.48	0.62	0.46	0.67	0.76	0.72	0.82	0.74	0.30	0.60	0.60	0.82
Pea	0.73	0.79	0.41	0.35	0.62	0.60	0.81	0.85	0.38	0.50	0.60	0.40
Average	0.61	0.63	0.44	0.55	0.66	0.67	0.80	0.76	0.33	0.40	0.52	0.55

The values of Margalef species richness index (*R*) were higher in organic variants (by 0.12–0.22) compared to conventional variants. Higher species richness indexes in organic variants were observed in plots with red clover and potato. The reason for this here lies also in the agrotechnological characteristics where the effect on the weeds is expressed by intensive mechanical weeding and manure applied with potato and dense canopy and manure applied to the preceding barley crop with red clover.

As an average the evenness index values of Org I and Org II weed seeds were lower than respective values for conventional systems: by 0.18 and 0.12, compared to Con I and by 0.16 and 0.10, compared to Con II variants. The changes in the evenness indexes appeared more clearly in the experiment than species richness and dominance indexes and these are presented in Fig. 3.

The lowest values for evenness index were observed in Org II and the highest values in control variant Con I (except for winter wheat plot), whereas the biggest difference (by 0.24) between conventional and organic systems was seen in plots with pea. The results of correlation analysis indicated that as an average there was a strong relationship ($r = 0.87$) between dominance and evenness indexes, while very strong relationships were seen with pea ($r = 0.98$), barley ($r = 0.93$) and clover ($r = 0.96$).

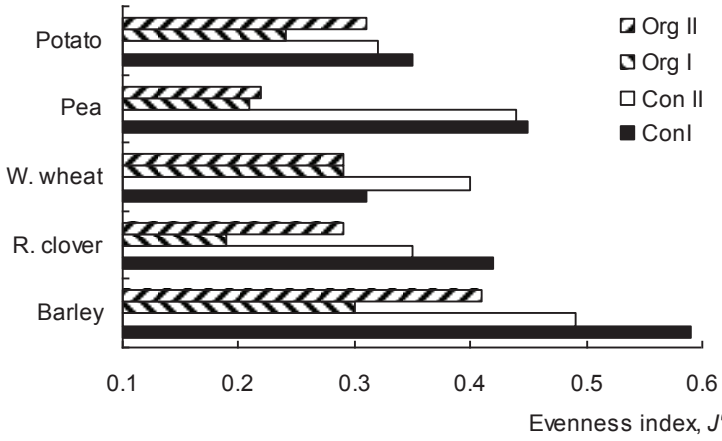

Figure 3. The values of evenness index (*J'*) of weed seeds in the soil of various crops depending on the cultivation system in 2011.

CONCLUSIONS

The yield of preceding crops and cultivation of post-harvest winter cover crops proved to be strong factors for reducing the number of weed seeds in the soil. There were significantly less viable annual weed seeds in conventional variants with mineral fertilizers and herbicides (Con II) and organic variants with winter cover crops and cattle manure (Org II) compared to other cultivation methods. In the soil of Org II variant as an average less weed seeds were found in the soils of potato and barley plots undersown with clover. Common lambsquarter in summer annuals and field pansy in winter annuals were the dominant species. Clear relationship ($r = 0.56$; $P < 0.05$) was found between the dry matter yield of crops in 2010 and the number of weed seeds in the soil in 2011, whereas very strong correlation was seen between Org II and Con II variants. The number of weed seeds was mostly affected by winter rye (sown as green manure for barley preceding crop and ploughed into the soil in spring) and ryegrass (ploughed into the soil before sowing the pea) the reduction in the number of weed seeds by 17.2% and 16.4% respectively. As an average, the Shannon-Wiener species richness indexes were lower in organic variants than in conventional variants (by 0.06–0.19). The lowest values for evenness index were observed in Org II and the highest values in control variant Con I (except for winter wheat plot), whereas the biggest difference (by 0.24) between conventional and organic systems was seen in plots with pea. The values of dominance and species richness index increased in organic variants compared to the conventional variants.

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II

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Organic Cropping Systems do not Increase Weed Seed Numbers but do Increase Weed Diversity

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Abstract

The influence of different cropping systems on the soil weed seed bank after the first crop rotation within a five-field crop rotation (barley undersown with red clover, red clover, winter wheat, pea, potato) in three organic (Org) and in two conventional (Conv) cropping systems was investigated. In organic systems Org I and Org II cover crops were incorporated as a source of nutrient inputs to the soil and in Org II composted cattle manure was also applied. The Org 0 acted as the organic control system without cover crops and manure. The two conventional cropping systems were treated with herbicides and fungicides and differed in fertilizer application (i.e. Conv I no fertilizer use (as control) and Conv II mineral fertilizer use). In general, the lowest number of annual weed seeds was found in system Conv I, the highest in Conv II. In organic systems with cover crops (Org I, II) there was a strong tendency for decreased weed seed numbers and increased biodiversity. The highest values of the Shannon-Wiener diversity index and Margalef richness index were in Org II system. In all systems the most abundant species in weed seed banks were Chenopodium album L. and Viola arvensis Murr.

Keywords: Equitability index; Margalef index; Shannon-Wiener diversity index; Weed seed bank; Winter cover crops

Introduction

In organic agriculture one of the main challenges is to acquire extensive review of the biological and ecological behaviour of weeds for effective weed control [1,2]. To overcome annual weed infestation, it is important to define the dynamics of weediness, which has been acknowledged to greatly depend on the quantity and distribution of the soil seed bank [3,4]. Soil seed banks are viable seed stocks in the soil and on its surface [5], accumulating or remaining until germination [6]. Seed banks consist of seeds, which may be produced over several years or emerged recently [5,7]. Both seed banks and aboveground vegetation in agroecosystems are very variable – seed banks due to emergence in seasonal patterns during the vegetation year [8] and aboveground vegetation is greatly affected by management during a given year and competition with the crop [2]. Correct evaluation of the composition of the weed seed bank reflects past field management and may make it possible to predict weed problems of the future [1,2].

Organic and conventional management systems address problems differently. Conventional farming depends mainly on short-term solutions e.g. herbicide and fertilizer application, which in turn affect the weed seed bank [9-11] and reduce species diversity [1,2,12]. Organic systems on the other hand rely on longer-term preventative solutions. Recognition of the importance of the nutrient cycling and weed, pest and disease control are essential either way in agronomy [11,13]. Successful weed seed management strategies include decreasing the germinable fraction of the seed bank, thereby manipulating the emergence and germination of weeds [4,14]. Also, for effective aboveground weed control it is necessary to limit weed seed production of already emerged plants and to stimulate seed death to reduce the seed bank size [15,16].

Using agricultural practices for changing the seed bank results in changes in weed flora [16,17]. The main practices which have a sufficiently severe impact on weed flora and thus on the weed seed bank are crop rotational sequences and tillage [17]. As a part of the rotational crop sequences, winter cover crops are introduced in the crop rotation with spring sown crops [18–22]. The content of organic carbon in the soil is improved if winter cover crops are

incorporated in the soil [23], benefitting microbial activity [24]. The seeds in the soil are subject to microbial decomposition by soil biota [4] thereby enriching the soil and helping to reduce weed problems in the field [22]. Cover crops have an effect on the establishment of weeds and thereby contribute to reduction of weed seed formation and accumulation of seeds in the soil [18].

Weed population dynamics as well as species composition are influenced by seed dynamics within the soil during farming practices [25]. The important role of seed in the weed life cycle as the origin of future populations [6] has been recognised. Therefore, the present study assesses the effects of different cropping systems with the same rotational schemes on soil weed seed bank and its changes after one 5-year crop rotation. The aim of the study was to investigate the influence of conventional and organic cropping systems on the weed seed bank. In organic systems winter cover crops were used. Therefore, the hypothesis was that winter cover crops regulate weed seed occurrence to a comparable level as herbicides in conventional systems.

Materials and Methods

Table 1: The treatments in the organic and conventional farming systems.

Crop rotation	Organic Systems			Conventional Systems	
	Org 0 – control (Crop rotation)	Org I (Crop rotation + green manure as winter cover crops) Winter oilseed turnip + winter rye	Org II (Crop rotation + green manure + composted cattle manure)	Conv I – control (Crop rotation + herbicides + fungicides + insecti-cides)	Conv II (Crop rotation + herbicides + fungicides + insecticides + mineral fertilizers)
Winter wheat		Winter oilseed turnip + winter rye	10 t ha^{-1}		25 kg ha^{-1} P, 95 kg ha^{-1} K; 150 kg ha^{-1} N
Pea		Winter oilseed turnip			25 kg ha^{-1} P and 95 kg ha^{-1} K; 20 kg ha^{-1} N
Potato		Winter rye	20 t ha^{-1}		25 kg ha^{-1} P and 95 kg ha^{-1} K; 150 kg ha^{-1} N
Barley us. red clover			10 t ha^{-1}		25 kg ha^{-1} P and 95 kg ha^{-1} K; 120 kg ha^{-1} N
Red clover		Red clover			

The five-field crop experiment with three different organic and two conventional systems was set up in 2008 and located at the test site of the Estonian University of Life Sciences in Eerika (58°22′ N, 26°40′ E). The soil type of the experiment area was sandy loam Stagnic Luvisol according to the World Reference Base classification [26]. The mean characteristics of the humus horizon were as follows: Corg 1.1-1.2%, Ntot 0.10-0.12%, P 110-120 mg kg-1, K 253-260 mg kg-1, pHKCl 5.9, soil bulk density 1.45–1.50 g cm-3. The crops grown in succession were as follows: barley (*Hordeum vulgare L.*) undersown with red clover (*Trifolium pratense L.*), red clover RC (*Trifolium pratense L.*), winter wheat (*Triticum aestivum L.*), pea (*Pisum sativum L.*) and potato (*Solanum tuberosum L.*). The experiment was established in 5 cropping systems (Org 0, Org I, Org II, Conv I and Conv II) with 5 crops in four replications (each plot 60 m2) situated in a systematic block design (100 plots in total); (Table 1) [24]. Organic (Org) and conventional (Conv) plots were separated by an 18 m long section of mixed grasses to avoid contamination with synthetic pesticides, mineral fertilisers and winter cover crops.

System Org 0 followed the above-mentioned rotation. In system Org I, winter cover crops as green manure was used: mixture of winter rye (*Secale cereale L.*) and winter oilseed turnip (*Brassica rapa L. var. oleifera*) after winter wheat, winter oilseed turnip after pea and winter rye after potato. In system Org II, in addition to winter cover crops, composted cattle manure was applied at the rate of 20 t ha-1 for potato, and 10 t ha-1 for winter wheat and barley [22]. Red clover was mown twice – in the middle of June and in the second half of August. Cover crops were sown immediately after harvest. However, prior to sowing the subsequent crop, all cover crops were incorporated into the soil as green manure. The organic systems were ploughed in spring (at the beginning of May), conventional systems in autumn (at the end of October).

Besides organic systems there were two conventional farming systems without winter cover crops: Conv I (no fertilizer use) and Conv II (all the crops received 25 kg ha-1 P and 95 kg ha-1 K; also winter wheat and potato 150 kg ha-1 N, barley undersown with red clover 120 kg ha-1 N and pea 20 kg ha-1 N). Both conventional systems were treated with herbicides, insecticides and fungicides. Plots with red clover did not receive any mineral fertilizers or chemical pest control [27].

The weed seed bank samples were taken in 2015 with soil borers (15 mm diameter) after crop harvest and before autumn ploughing. From each plot 16 soil samples were taken from the depth of 0-25 cm soil layer. Samples of each plot were mixed together in a bucket. Seeds were extracted from a 500 g portion of the soil sample using a flotation-based method [28]. Weed

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seeds were separated from the soil by potassium carbonate (K_2CO_3) aqueous solution. For preparation of the solution 2.0 kg of potassium carbonate were dissolved in 1.8 l of water. Weed seeds were counted and species identified under the microscope.

The number of weed seeds in the seed bank was calculated to an area of 1 m^2 of plot area using the formula Eq. 1 [29,30] as shown below:

$$N=(h*\rho*n*10)/Wd$$

where: N – number of viable seeds (n m^{-2}); h – depth of plough layer (cm); ρ – soil bulk density (g cm^{-3}); n – counted number of seeds in the soil sample; Wd – weight of dry soil sample (g).

The number of seeds and the species composition of weed seed communities were used to assess the diversity.

Species diversity indexes are aimed to unite information on the relative abundance and richness of species into a single value, varying on how much accent one of these two components are bearing [31–33]. The Shannon-Wiener is one of the oldest and most commonly used diversity indexes [34]. If Shannon-Wiener index is for taking account of how individuals are distributed within the species, then species richness (Margalef) index shows the total number of species present in a given sample or area [35].

The diversity indexes (Eq. 2) of weed seed species were calculated as Shannon-Wiener index [36,37] of weed seed species diversity H':

$$H' = -\Sigma_{i=1}^{s} pi \ln(pi) \quad (2)$$

The species richness measure was calculated as Margalef index (d), Eq 3 [38]:

$$d = \frac{s-1}{\ln N} \quad (3)$$

The Equitability index is the ratio of the population diversity and is affected by the relative quantity of species in a community [39]. It could be calculated when the variation between populations is missing [40] and is usually on a scale from 0 (shows high dominance by one species or low evenness) to 1 (indicates even abundance of all species or ultimate evenness) [41,42]. The formula to calculate Equitability index, Eq 4 [43,44] was as follows:

$$J' = \frac{H'}{H'\max} \quad (4)$$

Statistical analyses were performed using the Statistica software package (version 12.0). Significant differences between cropping systems were tested by Fisher's least significant difference test. The statistical significance level was set at p=0.05. Full-factorial analysis of variance (ANOVA) was used to test the statistical significance of crop and cropping systems and their interaction effects on summer and winter annual weed seed species. The normality of the data was assessed by the Kolmogorov-Smirnov test.

Results and Discussion

The number of seeds in the soil changes in time, but presumably seed production is related to aboveground density or biomass of weeds [45]. Seed bank size is also affected by different factors, such as annual in situ seed production, addition by wind-dispersed seeds, seed rain [1], contamination by machinery and manure [46]. The current study focuses on seed bank description depending on different treatments in fertilizing and cultivation.

In 2015 a total of 23 weed species were found. The most dominant species were Chenopodium album L. among summer annuals and Viola arvensis among winter annuals. The number of winter annual seeds was about 25 times less than summer annual seeds (Table 2). In 2011 [27] the same species were also dominant but the number of seeds was lower. The number of weed seeds was dependent on cropping systems as well as on the crop grown (Table 2) (Figure 1).

Table 2: Number of annual (summer, winter and total) weed seeds in the soil of crop rotation in 2015.

Crop	Weed seeds	Number of seeds, 1000 seeds per m2				
		Conv I	Conv II	Org 0	Org I	Org II
Red clover	Total summer annual	25.34a	36.19ab	43.26b	35.77ab	28.70ab
	Chenopodium album	23.24a	32.48ab	40.04b	32.06ab	25.55a
	Total winter annual	1.12a	2.87ab	2.24ab	3.08ab	4.90b
	Viola arvensis	0.84a	2.38ab	1.33ab	1.68ab	3.29b
	Total	26.46a	39.06ab	45.50b	38.85ab	33.60ab
Winter wheat	Total summer annual	33.04a	30.17a	31.64a	28.14a	27.86a
	Chenopodium album	30.87a	27.58a	27.37a	25.27a	24.78a
	Total winter annual	2.87a	5.95a	3.78a	4.06a	4.06a
	Viola arvensis	2.38a	5.18a	1.75a	2.38a	1.96a
	Total	35.91a	36.12a	35.42a	32.20a	31.92a

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Pea	Total summer annual	35.63ab	45.08b	27.30a	35.21ab	38.36ab
	Chenopodium album	32.41ab	41.86b	25.27a	32.13ab	33.53ab
	Total winter annual	3.43a	4.34a	3.08a	3.99a	3.71a
	Viola arvensis	2.87ab	4.20b	1.40a	1.61a	1.40a
	Total	39.06ab	49.42b	30.38a	39.20ab	42.07ab
Potato	Total summer annual	27.43a	33.02a	34.00a	30.29a	27.76a
	Chenopodium album	24.51a	31.14a	31.92a	26.98a	25.09a
	Total winter annual	1.37a	3.77b	3.06ab	2.15ab	3.25ab
	Viola arvensis	1.17a	2.67a	1.69a	1.17a	1.82a
	Total	28.80a	36.79a	37.05a	32.44a	31.01a
Barley, us. red clover	Total summer annual	34.23a	39.97a	34.93a	39.06a	37.10a
	Chenopodium album	31.29a	36.19a	32.27a	35.98a	34.86a
	Total winter annual	1.96a	3.29a	2.73a	1.96a	3.99a
	Viola arvensis	1.61ab	3.01b	1.89ab	1.05a	1.82ab
	Total	36.19a	43.26a	37.66a	41.02a	41.09a

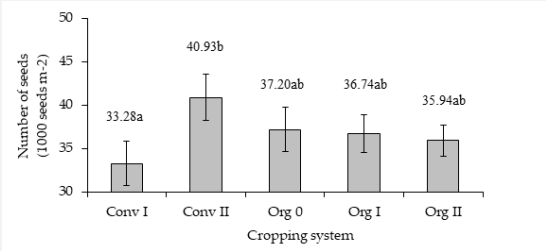

Figure 1: Total number of weed seeds, 1000 seeds per m2 in the soil of crop rotation crops in 2015 (ANOVA, Fisher (LSD) test). Means followed by different letters within each bar indicate significant differences ($p < 0.05$) within cropping systems; 2 – Vertical bars denote the standard errors

The seed bank of annual species varied from a minimum of 26,460 seeds m−2 in red clover in Conv I to a maximum of 49,420 seeds m−2 in pea in Conv II.

As an average of all cropping systems the highest seed number was found in Conv II compared to Conv I and all organic systems (Figure 1). It shows that the use of herbicides in systems Conv I and Conv II did not control the occurrence of seeds. In Conv II the highest seed number could be explained by the influence of mineral fertilizers on weed seed production. In all organic systems the number of seeds was lower than in Conv II and the lowest amount of seeds was found in system Org II where composted manure was used. System Org II had also the lowest number of seeds in 2011 [27]. Although manure in system Org II could be a source of weed seeds [46], it can also stimulate the activity of microorganisms and increase enzyme activity in soil [24]. The trend of larger weed seed number in system Org 0 was probably due to the lack of winter cover crops. As Dorn et al. [47] has stated, cover crops either growing or incorporated into the soil have an inhibitory effect on weeds.

Cover crops, when incorporated in a cropping system, have numerous beneficial effects: better weed suppression ability, increased soil microbiotic activity and abundance of seed predators, which can affect the abundance and distribution of weed seeds [48].

Compared to summer annual seed numbers, the percentage of winter annual was much lower (Table 2). The highest number of C. album seeds was found in the conventional system (Conv II) in the pea crop, although Barberi et al. [1] have stated that the population size of C. album did not depend on the management system. The effect in pea most likely occurred because the herbicide used did not have a comprehensive impact. In addition, eliminating some species may cause species impoverishment in general biodiversity [49] and will allow species such as C. album to establish a stable

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seed bank and thus the ability to maintain viability in the soil [6]. As shown in (Table 3), the main factor which influenced winter annual weed seeds (including V. arvensis) was the cropping system.

Table 3: The effects of different factors on summer and winter annual weed seed species in 2015.

Factor	Summer annual	incl. Chenopodium album	Winter annual	incl. Viola arvensis	Total
Crop (C)	F4.75 = 2.051, p = 0.096	F4.75 = 1.988, p = 0.105	F4.75 = 2.062, p = 0.094	F4.75 = 1.266, p = 0.291	F4.75 = 1.722, p = 0.154
Cropping system (CS)	F4.75 = 1.005, p = 0.411	F4.75 = 1.021, p = 0.402	F4.75 = 3.067, p = 0.021*	F4.75 = 4.722, p = 0.002*	F4.75 = 1.349, p = 0.260
C x CS	F16.75 = 0.858, p = 0.618	F16.75 = 0.823, p = 0.656	F16.75 = 0.484, p = 0.948	F16.75 = 0.774, p = 0.710	F16.75 = 0.756, p = 0.728

In red clover the number of summer annual seeds as well as the total seed count was statistically higher in system Org 0, with the lowest in system Conv I (Table 2). Both of the systems acted as control systems; however, the difference was remarkable mainly due to the use of herbicides in system Conv I. Ball and Miller [50] have reported that herbicides can influence seed bank composition, with some of the weed species decreasing and some increasing. Previous studies found that the composition of weeds and the weed seed communities were influenced by mowing the red clover [40]. The number of C. album was statistically higher in system Org 0. The increased weed seed amount may be a result of the previously sown barley's greater dependence on the growing conditions, especially weather and fertilization [22]. The results of our study showed that the weed seed number in the following winter wheat was lower than in the previous red clover.

In pea all of the peaks and lows appeared within systems Conv II and Org 0 (Table 2). The number of weed seeds of summer annual species was significantly higher in Conv II than in any of the other management system. Org 0 on the other hand had a trend of all of the lowest counts of weed seeds compared to the other systems. The high weediness in pea has been mentioned earlier over the course of the organic experiments on the same plots [22] and the reason for the high weed seed infestation in all of the systems (except for system Org 0 where no cover crops were grown) is the weak competitiveness of the pea, also the carry-over effect of the cover crops. This finding is inconsistent with De Cauwer et al. [4] who reported that the higher seed density occurred in plots where no mineral fertilizer was used.

In potato and barley undersown with red clover, the differences were not significant, but the least amount of weed seeds was found in system Conv I. Some researchers have noticed that when herbicides are applied continuously the total seed bank shows signs of declining [40,50,51]. In system Conv II the added mineral fertilizers may have had an effect on the weed seeds by increasing weed productivity [52]. Our data indicate that organic cropping systems, especially enriched by cover crops and compost, can regulate weed seed occurrence on an even better level than herbicides. Compared to the data of the initial study in 2011 [27] the dominant weed species, (Chenopodium album among summer annuals and Viola arvensis among winter annuals) remained unchanged during the 5-year crop rotation.

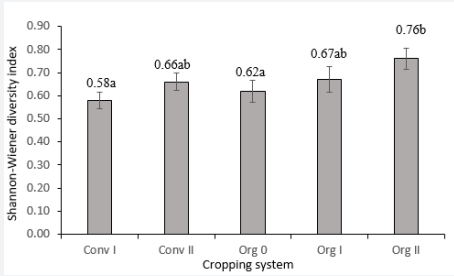

Figure 2: Shannon-Wiener diversity indexes in 2015 (ANOVA, Fisher (LSD) test). Means followed by different letters within each bar indicate significant differences ($p < 0.05$) cropping systems; Vertical bars denote the standard errors.

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Table 4: The effects of different factors on Shannon-Wiener diversity index, Margalef richness index and Equitability index in 2015.

Factor	Shannon-Wiener diversity index, H'	Margalef richness index	Equitability index, J´
Crop (C)	F4.75 = 1,929, p = 0,114	F4.75 = 0,359, p = 0,837	F4.75 = 2,034, p = 0,098
Cropping system (CS)	F4.75 = 2.368, p = 0,060	F4.75 = 3,163, p = 0,019*	F4.75 = 1,395, p = 0,244
C x CS	F16.75 = 0,642, p = 0,839	F16.75 = 1,126, p = 0,348	F16.75 = 0,932, p = 0,981

As an average, Shannon-Wiener diversity index values (Figure 2) were higher in organic systems. The lowest indexes were calculated in systems where no winter cover crops were used – Conv I and Org 0 and highest S-W index was in Org II system. Major et al. [53] reported that addition of compost and inorganic fertilizer has an effect on soil fertility and thus an increase in weed species richness. Some authors [33,51,54] have shown, that the addition of mineral and/or organic fertilizer may reduce plant diversity by favouring competitive species, but this did not occur in the present study. The analysis of effects of different factors on S-W index (Table 4) was made, but no significant conclusions could be made.

Margalef richness indexes were highest in organic systems with treatment (Org I, Org II); (Figure 3). The richness index was affected by field management, where control system (Org 0) without fertilizer decreased the index and winter cover crops and manure (Org II) increased it. This is also confirmed by Dölle and Wolfgang [55], who pointed out that species richness is greatly linked to yearly disturbance – the process of incorporating manure into the soil.

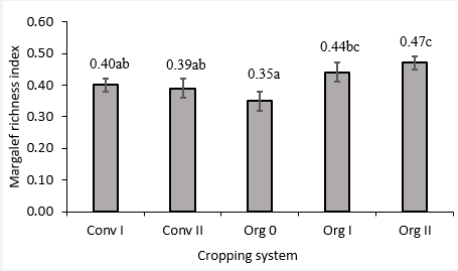

Figure 3: Margalef richness indexes in 2015 (ANOVA, Fisher (LSD) test). Means followed by different letters within each bar indicate significant differences ($p < 0.05$) in cropping systems; Vertical bars denote the standard errors.

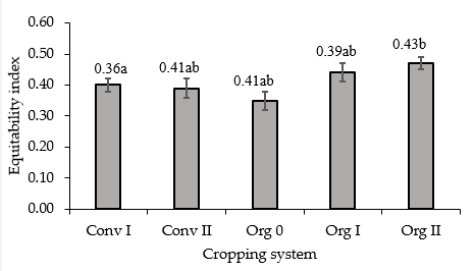

Figure 4: Equitability indexes in 2015 (ANOVA, Fisher (LSD) test). Means followed by different letters within each bar indicate significant differences ($p < 0.05$) in cropping systems; Vertical bars denote the standard errors.

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All values of the Equitability indexes were under 0.5 (Figure 4), which indicates the unevenness of the weed species in the seed bank. In cropping systems, the statistical difference was seen in Org II and Conv I. This indicates that herbicide use does not affect the weed seeds of the different weed species equally in the soil seed bank. The lowest E index found in system Conv I (0.36), where herbicides were used, indicates that there were few dominant weed species in this system.

Conclusion

After one rotation a total of 23 weed species was found. The most abundant species in the weed seed bank were Chenopodium album and Viola arvensis. The highest number of V. arvensis as well as C. album seeds were found in conventional systems with the highest rate in pea (for C. album), where herbicides and fertilizers were used.

Differences in weed seed number between systems were inconsistent, but overall not higher in organic than conventional. Weed diversity tended to be a little higher in organic systems, which has potential environmental benefits. In general, all the organic systems showed tendencies of having the lowest seed numbers and highest Shannon-Wiener biodiversity and Equitability indexes. This tendency was clearest in system Org II, where winter cover crops were used in combination with composted manure. However, it is not clear from a system comparison which factor was affecting weeds – was it the fertilizer type, herbicides or cover crops? Such questions can be answered by future research, but from this study we conclude that organic systems have better weed management outcomes than conventional systems.

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III

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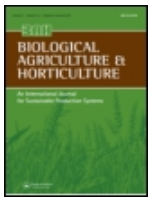

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Do green manures as winter cover crops impact the weediness and crop yield in an organic crop rotation?

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ABSTRACT

The effects of different winter cover crops and their combination with composted cattle manure on weeds and crop yields were investigated within a five-field crop rotation (barley undersown with red clover, red clover, winter wheat, pea, potato) in three organic cropping systems. The control system (Org 0) followed the rotation. In organic systems Org I and Org II the winter cover crops were used as follows: ryegrass (*Lolium perenne* L. in 2011/2012) and a mixture of winter oilseed-rape (*Brassica napus* ssp. *oleifera* var. *biennis*) and winter rye (*Secale cereale* L.) in 2012/2013 before pea; winter oilseed rape before potato and winter rye before barley. In Org II system composted cattle manure was also applied. In comparison with the control system, the winter cover crops, depending on plant species used, reduced the biomass and density of the weeds. In both years winter rye was a better suppressor of weeds than the other winter cover crops. Cover crops increased the yield of potato in rotation crops. When used together with composted cattle manure the cover crops caused significant yield increase in cereals.

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Cropping systems; dry biomass of weeds; organic farming; winter oilseed rape; winter rye

Introduction

The problems of cost-effective control of weeds without synthetic herbicides and increasing crop yield under organic agriculture are challenging (Kruidhof et al. 2008; Linares et al. 2008; Doltra & Olesen 2013). In organic farming the approach to weed management involves the whole cropping system (Liebman & Davis 2000). Crop rotation and timing of soil cultivations are usually linked, both contributing in different ways to manipulating the weed population (Bond & Grundy 2001). Within a rotation, crop choice will determine both current and future weed problems. Cover crops are included in the rotation to reduce weed problems before a less competitive crop is grown. Also, well-designed cover-crop systems can reduce the cost of weed control (Anderson et al. 2001). The inclusion of cover crops in the rotation during vegetation-free periods will suppress weed development (Creamer et al. 1996; Liebman & Davis 2000; Shrestha et al. 2002; Charles et al. 2006). Fageria et al. (2005) found that cover crops suppress weeds via resource competition and release of phytotoxins from root exudates and decomposing residues, thereby minimizing seed germination and reproduction of weeds. The efficacy of a cover crop in suppressing weeds is affected by plant density and aboveground biomass

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Table 1. Experimental design of five-field crop rotation (winter wheat, pea, potato, barley undersown with red clover, red clover) in three cropping systems.

Org 0 Crop rotation (CR)	Org I CR + winter cover crops (CC)	Org II CR + CC + manure (t ha^{-1})
Winter wheat	Ryegrass (2011/2012), mixture of oilseed rape and winter rye (2012/2013)	10
Pea	Winter oilseed rape	
Potato	Winter rye	20
Barley undersown with red clover		10
Red clover		

(Linares et al. 2008), time of sowing of subsequent crop (Stivers-Young 1998) and duration of cover crop growing period (Charles et al. 2006).

Large differences in the effects of cover crops on yields of succeeding crops have been observed. Doltra and Olesen (2013) reported that in Nordic climates, winter cover crops can improve yields but this can vary considerably between years (Olesen et al. 2007). An experiment in Sweden (Stenberg et al. 1999) showed that a cover crop did not reduce grain yields significantly, but negative effects have also been reported. Jensen (1991) found a negative effect of cover crop on the yield of following barley. Teasdale et al. (2007) found that management that increased weed suppression tended to increase the risk of crop yield reduction. Tonitto et al. (2006) showed that, in comparison with fertilized crops without overwintering catch crops, unfertilized legume cover crop based systems reduced crop yields by an average of 10%.

Hence, the effect of winter cover crops can depend on various factors such as agro-climatic conditions, length of growth period and crop species, so it is important to investigate the effect of particular winter cover crop under local conditions. Moreover, in Estonian conditions, green manures as winter cover crops have not been investigated in crop rotations. Therefore, the aim of this investigation was to study the effect of different green manures as winter cover crops (catch crops) and their combination with composted cattle manure under a five-field crop rotation in three organic cropping systems on weed biomass and crop yield. The hypothesis was that green manures suppress weeds and increase the yield of following crops.

Materials and methods

Experimental site and design

The crop rotation experiment in three organic cropping systems was started in 2008, but the results presented in this article are from two seasons (2012 and 2013). In a five-field crop rotation, barley (*Hordeum vulgare* L.) cv. Anni undersown with red clover (*Trifolium pratense* L.) cv. Varte, red clover, winter wheat (*Triticum aestivum* L.) cv. Fredis, peas (*Pisum sativum* L.) cv. Tudor, and potato (*Solanum tuberosum* L.) cv. Maret were grown in succession. These crops are most common in Estonian agriculture. All varieties are early-ripening and suitable for Estonian conditions and organic farming. System Org 0, as control, followed this rotation. In System Org I, green manures as winter cover crops were used: ryegrass in 2011/2012 and the mixture of oilseed rape and winter rye in 2012/2013 before pea, winter oilseed rape before potato and winter rye before barley (Table 1). In System Org II, green manures as winter cover crops plus composted cattle manure at 20 t ha^{-1} for potato and 10 t ha^{-1} for both cereals were applied. The experiment was set up with four replications with each plot (60 m^2) in a systematic block design. The field belongs to the Department of Field Crops and Grassland Husbandry of the Estonian University of Life Sciences and is located near Tartu (58°23′N, 26°44′E). The soil type of the experiment area is sandy loam Stagnic Luvisol according to the World Reference Base classification (FAO 2014) with a humus layer of 20–30 cm (Reintam & Köster 2006). The mean characteristics of the humus horizon were: C_{org} 1.1–1.2%, N_{tot} 0.10–0.12%, P 110–120 mg kg^{-1}, K 253–260 mg kg^{-1}, pH_{KCl} 5.9 and soil bulk density 1.45–1.50 g cm^{-3}. The ploughing layer was 27–29 cm.

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Cereals and pea were sown at a row distance of 12.5 cm. Seeding rate of pea was 100 and 450 seeds m^{-2} for cereals. The distance between potato tubers was 27 cm and the distance between rows was 70 cm. The target density of potato was 52,910 tubers ha^{-1}. The sowing was done during the period from the beginning of May (cereals, pea) to the third week of May (potato).

The winter cover crops used were winter oilseed rape cv. Banjo (seeding rate 6 kg ha^{-1}), winter rye cv. Tulvi (seeding rate 220 kg ha^{-1}) and ryegrass cv. Talvike (seeding rate 25 kg ha^{-1}) in 2012 or a mixture of rye and oilseed rape (seeding rate accordingly 180 and 6 kg ha^{-1}) in 2013. In organic system Org II, fully composted cattle manure was added in the spring: 20 t ha^{-1} for potato and 10 t ha^{-1} for both cereals (barley and winter wheat). On average, the dry matter of composted cattle manure contained 138 g C kg^{-1}, 9.7 g N kg^{-1}, 4.6 g P kg^{-1}, 8.6 g K kg^{-1}, average dry matter content 44.8%.

The field was prepared and cover crops were sown with a Kongskilde sowing machine (Kongskilde Agro GmbH, Kassel, Germany) (width 3 m, row line width 12.5 cm) immediately after harvesting the main crop and ploughed into the soil in the beginning of May. Mechanical weed harrowing was used twice to control weeds in cereals, potato and pea. A spring-tine harrow (Same, Puurmani, Estonia) with a working width of 3 m, was used for harrowing. In all three organic systems, the red clover was cut and ploughed into the soil in mid-July. Ploughing depth was 20–22 cm.

Weed samples

All data was collected in accordance with the TILMAN-ORG Handbook of Methods (Cooper et al. 2012). The composition, density and biomass (dry mass) of the weed species were established before the cover crops were ploughed into the soil at the beginning of May, before first harrowing of winter wheat and 3 weeks before harvesting of rotation crops. In red clover plots weed studies were carried out before first cutting (June) and before aftermath incorporation (August). All assessments were made in four replicates per plot, using a 25 × 25 cm frame. At each assessment, all weeds were collected and the species were determined and counted. Aboveground biomass was collected and weighed for total biomass (not by species). All weed samples were dried (80 °C) to constant weight and weighed immediately.

Crop yield

Cereals and pea were harvested at the beginning of August using a Sampo Rosenlew experimental harvester (Sampo Rosenlew Lt, Pori, Finland). Potato tubers were hand-collected at the end of August. Yield data was adjusted to dry matter content. The straw of cereals and pea was left on the field and then ploughed into the soil together with cover crops at the beginning of May in all systems.

Weather conditions

The experimental field is 59 m above sea level and belongs to the South-Estonian upland agro climatic region where the average annual sum of active air temperatures (sum >5 °C) is 1750–1800 °C, mean annual temperature +4.4 °C with precipitation 550–650 mm. The weather during the experimental period was monitored with a Metos Model MCR300 electronic weather station (Pessl Instruments. GmbH, Weiz, Austria), which automatically calculates the average daily temperatures and the sum of precipitation. The measurements were made from Rõhu weather station of the Institute of Agricultural and Environmental Sciences of the Estonian University of Life Sciences. Weather conditions during the study period differed substantially; in 2012, summer temperature was similar to the long-term average (in July and August +16.7 and +15.8 °C, respectively), but total precipitation during the growth period of 2012 was 102 mm higher than usual. Winter 2012/2013 was extremely long and snowy which damaged the winter crops. June 2013 was hot and dry compared with the long-term mean (Table 2).

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Table 2. Weather during 2011–2013 and long-term average (1969–2011).

	Temperature (°C)				Precipitation (mm)			
Month	2011	2012	2013	1969–2011	2011	2012	2013	1969–2011
January	−4.7	−6.1	−7.3	−5.2	19.0	30.0	8.8	29.6
February	−11.2	−11.5	−3.5	−5.8	9.0	18.6	14.4	22.5
March	−1.9	−0.3	−7.8	−1.7	4.4	39.4	15.4	23.2
April	6.4	5.0	3.3	4.7	11.2	42.0	16.8	26.5
May	11.0	11.8	14.7	11.4	58.4	81.6	61.2	57.6
June	17.2	13.6	17.8	15.4	35.2	100.6	29.4	75.9
July	19.9	16.7	17.5	17.5	48.2	75.0	67.0	70.4
August	15.8	15.8	16.6	16.1	54.6	87.4	72.8	89.2
September	12.3	12.2	10.8	10.8	80.0	59.8	37.6	57.1
October	6.8	5.7	6.6	5.6	47.8	45.2	44.6	57.2
November	2.9	2.6	3.5	0.4	34.4	50.2	69.8	45.5
December	1.0	−6.8	1.1	−3.4	52.6	9.0	47	34.1

Data analyses

The Statistica version 11.0 (Statsoft Inc., USA, 2005) software package was used for all statistical analyses. The three-way ANOVA was applied for the analysis of variance to test the effect of year, cropping systems, cover crop and their interactions on the weed dry biomass, weed density and main crop yield. Main effect mean separations were determined with Fisher's least significant difference. A correlation analysis was conducted to quantify the relationships between weed biomass and crop yield, as well as between crop yield, experimental year and cropping systems. The level of statistical significance was set at $p < 0.05$ if not indicated otherwise.

Results and discussion

Weed infestation before cover crop incorporation

Early harvested crops provide very good opportunities for growing winter cover crops within a crop rotation. The quantity of winter cover crop biomass depended on the sum of effective temperatures (above 5 °C) during the growing season. Before winter cover crop ploughing in 2012 the aboveground

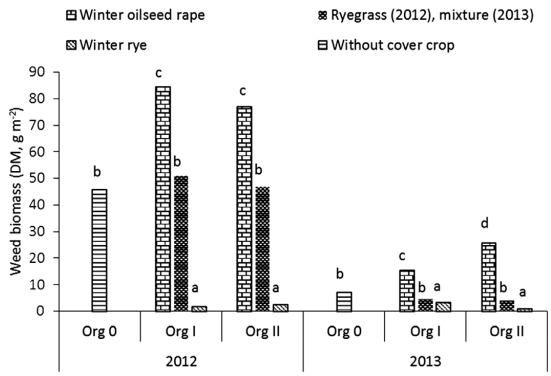

Figure 1. Weed dry biomass in different cropping systems before incorporation to soil in organic cropping systems in 2012 and 2013. Notes: Org 0 – without cover crops (CC), Org I – with CC; Org II – with CC and composted cattle manure. Means followed by a different letters indicate significant influence ($p < 0.05$) of cropping systems within years (Fisher's test).

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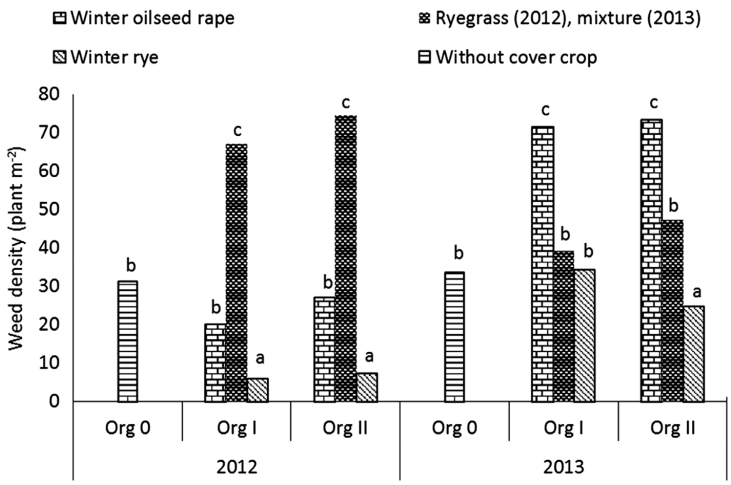

Figure 2. Weed density in different cropping systems before incorporation to soil in organic cropping systems in 2012 and 2013. Notes: Org 0 – without cover crops (CC), Org I – with CC; Org II – with CC and composted cattle manure. Means followed by a different letters indicate significant influence ($p < 0.05$) of cropping systems within years (Fisher's test).

Table 3. Analysis of variance on weed dry biomass before cover crop incorporation.

	Weed dry biomass (g m^{-2})
Year (Y)	***
Cropping system (CS)	Ns
Cover crop (CC)	***
Y*CS	Ns
Y*CC	***
CS*CC	***
Y*CS*CC	***

Note: ns, statistically non-significant.
*Significant at 1% level of probability;
***Significant at 0.1% level of probability.

biomass of winter cover crops varied from 580 kg ha^{-1} for winter oilseed rape to 990 kg ha^{-1} for winter rye. Because of very hard overwintering conditions in 2012/2013 biomass of winter cover crops was lower than in 2011/2012.

Cover crops are expected to control weeds in arable crops under organic farming conditions. However, weeds provide a wider range of species and functions, i.e. food for many beneficial organisms (predators, parasitoids) and a role in soil organic matter formation, than the few crop species which dominate the agricultural land (Bajwa 2014). In the current experiment it was clear that winter cover crops influenced the composition of dominant weed species and weed biomass as well as weed density.

The dominant weed species in the control system (Org 0) were *Matricaria inodora* L., *Viola arvensis* Murr., *Veronica persica* Poir. and *Capsella bursa pastoris* L. Medicus. The composition of weed species did not differ between cover crops in systems Org I and Org II. *M. inodora* L. and *V. arvensis* Murr. were dominant in all cover crops except winter oilseed rape where *C. bursa pastoris* L., *Lamium purpureum* L. and *Myosotis arvensis* L. (Hill) prevailed. The last two were also dominant in the cover crop in winter rye, in ryegrass (2012) and in the mixture of cover crops (2013). Dominance can be

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explained by low biomass of cover crops. Bàrberi and Mazzoncini (2001) also found that cover crops influenced the weed composition only in years when cover crops produced large biomass.

Before cover crop incorporation, weed biomass and density were dependent on cropping system, cover crop and year. In 2012, weed biomass was the lowest in winter rye, and highest in winter oilseed rape due to the latter's poor overwintering (Figure 1). Ryegrass as a green manure cover crop was replaced by a mixture of winter rye and oilseed rape in autumn 2012 because the ryegrass produced very little biomass and did not efficiently suppress weeds under Estonian climatic conditions. Earlier findings confirm the low biomass of ryegrass in these conditions (Talgre et al. 2011). Moreover, the use of cover crop mixtures of two or more species usually enhances biomass production (Scholberg et al. 2010).

In 2013, results were similar; biomass was lowest in winter rye in Org I and II, intermediate in the mixture of winter oilseed rape and rye and the highest in winter oilseed rape (Figure 1). But, due to the very difficult overwintering conditions in winter 2012/2013, weed biomass was up to five times smaller than in 2012. In both years, winter rye was a better suppressor of weed dry biomass and weed density than the other winter cover crops (Figures 1 and 2). Fageria et al. (2005) and Linares et al. (2008) also found that winter rye as a winter cover crop can provide very effective weed control. Bàrberi and Mazzoncini (2001) found that rye reduced weed biomass significantly, but this suppression depended on cover crop biomass and in years when it was higher, the weed biomass was reduced by up to 99%. Kołota & Adamczewska-Sowińska 2013 considered that allelopathic compounds had an important role in weed reduction by rye, inhibiting the germination of weed seed. Crucifer species, through glucosinolate compounds, can also have allelopathic effects and contribute to weed management (Liebman & Davis 2000). Boydston and Hang (1995) found that incorporated residues of rapeseed can reduce weed density up to 85% in a subsequent crop. This effect of Brassicaceae did not appear in our study in either year.

A summary of analyses of variance of the effects of year, cover crops and cropping system as well as their interactions on each of these variables is shown in Table 3. Weed biomass was significantly influenced by year and cover crops ($p < 0.001$) and their interaction ($p < 0.001$). The cropping system alone and interaction between the experimental year and cropping system had no significant effect on weediness.

Weed infestation before main crop harvest

The weed infestation in the experiment differed between each crop. In 2012, weed biomass (84–118 g m^{-2}) was greatest in potato crop after winter oilseed rape, although there were no statistically significant differences between cropping systems (Figure 3). The analysis of species composition of weeds growing after the investigated cover crop showed that perennial weeds (*Sonchus arvensis* L., *Elytrigia repens* L. and *Cirsium arvense* L.) dominated in potato, with higher biomass and annual weeds in cereal crops. Perennial weed species are difficult to control and they can lead to yield reduction in organic cereal production (Olesen et al. 2009). In 2013, *Equisetum arvense* L. started to dominate significantly in potato grown in the Org 0 system where soil remained more acid while in other systems the soil pH increased under the influence of cover crops (Luik et al. 2014). In 2013 the smallest weed biomass in Org I systems was recorded in barley (us) and winter wheat (Figure 3). This can be explained by the influence of red clover in all systems.

In 2013, the largest weed biomass was in peas with the tendency to increase under the influence of cover crops in Org I. Significantly higher weed biomass was observed in peas in Org II than in Org 0 (Figure 3). Weed biomass was also affected by higher C content (Luik et al. 2014), and hence higher nutrient content in soil in Org I and II. Also, weed density was highest in pea, although there was no statistically significant difference from their number in the control ($p < 0.05$) (Figure 4). First reason of high weediness in pea was the carry-over effect of cover crops and secondly, the weak competitiveness of the pea. Also, Lundkvist et al. (2008) showed that pea, a weak competitor, had significantly higher weed biomass before harvest compared, for example, with winter wheat.

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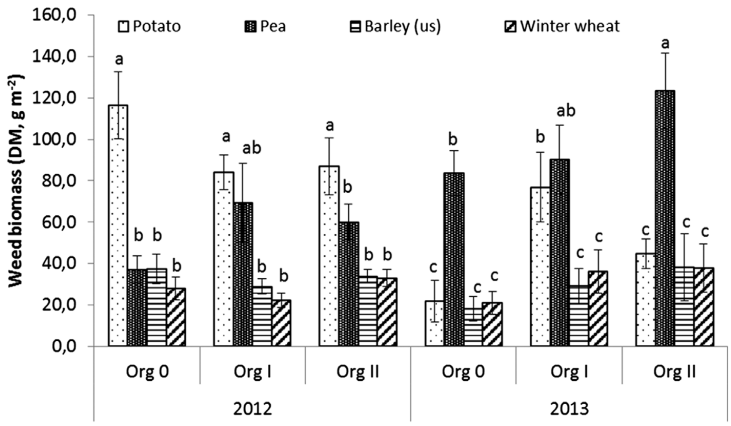

Figure 3. Weed dry biomass in main crops 3 weeks before harvesting.
Notes: (Org 0 – without winter cover crops (CC as control variant), Org I – with CC; Org II – with CC and composted cattle manure). Bars are standard error of the means Different letters indicate significant influence ($p < 0.05$) of cropping systems on crops in different years (Fisher's test).

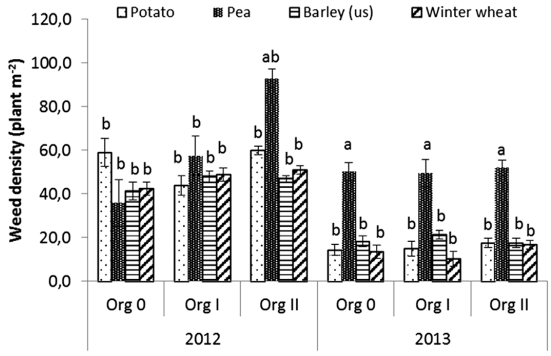

Figure 4. Weed density in main crops 3 weeks before harvesting.

Table 4. Analysis of variance on weed dry biomass in different crops 3 weeks before harvest.

	Weed dry biomass (g m^{-2})
Year (Y)	Ns
Cropping system (CS)	Ns
Crop (C)	***
Y*CS	*
Y*C	***
CS*C	Ns
Y*CS*C	*

Note: ns, statistically non-significant.
*Significant at 5% level of probability;
***Significant at 0.1% level of probability.

Table 5. Crop yield depending on the cropping system (CS) in 2012, 2013 and two year average

Crop CS	2012	2013	Average 2012–2013
Barley			
Org 0	1.44 a[1] ± 0.04[2]	2.65 a ± 0.17	2.05 a ± 0.24
Org I	1.34 a ± 0.17	2.77 a ± 0.12	2.06 a ± 0.29
Org II	2.17 b ± 0.29	3.41 b ± 0.10	2.79 a ± 0.27
Winter wheat			
Org 0	5.11 a ± 0.28	3.62 a ± 0.18	4.37 a ± 0.32
Org I	5.86 ab ± 0.29	3.94 a ± 0.49	4.90 a ± 0.45
Org II	6.58 b ± 0.37	3.79 a ± 0.15	5.19 a ± 0.56
Potato			
Org 0	36.7 a ± 2.5	18.2 a ± 0.7	27.5 a ± 3.7
Org I	35.8 a ± 2.3	21.2 b ± 0.4	28.5 a ± 3.0
Org II	32.4 a ± 1.4	21.3 b ± 1.2	26.9 a ± 2.3
Pea			
Org 0	2.11a ± 0.24	2.84a ± 0.13	2.48a ± 0.19
Org I	2.07a ± 1.10	3.46b ± 0.20	2.77a ± 0.28
Org II	1.81a ± 0.08	3.16b ± 0.16	2.48a ± 0.27

[1]Means followed by a different letters within each column indicate significant influence ($p < 0.05$) of cropping systems;
[2]Standard error of the means.
Note: (Org 0 – without winter cover crops (CC), Org I – with CC; Org II – with CC and composted cattle manure).

Analysis of variance of the influence of cropping system and year on weed dry biomass in main crops showed that weather (year) and cropping system had no significant effect on weed biomass, the weediness was significantly influenced by their interaction ($p < 0.05$). The weediness was significantly influenced by crop and crop × year interaction ($p < 0.001$) (Table 4).

Crop yields

Differences in the effects of winter cover crops on the yield of following crops have been observed but these were dependent on the crop (Table 5). In both years, a significant yield increase was obtained in barley (us) (Org II), which was affected by co-influence of cover crop and manure. In 2012, a significant yield increase was obtained under the influence of green manure in combination with cattle manure in winter wheat (Org II). The positive effects of manure and organic fertilizers derived from plant materials on soil fertility have been shown in previous studies (Raupp & Oltmanns 2006; Olesen et al. 2009; Marinari et al. 2010). In 2013, the two cereals reacted quite differently. The yield of barley was significantly higher in Org II than in Org 0 and Org I, whereas winter wheat showed no yield increase (Table 5). The reason for this was the extremely long and snowy winter of 2012/2013, which damaged winter wheat plants, and a very dry and hot summer, which decreased the yield level. It is assumed that the reason for the increased yield of barley in Org II was the improvement of soil properties. In 2012, a significant increase of C was obtained in the Org I system and this increase continued in 2013 (Sanchez de Cima et al. 2013; Luik et al. 2014). Both cover crops and their combination with manure application significantly increased the grain yield of pea and potato yield in 2013. This can probably be explained by the improved soil properties: higher organic carbon content and increased water holding capacity as well as water permeability in Org I and especially in Org II (Luik et al. 2014). Therefore, the effect of green manures and their combination with composted manure became more evident in unfavourable, very dry weather conditions.

In the present experiment, weed pressure did not reduce the crop yield significantly compared with the potential yields in the region. In 2013, correlation analysis of relationships between weed biomass and yield of crops in the rotation indicated a positive correlation ($r = 0.58$, $p < 0.05$) between yield of potato and weediness. Thus, to a certain extent, weediness had a positive effect on yield of potato. However, there were no significant correlations between weed biomass and yields of other crops under study. As weeds, by increasing biological diversity support an increased functionality of agricultural

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ecosystems, their presence to some extent may be beneficial for crop production. This is supported by Ryan et al. (2009) who found that, despite higher weed biomass in the organic systems, there was no difference in maize yields between organic and conventional systems.

Conclusions

The results show that winter cover crops had an effect on weed density and biomass. The effect of winter cover crops depends on the crop species grown. From the winter cover crops tested, winter rye was the best suppressor of weed dry biomass and weed density compared to other winter cover crops in the trial. Winter cover crops tended to increase yields in all rotation crops. Their influence on rotation crop yield was enhanced when combined with composted cattle manure in cereals. The effect of green manures and their combination with composted manure became more evident in unfavourable, dry weather conditions.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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IV

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UMBROHTUDE BIOMASSI, ARVUKUSE JA MITMEKESISUSE MUUTUSED PIKAAJALISE KÜLVIKORRA KATSE TEISES ROTATSIOONIS

CHANGES IN WEED BIOMASS, DENSITY AND DIVERSITY IN LONG-TERM CROP ROTATION EXPERIMENT DURING SECOND ROTATION

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ABSTRACT. The effects of long term (established in 2008) five-field crop rotation (barley (*Hordeum vulgare* L.) with undersown red clover (*Trifoium pratense* L.), red clover, winter wheat (*Triticum aestivum* L.), pea (*Pisum sativum* L.), potato (*Solanum tuberosum* L.)) on the biomass, abundance and diversity (Shannon-Wiener index) of weeds in three organic (Org) and two conventional (Conv) systems after the second rotation were investigated. The results include data from the second rotation in 2013 – 2017. The control system (Org 0) followed only the crop rotation. In the organic systems Org I and Org II winter cover crops were used. In Org II system composted cattle manure was also applied. The conventional cropping systems were treated with herbicides and fungicides and system Conv 0 acted as control (no fertilizer use). Mineral fertilizer was used in Conv II. In general, the significant differences were evident between conventional and organic cropping systems. There were also some differences depending on the crop. The weed biomass was the lowest in barley and potato plots, with significantly higher values in organic than in conventional systems. In clover plots the highest biomass of weeds occurred in Conv II whilst the lowest in Org I. In winter wheat plots the biomass of weeds was significantly lower in conventional systems than in any of the organic systems. Pea plots had the highest biomass, abundance and diversity of weeds in all systems within all rotational crops.

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Sissejuhatus

Umbrohud on põllukoosluste loomulik osa, ent konkurents põhikultuuridega vee ja toitainete pärast võib oluliselt mõjutada saagi kujunemist. Samas on umbrohtudel ka mitmeid positiivseid omadusi: väheneb erosioon ning muld rikastub orgaanilise ainega. Rohke orgaanilise aine lisandumine mulda parandab mulla omadusi ja suurendab mullaelustiku mitmekesisust. Lisaks tagavad umbrohud toidubaasi paljudele õitel toituvatele tolmeldajatele ja taimtoiduliste putukate arvukust reguleerivatele kasuritele. Umbrohuseemnetel on tähtis osa lindude ning maapinnal liikuvate röövtoiduliste organismide toidulaual (Marshall jt, 2003; Eraud jt, 2015; Rollin jt, 2016). Seega on keskkonna ökoloogiliste talitluste tagamiseks umbrohtude säilimine vajalik, kuid piisava saagikuse saamine toob esile ka vajaduse nende piiramiseks. Kasutatavad meetodid umbrohtumuse reguleerimiseks sõltuvad taimekasvatusviisist. Intensiivne herbitsiididel põhinev põllumajandus toodab küll suuri saake, kuid selle kõrvaltoimeteks on ulatuslikud keskkonnaprobleemid (Mäder jt, 2002). Monokultuuride kasvatamine suurtel maaaladel ning liigne pestitsiidide kasutamine mõjutavad eelkõige bioloogilist mitmekesisust ja seeläbi ka mullaviljakust. Mullaviljakus on peamine saagikust mõjutav komponent (Trewavas, 2001; Hole jt, 2005; Azadi jt, 2011). Mitmed uurimused (Weil, 1982; Afandi jt, 2002;

Blavet jt, 2009; García-Orenes jt, 2009; Arnhold jt, 2014) on näidanud, et herbitsiidide kasutamine suurendab erosiooni. Samas umbrohud seovad juurestikuga vett ja kaitsevad oma olemasoluga mulla pinda (Arnhold jt, 2014). Umbrohud võivad herbitsiidide pideva kasutamisega muutuda nende suhtes resistentseteks, mis omakorda võib suurendada vajadust täiendavate taimekaitsevahendite järele ning põhjustada keskkonna saastatust (Rotches-Ribalta jt, 2017). Kuigi herbitsiide kasutamist peetakse kõige efektiivsemaks meetodiks vabanemaks umbrohtudest ning vähendamaks umbrohtude seemnepanka mullas (Bàrberi jt, 1998; Rotches-Ribalta jt, 2017), mõjutab see kooslustes liikidevahelist tasakaalu (Rotches-Ribalta jt, 2017), vähendades herbitsiididele tundlike liikide mitmekesisust (Bàrberi jt, 1998; Squire jt, 2000; Robinson, Sutherland, 2002; Hawes jt, 2010; Ryan jt, 2010; José-María, Sans, 2011; Rotches-Ribalta jt, 2017) ning soodustades resistentsete liikide teket.

Maheviljelust iseloomustab kohalike taastuvate ressursside tasakaalustatud kasutamine, mis muuhulgas aitab mitmekesistada põllukooslusi. Selle viljelusviisi eeldus on optimaalse tasakaalu leidmine põhikultuuri ja umbrohtude vahel. Maheviljeluses on sellise tasakaalu saavutamine palju keerulisem, kuna ei kasutata sünteetilisi herbitsiide (Bond, Grundy, 2001). Siiski on ka mahetootmises mitmeid võimalusi umbrohtude kontrolli all hoidmiseks nagu nt künd, vahekultuuride kasvatamine ja mitmekesine külvikord. Samas on leitud, et sügav künd võib rikkuda mullaagregaatide struktuuri (Colquhoun, Bellinder, 1996; Bond, Grundy, 2001) ning kahjustada mulla makro- ja mikroelustikku (Carcamo jt, 1995; Kromp, 1999; Hole jt, 2005). Vahekultuure kasvatatakse põhikultuuride vahelisel ajal, ennetamaks toitainete leostumist ja mullaerosiooni (Liebman, Davis, 2000; Bond, Grundy, 2001). Kiire kasvuga vahekultuurid takistavad umbrohtude kasvu nii otsese konkurentsi kui allelopaatiliste ainete eritamise läbi (Bond, Grundy, 2001; Madsen jt, 2016). Umbrohtumus sõltub oluliselt ka külvikorrast, kuivõrd selle kultuurid erinevad nii survetõrje kui ka kasutatava agrotehnika poolest. Varasemad uuringud (Butkevičiene jt, 2021) on näidanud, et pikaajalistes tavaviljeluse külvikordades on ilmnenud muutused aja jooksul nii umbrohtude liigilises koosseisus kui ka arvukuses. Toimunud muutusi on võimalik kindlaks teha vaid konkreetsetes oludes erinevates kasvatussüsteemides külvikordi uurides, leidmaks optimaalseid lahendusi umbrohtude reguleerimiseks.

Käesoleva töö eesmärgiks oli välja selgitada umbrohtude biomass, arvukus ja mitmekesisus viieväljalise külvikorra kultuurides teises rotatsioonis sõltuvalt kolmest maheviljeluse ning kahest tavaviljeluse süsteemist. Kahes maheviljelussüsteemis mitmekesistati külvikorda talviste vahekultuuridega, mille eesmärk oli kaasa aidata umbrohtumuse reguleerimisele. Tavaviljelussüsteemides kasutati herbitsiide. Töö hüpotees oli, et sõltuvalt kultuurist ning kasvatussüsteemist on võrreldes esimese rotatsiooniga umbrohtude biomass, arvukus ja mitmekesisus suurenenud.

Materjal ja metoodika

Viieväljaline põldkatse viidi läbi Eesti Maaülikooli katsepõldudel, mis paiknesid Tartu lähedal (58°23′N, 26°44′E). Katse rajati 2008. aastal, kuid antud artiklis on vaatluse all umbrohtude biomassi ning arvukuse teise rotatsiooni aegsed (2013–2017. a) andmed. Katsepõllu mullatüüp oli pruun kahkjas (näivleetunud) liivsavimuld. Põldude umbrohtumust uuriti viieväljalises külvikorras kolmes erinevas maheviljelussüsteemis (Mahe 0, Mahe I ja Mahe II) ning kahes tavaviljelussüsteemis (Tava 0 ja Tava II). Kõikide süsteemide külvikorra kultuuride järjestus terve rotatsiooni jooksul oli järgmine: oder (*Hordeum vulgare* L.) 'Anni' punase ristiku (*Trifolium pratense* L.) 'Varte' allakülviga – punane ristik – talinisu (*Triticum aestivum* L.) 'Fredis'– hernes (*Pisum sativum* L.) 'Tudor' – kartul (*Solanum tuberosum* L.) 'Teele'. Mahesüsteemides Mahe I ning Mahe II külvati kohe pärast põhikultuuri koristamist järgmised vahekultuurid: talinisu järgselt (herne eelselt) talirapsi (*Brassica rapa* L. var. *oleifera*) ja talirukki (*Secale cereale* L.) segu, herne järgi (kartuli eelselt) taliraps ja kartuli järgi (odra eelselt) talirukis. Mahesüsteemidest Mahe 0 oli kontrollsüsteem, mis järgis vaid külvikorda ning peale põhikultuuri koristust sellel katse osal sügisel mullaharimist ei toimunud. Mahesüsteemis Mahe II kasutati peale vahekultuuride ka kompostitud veisesõnnikut – kartulile 20 t ha^{-1} ja teraviljadele (talinisu ja oder) 10 t ha^{-1}. Sõnnik laotati kevadel vahetult enne vahekultuuride mulda kündi aprilli lõpus. Talvel olid kõik Mahe I ja Mahe II väljad taimikuga kaetud. Mahe 0 süsteemis jäid kolm välja talvel taimikuta. Külvikorras olev ristik niideti kahel korral suve jooksul, misjärel künti enne talinisu külvamist sisse. Tavaviljelusega süsteemides Tava 0 ja Tava II oli mahedaga sama külvikord, kuid mõlemas süsteemis kasutati keemilisi taimekaitsevahendeid ja Tava II süsteemis ka mineraalväetisi. Umbrohtude tõrjeks kasutati talinisul kevadel (mai algul) herbitsiidi Secator OD normiga 150 ml ha^{-1}; kartulil Titus, 50 g ha^{-1} (2 × 0,25 g korraga); hernel MCPA 750, 1 l ha^{-1}; ristiku allakülviga odral MCPA 750, 1 l ha^{-1}. Ristikus herbitsiidi ei kasutatud. Kartuli umbrohutõrje tehti umbrohtude tärkamisel ja teist korda nädala möödudes; odral ja hernel, siis kui umbrohtudel oli valdavalt 2–3 pärislehte ja hernel 4–5 lehte, teravili oli sel ajal võrsumisfaasis. Tavasüsteemides ei kasutatud talviseid vahekultuure. Tavasüsteemis Tava 0 ei kasutatud mineraalväetisi; Tava II süsteemis kasutati põhiväetisena mineraalväetisi 25 kg P ha^{-1} ja 95 kg K ha^{-1} ning lisaks lämmastikväetist olenevalt kultuurist: talinisule ja kartulile 150 kg ha^{-1} N, odrale ristiku allakülviga 120 kg N ha^{-1} ja hernele 20 kg N ha^{-1}. Kõik variandid rajati neljas korduses; iga katselapi pindala oli 60 m^2. Katse metoodika kirjeldus on olemas ka Madsen jt (2016) ja Kauer jt (2021). Umbrohtude liigiline koosseis, maapealne biomass ning arvukus määrati kolm nädalat enne kultuuride koristamist. Punase ristiku umbrohtumus määrati enne taimiku niitmist ning enne ädala sissekündi. Umbrohud koguti kõikidelt katselappidelt kolmes korduses 25 × 25 cm raamiga.

Liigilise mitmekesisuse iseloomustamiseks kasutati Shannon-Weiner´i mitmekesisuse indeksit (H') mis arvutati järgnevalt (Murphy jt, 2006):

$$H' = -\sum_{i=1}^{s} pi \ln(pi) \quad (1)$$

i – isendite arv i-ndast liigist;
pi – liigi (suhteline) ohtrus (võrrelduna teiste liikidega).

Katseandmeid töödeldi statistiliselt disperssioonanalüüsi (ANOVA) meetodil, kasutati andmetöötlusprogrammi Statistica 13 (Quest Software Inc). Variantide vaheliste erinevuste hindamiseks kasutati Tukey HSD testi, $p < 0,05$, kui tabelis või joonisel ei ole teisiti välja toodud.

Ilmastikutingimused varieerusid märkimisväärselt katseperioodi jooksul (tabel 1). 2012. aasta keskmised temperatuurid olid võrreldavad pikaajaliste keskmiste temperatuuridega, kuid sademete summa märtsist juunini oli 78 mm suurem kui tavaliselt. 2013. aasta mai ja juuni olid keskmisest soojemad, juuni oli oluliselt sademetevaesem kui pikaajaline keskmine (tabel 2).

Tabel 1. Keskmine temperatuur (°C) aastatel 2012–2017
Table 1. *Average temperature (°C) in 2012–2017*

Kuu / *Month*	Temperatuur °C / *Temperature °C*						
	2012	2013	2014	2015	2016	2017	1969–2015*
Jaanuar/*January*	–6.1	–7.2	–7.8	–1.9	–9.4	–3.5	–5.2
Veebruar/*February*	–11.2	–3.6	–0.3	–0.8	0.3	–2.9	–5.6
Märts/*March*	–0.4	–7.8	2.2	2.7	–0.1	1.4	–1.5
Aprill/*April*	5.0	3.5	6.5	5.4	6.1	3.4	4.8
Mai/*May*	11.6	14.8	11.9	10.2	14.0	10.3	11.4
Juuni/*June*	13.6	18.2	13.4	14.2	15.9	14.0	15.4
Juuli/*July*	18.1	17.8	19.3	15.7	17.8	15.9	17.5
August/*August*	15.3	16.9	16.8	17.0	16.1	16.8	16.2
September/*September*	12.2	11.0	12.1	12.5	12.3	12.2	10.9
Oktoober/*October*	5.6	6.6	5.3	4.2	4.1	5.4	5.6
November/*November*	2.6	3.5	1.5	3.1	–1.0	2.4	0.6
Detsember/*December*	–6.6	1.0	–1.5	1.4	–0.4	0.2	–3.1

* 1969–2015. a keskmine, *long-term average of 1969–2015*

Tabel 2. Sademete summa (mm) aastatel 2012–2017
Table 2. *Precipitation (mm) in 2012–2017*

Kuu /*Month*	Sademete summa, mm / *Precipitation, mm*						
	2012	2013	2014	2015	2016	2017	1969–2015*
Jaanuar/*January*	30	9	25	30	34	27	30
Veebruar/*February*	18	14	12	8	56	22	22
Märts/*March*	39	15	9	12	23	17	23
Aprill/*April*	42	17	14	69	52	51	28
Mai/*May*	82	61	84	62	2	15	59
Juuni/*June*	101	52	103	39	125	94	76
Juuli/*July*	74	63	71	61	82	61	70
August/*August*	87	75	113	41	42	106	88
September/*September*	58	27	22	59	15	83	56
Oktoober/*October*	45	45	36	13	33	75	56
November/*November*	50	70	10	54	46	26	45
Detsember/*December*	9	47	42	46	31	52	35

* 1969–2015. a keskmine, *long-term average of 1969–2015*

Hilinenud lumesadu 2013. aastal võis mõjutada vahekultuuride talvitumistingimusi. 2014. aasta temperatuurid sarnanesid pikaajaliste keskmistega, kuid sademete poolest olid märts, aprill ja september väga põuased, samas kui mai, juuni ja august väga sademeterohked. 2015. aasta temperatuurid ei erinenud kuigivõrd keskmisest, kuid sademete poolest oli aasta põuane. 2016. aastal oli mai veidi soojem, kuid sademed praktiliselt puudusid terve kuu kuni juunini, mil sademeid langes 49 mm üle keskmise. 2017. aastal oli sademeid kõige vähem mais, rohkem aga juunis, augustis ja septembris. Meteoroloogilised andmed koguti Rõhu ilmajaamast.

Tulemused

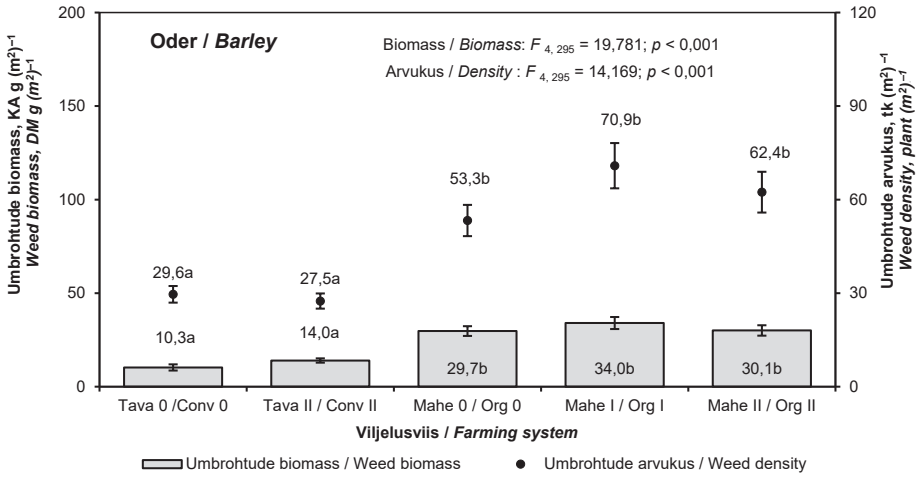
Umbrohtude arvukus ja biomass

Tulemused hõlmavad külvikorra teist rotatsiooni aastatel 2013–2017; esimese rotatsiooni andmed ning kirjeldus on avaldatud Madsen jt (2020) artiklis (artikkel puudutab eelkõige umbrohuseemneid ja nende püsimist mullas). Võrreldes esimese rotatsiooni lõpuga (Madsen jt, 2016) tõusid süsteemides nii umbrohtude arvukus kui biomass. Külvikorra kultuuri odra analüüsist selgus, et mahesüsteemide vahel usaldusväärset erinevust ei tekkinud (joonis 1). Vahekultuuridega külvikorra rikastamine Mahe I ja II süsteemides ei pärsinud umbrohtude arvukust ega biomassi. Herbitsiidide toimel oli umbrohtude arvukus ja biomass tavasüsteemides statistiliselt usaldusväärselt madalamad võrreldes mahesüsteemidega. Kõrgete väetisnormidega Tava II ei erinenud statistiliselt oluliselt kontrollsüsteemist Tava 0.

Ristikus, mis tuli külvikorda odra allakülvina ja jäi järgnevalt talinisu eelkultuuriks, oli tavasüsteemides umbrohtude biomass odraga võrreldes ligi kaks korda kõrgem, kuid arvukus madalam (joonis 2). Kõrgel väetusfoonil kasvanud Tava II süsteemi umbrohtude biomass ületas usutavalt Tava 0 ja Mahe I süsteemide omi. Samas umbrohtude arvukuse poolest sellist erinevust ei olnud. Mahesüsteemides oli umbrohtude arvukus odraga võrreldes mitmekordselt väiksem, kuid biomass jäi samale tasemele. Sealjuures mahesüsteemid üksteisest usutavalt ei erinenud.

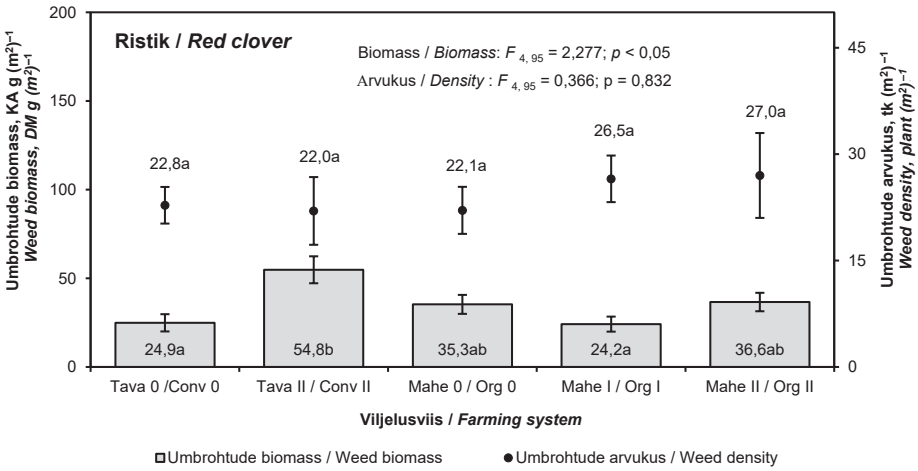
Ristikule järgneva talinisu tavasüsteemid umbrohtude tulemustelt üksteisest ei erinenud, kuid võrreldes eelneva kultuuriga olid arvukused kõrgemad, biomassid jäid madalamaks (joonis 3). Mahesüsteemide umbrohtude biomassid olid tavasüsteemide omadest usutavalt suuremad ning ka arvukus oli kõrgem. Mahe I ja II süsteemis avalduv väiksema arvukuse tendents võrreldes Mahe kontrollsüsteemiga võis seostuda vahekultuuride mõjuga, ent üldiselt mahesüsteemide vahel usaldusväärseid erinevusi ei esinenud.

Herne kõikides süsteemides ületasid nii umbrohtude arvukus kui biomass kõiki teisi külvikorra kultuure (joonis 4). Tavasüsteemides olid arvukus ja biomass usaldusväärselt madalamad mahesüsteemidest. Tava 0 oli kõige väiksem biomass võrreldes kõigi teiste süsteemidega. Mahesüsteemides Mahe I ja Mahe II avaldus vahekultuuride mõjul madalama umbrohtude arvukuse tendents, samas biomassis olulisi erinevusi ei olnud.



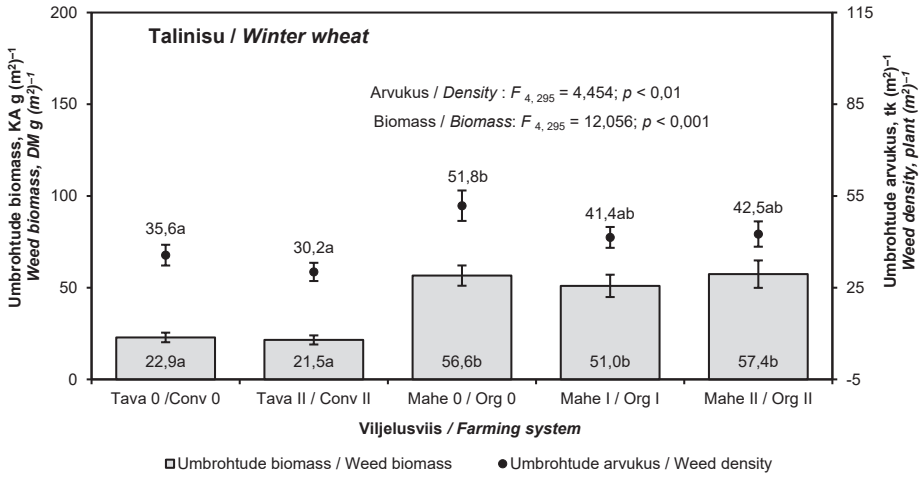
Joonis 1. Umbrohtude biomass (KA – kuivaine g $(m^2)^{-1}$) ja arvukus (taime $(m^2)^{-1}$) odras keskmistena aastatel 2013–2017. Statistiliselt usaldusväärsed erinevused (Tukey HSD post-hoc test, p < 0,05) on märgitud variantide vahelistes võrdlustes erinevate tähtedega. Vearibad joonisel tähistavad standardhälvet, n = 60

Figure 1. *Weed biomass (DM, g $(m^2)^{-1}$) and density (plant $(m^2)^{-1}$) in barley plots, average of 2013–2017. Means followed by a different letters indicate significant influence of crops (Tukey HSD post-hoc test, p < 0.05). Error bars denote the standard error of the means, n = 60*



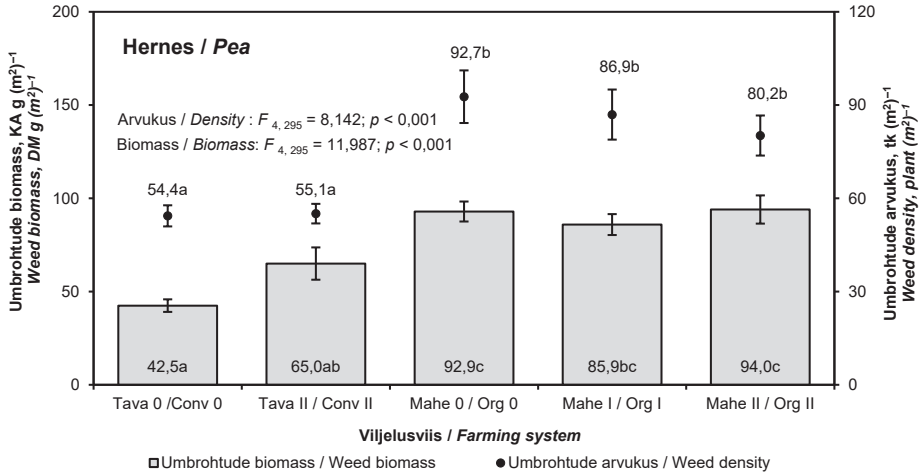
Joonis 2. Umbrohtude biomass (KA – kuivaine g $(m^2)^{-1}$) ja arvukus (taime $(m^2)^{-1}$) punases ristikus keskmistena aastatel 2013–2017. Statistiliselt usaldusväärsed erinevused (Tukey HSD post-hoc test, p < 0,05) on märgitud variantide vahelistes võrdlustes erinevate tähtedega. Vearibad joonisel tähistavad standardhälvet, n = 60

Figure 2. *Weed biomass (DM, g $(m^2)^{-1}$) and density (plant $(m^2)^{-1}$) in red clover plots, average of 2013–2017. Means followed by a different letters indicate significant influence of crops (Tukey HSD post-hoc test, p < 0.05). Error bars denote the standard error of the means, n = 60*



Joonis 3. Umbrohtude biomass (KA – kuivaine g $(m^2)^{-1}$) ja arvukus (taime $(m^2)^{-1}$) talinisus keskmistena aastatel 2013–2017. Statistiliselt usaldusväärsed erinevused (Tukey HSD post-hoc test, p < 0,05) on märgitud variantide vahelistes võrdlustes erinevate tähtedega. Vearibad joonisel tähistavad standardhälvet, n = 60

Figure 3. *Weed biomass (DM, g $(m^2)^{-1}$) and density (plant $(m^2)^{-1}$) in winter wheat plots, average of 2013–2017. Means followed by a different letters indicate significant influence of crops (Tukey HSD post-hoc test, p < 0.05). Error bars denote the standard error of the means, n = 60*

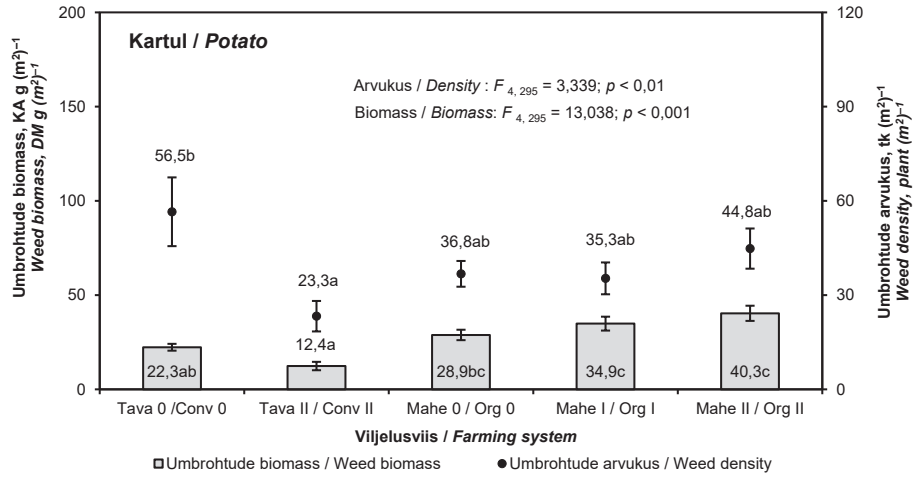


Joonis 4. Umbrohtude biomass (KA – kuivaine g $(m^2)^{-1}$) ja arvukus (taime $(m^2)^{-1}$) hernes keskmistena aastatel 2013–2017. Statistiliselt usaldusväärsed erinevused (Tukey HSD post-hoc test, p < 0,05) on märgitud variantide vahelistes võrdlustes erinevate tähtedega. Vearibad joonisel tähistavad standardhälvet, n = 60

Figure 4. *Weed biomass (DM, g $(m^2)^{-1}$) and density (plant $(m^2)^{-1}$) in pea plots, average of 2013–2017. Means followed by a different letters indicate significant influence of crops (Tukey HSD post-hoc test, p < 0.05). Error bars denote the standard error of the means, n = 60*

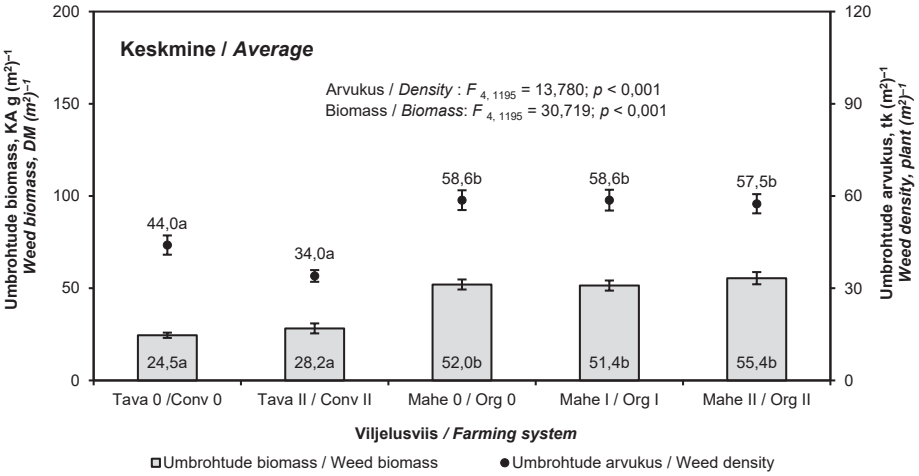
Ühes vähesema umbrohtumisega kultuuris kartulis erinesid statistiliselt üksteisest vaid tavasüsteemid, kusjuures tava kontrollsüsteemis (Tava 0) ületas umbrohtude arvukus usaldusväärselt kõiki süsteeme (joonis 5). Umbrohtude biomassid olid tavasüsteemides mahesüsteemidest madalamad. Mahesüsteemides oli umbrohtude arvukus statistilise erinevuseta, biomassi madalam tendents esines Mahe 0 süsteemis. Võrreldes teises rotatsioonis kõikide kultuuride keskmisena

viljelusviiside mõju umbrohtude arvukusele ning biomassile, selgus et usaldusväärselt erinesid üksteisest üksnes tava- ja mahesüsteemid, samas kummaski ei olnud süsteemide vahel usutavat erinevust (joonis 6). Tavasüsteemides avaldus tendents, et kontrollsüsteemis Tava 0 oli kõrgem arvukus kui kõrgema väetisfooniga Tava II süsteemis, mis võis olla mõjutatud eelkõige kartulis olnud umbrohtude kõrgeimast arvukusest selles süsteemis. Mahesüsteemide umbrohtude arvukus ja biomass ei sõltunud viljelussüsteemist.



Joonis 5. Umbrohtude biomass (KA – kuivaine g $(m^2)^{-1}$) ja umbrohtude arvukus (taime $(m^2)^{-1}$) kartulis keskmistena aastatel 2013–2017. Statistiliselt usaldusväärsed erinevused (Tukey HSD post-hoc test, p < 0,05) on märgitud variantide vahelistes võrdlustes erinevate tähtedega. Vearibad joonisel tähistavad standardhälvet, n = 60

Figure 5. *Weed biomass (DM, g $(m^2)^{-1}$) and weed density (plant $(m^2)^{-1}$) in potato plots, average of 2013–2017. Means followed by a different letters indicate significant influence of crops (Tukey HSD post-hoc test, p < 0.05). Error bars denote the standard error of the means, n = 60*



Joonis 6. Umbrohtude biomass (KA, g $(m^2)^{-1}$) ja umbrohtude arvukus (taime $(m^2)^{-1}$) 5 kultuuri keskmistena aastatel 2013–2017. Statistiliselt usaldusväärsed erinevused (Tukey HSD post-hoc test, p < 0,05) on märgitud variantide vahelistes võrdlustes erinevate tähtedega, Vearibad joonisel tähistavad standardhälvet, n = 260

Figure 6. *Weed biomass (DM, g $(m^2)^{-1}$) and weed density (plant $(m^2)^{-1}$) of the average of 5 crops, average of 2013–2017. Means followed by a different letters indicate significant influence of crops (Tukey HSD post-hoc test, p < 0.05). Error bars denote the standard error of the means, n = 260*

Katsetulemuste dispersioonanalüüs näitas, et umbrohtude biomassi ning arvukust mõjutasid statistiliselt usutavalt nii kasvatatav kultuur, viljelussüsteem kui aasta, samuti oli usutav nende faktorite koosmõju (tabel 3).

Tabel 3. Dispersioonanalüüs viljelusviisi, kultuuri, aasta ja nende koosmõjust umbrohtude biomassile ning arvukusele aastatel 2013–2017

Table 3. *Analyses of variance for weed biomass and weed density depending on farming system, crop, year and their interaction in 2013–2017*

Tunnus *Characteristic*	Variatsiooni allikas *Source of Variation*	df	SS	MS	F	p
Umbrohtude biomass *Weed biomass*	Aasta (Y) *Year (Y)*	4	101E3	253E2	14.40	<0.001
	Kultuur (C) *Crop (C)*	4	515E3	129E3	89.62	<0.001
	Viljelus-süsteem (FS) *Farming system (FS)*	4	187E3	468E2	27.68	<0.001
	Y x C	16	196E3	123E2	10.00	<0.001
	Y x FS	16	128E3	8001	5.21	<0.001
	C x FS	16	776E2	4851	3.90	<0.001
	Y x C x FS	64	201E3	3196	3.90	<0.001
Umbrohtude arvukus *Weed density*	Aasta (Y) *Year (Y)*	4	769E3	192E3	122.8	<0.001
	Kultuur (C) *Crop (C)*	4	299E3	747E2	38.76	<0.001
	Viljelussüstee m (FS) *Farming system (FS)*	4	112E3	280E2	13.52	<0.001
	Y x C	16	198E3	123E2	10.29	<0.001
	Y x FS	16	197E3	123E3	9.20	<0.001
	C x FS	16	110E3	6874	3.84	<0.001
	Y x C x FS	64	259E3	4110	5.70	<0.001

df – vabadusastmed; SS – ruutude summa; MS – keskmiste ruut; F – töötluse keskmine ruut/vea keskmine ruut; p – olulisuse tõenäosuse väärtus.
*** - oluline tõenäosus p < 0,001 juures.
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 < 0.001.*

Umbrohtude liigiline mitmekesisus

Tava ja mahesüsteemid erinesid umbrohtude arvukuselt ja biomassilt, kuid kas ka umbrohtude mitmekesisuselt ning rotatsiooni mõjult sellele? Tulemused näitasid, et mahesüsteemides umbrohuliikide arvukus kasvas – kui rotatsiooni alguses oli 24 liiki, siis lõpus juba 31 liiki. Tavasüsteemides oli alguses 23 liiki, mis kahanes rotatsiooni lõpuks ühe võrra. Analüüs näitas, et süsteemid erinesid liikide mitmekesisuselt. Kõige arvukamalt esines nii tava- kui mahesüsteemides põldkannikest (*Viola arvensis* Murray), harilikku kesalille (*Matricaria perforata* Merat), mailast (*Veronica persica* Poiret), harilikku orasheina (*Elytrigia repens* (Nevski)) ja valget hanemaltsa (*Chenopodium album* L.), kuid näiteks karvane hiirehernes (*Vicia hirsuta* (L.) S. F Gray) esines üksnes mahesüsteemides. Humallutsern (*Medicago lupulina* L.) oli alguses üksnes mahesüsteemides, kuid puudus sealt rotatsiooni lõpus ning täielikult tavasüsteemidest. Karukeel (*Anchusa arvensis* (L.) M. Bieb) esines vaid mahesüsteemides. Kahar kirburohi (*Polygonum lapatipholium* L.) ilmus mõlemasse süsteemi rotatsiooni lõpuks. Harilik liivkann (*Arenaria serpyllifolia* L.) tuli üksnes mahesüsteemidesse alles rotatsiooni lõpus. Põld-lõosilm (*Myosotis arvensis* (L.) Hill) ja lõhnav kummel [(*Matricaria suaveolens* (*Chamomilla suaveolens* (Pursh) Rydb. või *Ch. recutita* (L.) Rauschert)] olid kogu katseperioodi vältel mahesüsteemides ning tavasüsteemidesse ilmusid alles rotatsiooni lõpus.

Shannon-Wiener (S-W) ehk mitmekesisuse indeks võimaldab võrrelda liigilise mitmekesisuse erinevuste usaldusväärsust kultuuridest ja süsteemidest sõltuvalt. Indeksi kõrgem väärtus iseloomustab suuremat mitmekesisust, mis omakorda võimaldab hinnata umbrohtumusele avalduvat otsest mõju viljelussüsteemist olenevalt. Kui umbrohtude arvukus ja tihedus hindavad eelkõige teostatud tõrjevõtete efektiivsust, siis S-W indeks aitab välja selgitada tõrjevõtetega kaasnenud mullaviljakuse kõikumisi umbrohuliikide kasvukoha eelistustest sõltuvalt.

Teise rotatsiooni alguses 2013. a. olid S-W indeksid odras kõikides mahesüsteemides tavasüsteemidest kõrgemad ja tõusid teiste kultuuridega võrreldes kõige enam teise rotatsiooni lõpuks, mis viitab liigirikkuse olulisele tõusule (tabel 4). Rotatsiooni lõpuks erinesid usaldusväärselt süsteemid Tava 0 ja Mahe I, kusjuures Mahe I süsteemi mitmekesisus oli suurim nii kultuuri lõikes kui kogu rotatsiooni arvestuses.

Ristikus ületasid rotatsiooni alguses tavasüsteemide S-W indeksid mahesüsteemide omi. Rotatsiooni jooksul vähenes vaid süsteemi Tava II mitmekesisus, samas kui Tava 0 S-W indeks ületas kõiki teisi, ka mahesüsteeme.

Talinisus umbrohtude mitmekesisus suurenes rotatsiooni lõpuks kõigis süsteemides, usaldusväärselt toimus S-W indeksi kasv Tava 0, Mahe I ja Mahe II süsteemides. Suurim indeksi muutus toimus süsteemis Tava II.

Kõrgemad S-W indeksite väärtused hernes rotatsiooni alguses viitavad mitmekesisemale umbrohtumusele ülejäänud kultuuridega võrreldes. Rotatsiooni lõpuks erines usaldusväärselt vaid süsteem Tava II.

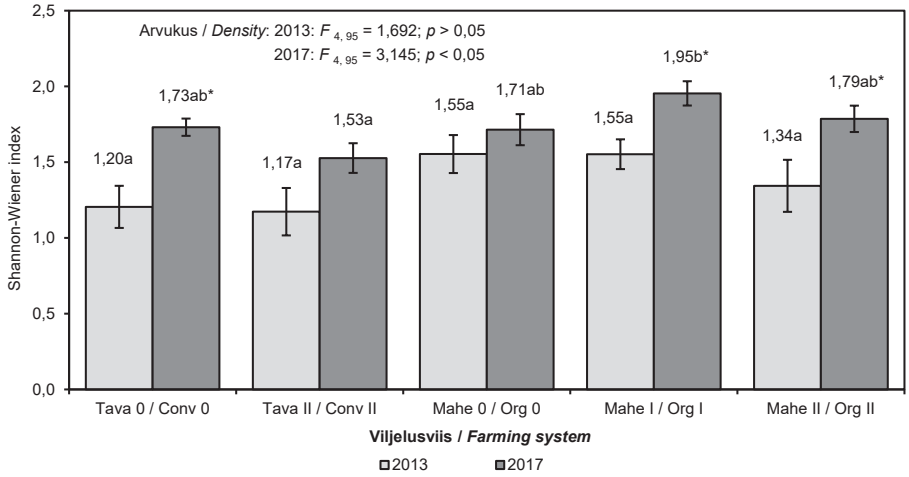
Kartulis olid tavasüsteemide S-W indeksite väärtused rotatsiooni alguses teiste kultuuridega võrreldes kõige madalamad. Kuid rotatsiooni lõpuks toimus mitmekesisuse märkimisväärne suurenemine, usaldusväärselt süsteemides Tava II ja Mahe II.

Kõikide külvikorrakultuuride keskmiste erivevate kasvatussüsteemide S-W indeksite väärtuste võrdlus teise rotatsiooni alguses ja lõpus näitas, et rotatsiooni lõpuks kasvas mitmekesisus usaldusväärselt süsteemides Tava 0, Mahe I ning Mahe II (joonis 7). Usaldusväärne erinevus rotatsiooni lõpuks ilmnes süsteemide Tava II ja Mahe I vahel, sealjuures Mahe I S-W indeks ületab kõiki teisi süsteeme.

Tabel 4. Viljelussüsteemi ja kultuuri mõju Shannon-Wieneri indeksile peale esimest rotatsiooni (2013) ning peale teist rotatsiooni (2017)
Table 4. *The effect of farming system and crop on Shannon-Wiener index after the 1st crop rotation (2013) and after the 2nd crop rotation (2017)*

Viljelussüsteem *Farming System*	Peale esimest rotatsiooni (2013) / *After 1st crop rotation (2013)*					
	Tava 0 / *Conv 0*	Tava II / *Conv II*	Mahe 0 / *Org 0*	Mahe I / *Org I*	Mahe II / *Org II*	Keksmine / *Average*
Oder (allakülv) *Barley (undersown)*	0,93 AB ± 0,10	1,09 B ± 0,30	1,42 AB ± 0,33	1,59 B ± 0,19	1,74 B ± 0,13	1,35 A ± 0,11
Punane ristik *Red clover*	1,73 Be ± 0,03	1,54 BCd ± 0,01	0,87 Aa ± 0,01	0,99 Ab ± 0,01	1,29 ABc ± 0,03	1,28 A ± 0,07
Talinisu *Winter wheat*	0,92 ABb ± 0,10	1,40 BCc ± 0,06	1,84 BCc ± 0,11	1,41 ABc ± 0,04	0,17 Aa ± 0,17	1,15 A ± 0,14
Hernes *Pea*	1,82 B ± 0,11	1,84 C ± 0,10	2,22 C ± 0,17	2,16 C ± 0,16	2,35 C ± 0,15	2,08 B ± 0,07
Kartul *Potato*	0,62 Aab ± 0,44	0,00 Aa ± 0,00	1,42 ABbc ± 0,05	1,62 Bc ± 0,07	1,17 Abc ± 0,09	0,97 A ± 0,16
	Peale teist rotatsiooni (2017) / *After 2nd crop rotation (2017)*					
Oder (allakülv) *Barley (undersown)*	1,85 ab* ± 0,09	1,52 Ba ± 0,05	2,12 Cb ± 0,06	2,46 Bc* ± 0,09	2,12 Cb ± 0,09	2,01 B* ± 0,08
Punane ristik *Red clover*	1,80 c ± 0,02	1,30 ABb* ± 0,06	1,07 Aa* ± 0,01	1,73 Ac* ± 0,03	1,10 Aa ± 0,07	1,40 A ± 0,07
Talinisu *Winter wheat*	1,71* ± 0,08	1,66 BC ± 0,15	1,90 BC ± 0,09	1,79 A* ± 0,13	1,88 BC* ± 0,03	1,79 B* ± 0,05
Hernes *Pea*	1,84 ± 0,13	2,14 C* ± 0,05	2,02 C ± 0,16	2,12 AB ± 0,14	2,05 BC ± 0,05	2,04 B ± 0,05
Kartul *Potato*	1,46 ab ± 0,20	1,01 Aa* ± 0,18	1,46 ABab ± 0,20	1,68 Aab ± 0,10	1,78 Bb* ± 0,07	1,48 A* ± 0,09

Igas veerus suurtähele järgnev keskmine näitab kultuuride olulist mõju (Tukey HSD post-hoc test, $p < 0,05$); igas reas kirjatähele järgnev keskmine näitab viljelussüsteemi olulist mõju (Tukey HSD post-hoc test, $p < 0,05$); iga keskmine, millele järgneb tärn (*) näitab olulist erinevust esimese (2013) ja teise (2017) rotatsiooni vahel (Tukey HSD post-hoc test, $p < 0,05$).
*Means followed by a different capital letter within each column indicate significant influence of crops (Tukey HSD post-hoc test, $p < 0.05$); means followed by a different small letter within each row indicate significant influence of farming systems (Tukey HSD post-hoc test, $p < 0.05$); means followed by a * indicate significant difference between values after 1st (2013) and after 2nd (2017) crop rotation (Tukey HSD post-hoc test, $p < 0.05$).*



Joonis 7. Shannon-Wieneri indeks vastavalt viljelusviisile 2013. a (peale esimest rotatsiooni) ning 2017. a (peale teist rotatsiooni). Statistiliselt usaldusväärsed erinevused (Tukey HSD post-hoc test, $p < 0,05$) on märgitud variantide vahelistes võrdlustes erinevate tähtedega. Vearibad joonisel tähistavad standardhälvet
Figure 7. *Shannon-Wiener index in 2013 (after the 1st crop rotation) and in 2017 (after the 2nd crop rotation) according to farming systems. Means followed by a different letters indicate significant influence of crops (Tukey HSD post-hoc test, $p < 0.05$). Error bars denote the standard error of the means*

Arutelu

Umbrohi on põllukoosluste loomulik osa, mille küllust ja liigilist koosseisu mõjutavad külvikord seal kasvatatavate kultuuridega, mullaharimine ning viljelusviisid (Weisberger jt, 2019; Saulic jt, 2022). Käesolevas uurimuses, kus pikaajalises viieväljalise külvikorra katses uuriti teise rotatsiooni jooksul toimunud muutusi umbrohtude biomassis, arvukuses ja liigilises mitmekesisuses sõltuvalt kultuurist ja viljelusviisist, näitasid tulemused, et teise rotatsiooni lõpuks kasvasid kõik näidud.

Odras ja kartulis oli teiste külvikorrakultuuridega võrreldes umbrohtude biomass väiksem (joonis 1 ja 5). Kartuli umbrohtumist mõjutas eelkõige mehaaniline vaheltharimine ning kuna viimase külvikorra kultuurina oli kartul odra eelkultuur, võis selle järelmõju mõjutada ka otra. Keemilise umbrohutõrje ning väetiste kasutamise tõttu oli odra tavasüsteemides usaldusväärselt väiksem umbrohtude biomass ja arvukus kui mahesüsteemides (joonis 1, tabel 4). Keemilise umbrohutõrje ja väetamise mõju umbrohtumuse vähenemisele kinnitavad ka varasemate uuringute tulemused (Berbéc jt, 2020). Talviste vahekultuuride kasutamine Mahe I ja Mahe II süsteemides suurendas mulda viidavat biomassi ning seega suurenes süsiniku sisaldus mullas. Kõrgema süsiniku sisaldusega kaasneb ka mulla mikroorganismide aktiivsuse kasv, mis aitab viia taimetoitained kiiremini taimedele omastatavasse vormi ning kahjustab umbrohtude seemneid (Kuht jt, 2022a, b). Peale selle mõjutasid umbrohtumuse arvukuse, biomassi ning liigilise mitmekesisuse kasvu mahesüsteemides odrale allakülvatud punane ristik (joonis 1, tabel 4).

Kartuli mahesüsteemides umbrohu arvukuses olulist erinevust ei olnud, kuid vahekultuurid avaldasid usaldusväärselt positiivset mõju liigilisele mitmekesisusele võrreldes tavasüsteemidega (joonis 5, tabel 4). Umbrohtude arvukus osutus suurimaks Tava 0 süsteemis – arvukus oli kaks korda kõrgem kui Tava II süsteemis ning selge tendentsina kõrgem ka mahesüsteemidest. Selline arvukus võis tuleneda mõne umbrohuliigi domineerimisest, mineraalväetiste puudumisest tingitud väiksemast toitainete sisaldusest mullas ning umbrohutõrjeks kasutatud herbitsiidide tõttu (De Cauwer jt, 2010; Rotchés-Ribalta jt, 2017; Rotches-Ribalta jt, 2020). Samad autorid on leidnud, et teatud liiki umbrohud on võimelised kohanema toitainevaesema mulla ning pestitsiidide olemasoluga. Meie katsed näitasid, et umbrohtude mitmekesisus S-W indeks oli madalaim rotatsiooni alguses, samas kui rotatsiooni lõpuks toimus indeksi märgatav tõus (tabel 4). Seega esines algul väiksem hulk sellistele tingimustele kohastunud liike, kuid see-eest arvukalt. Paljud autorid ongi esile toonud, et herbitsiidide kasutus mõjutab kooslustes liikide vahelist tasakaalu, vähendades herbitsiididele tundlike liikide mitmekesisust samas soodustades resistentsete liike (Bàrberi jt, 1998; Squire jt, 2000; Robinson, Sutherland, 2002; Hawes jt, 2010; Ryan jt, 2010; José-María, Sans, 2011).

Odrale allakülvina järgnenud ristikus oli umbrohtude biomass kõrgem kõikides süsteemides, kuid arvukus eelneva kultuuriga võrreldes madalam (joonis 2). Ristik täiendab külvikorras oluliselt mullaviljakust tänu õhulämmastiku fikseerimisele (Bybee-Finley, Ryan, 2018) ning suurele maapealsele ja -alusele biomassile. Lisaks ta varjutab ja surub hästi alla umbrohtumust (Law jt, 2021). Teistest süsteemidest kõrgem biomass Tava II süsteemi ristikus (joonis 2) seletub eelnenud odra suurte normidega lämmastikväetistega väetamisest, mis kahjustas odra allakülvina rajatud noort ristikut. See põhjustas tühikuid ka selle süsteemi järgneva aasta ristikus. Tühikutes hakkas kasvama umbrohi, mis oli lisaks ka mitmekesisem kui mahesüsteemides rotatsiooni algul (tabel 4). Rotatsiooni lõpus suurenes umbrohtude mitmekesisus ka mahesüsteemides, kuid tavasüsteemides jäi see keskmiselt kõrgemaks. Võimalik, et tavasüsteemides avaldus kerge herbitsiidi resistentsuse tendents. Ristikus domineerisid just pikaealised umbrohud, mille kontrolli all hoidmise seisukohalt on oluline ristiku niitmine ja umbrohtude väljakurnamine. Ristiku mullaviljakust tõstvad omadused võisid stimuleerida teatavate resistentsemate umbrohuliikide kasvu.

Tavasüsteemide talinisus oli võrreldes eelnenud ristikuga umbrohtude biomass madalam, kuid arvukus kõrgem. Tava 0 süsteemis oli rotatsiooni algul kõrgem arvukus ja väiksem mitmekesisus (joonis 3, tabel 4), mis viitavad teatavate liikide domineerimisele. Rotatsiooni jooksul mitmekesisus küll tõusis mõlemas tavasüsteemis, ent jäi madalamaks kui mahesüsteemides. Woźniac ja Soroka (2022) mainisid oma artiklis, et viljavaheldus soosib bioloogilist mitmekesisust põllul ning vähendab domineerivaid umbrohuliike, soodustades seega kultuurtaimede kasvu. Umbrohtude biomass mahesüsteemides ületas usaldusväärselt tavasüsteeme, kusjuures ka arvukus jäi tendentsilt kõrgemaks. Rotatsiooni lõpus ületasid kõik talinisu mahesüsteemid mitmekesisuselt tavasüsteeme. Mahesüsteemide mullas avaldus ristiku kasulik mõju mullaomadustele (Kuht jt, 2020) ja see avas paremad toitumistingimused ka umbrohtudele. Tavasüsteemides aga pärsiti mullaaktiivsust pestitsiididega (Luik jt, 2017), mistõttu taimedele kättesaadavaid toitaineid ei vabanenud kiirelt. Mahesüsteemide suur umbrohtude biomass talinisus võis olla põhjustatud kesalille ohtrast levikust talinisus – ka väiksem arvukus andis märkimisväärsemat biomassi. Kesalille rohke esinemine mahesüsteemides on tingitud sellest, et talvituva umbrohuna on ta kevadise äestamise ajaks tugevasti juurdunud ja äestamine tema arvukust ei vähenda. Tavasüsteemides kesalille praktiliselt ei esinenud.

Hernes kultuurina ei avaldanud umbrohtudele olulist survetõrjet ning oli kõikides kasvatusüsteemides rotatsiooni algusest lõpuni kõige umbrohurikkam kultuur nii biomassilt, arvukuselt kui mitmekesisuselt (joonis 4, tabel 4). Tõenäoliselt hernes, kui liblikõieline kultuur, tõstes toitainete sisaldust mullas, lõi umbrohtudele soodsamad tingimused kasvuks (Luik jt, 2014; Madsen jt, 2016). Samas, nagu nähtus Mahe II süsteemi kõrgeimast biomassist, võis kasutatud kompostist tulenev

suurenenud süsiniku hulk mullas anda umbrohtudele eelise herne ees. Mahesüsteemides kasvas tiheda taimikuga hernes umbrohtude biomass peamiselt mitmeaastaste umbrohtude arvelt (põldohakas, põldosi). Tava II süsteemis, kus kasutati mineraalväetisi, oli umbrohtude biomass märgatavalt kõrgem kui Tava 0 kontrollsüsteemis. Mõlemas aga olid nii biomass kui arvukus usaldusväärselt väiksemad võrreldes mahesüsteemidega. Viimastes avaldus umbrohtude arvukuse ning mitmekesisuse vähenemise tendents vahekultuuride (Mahe I) ja vahekultuuride ning kompostitud sõnniku koosmõjus (Mahe II).

Järeldused

Kuigi eri kultuurides avaldus kasvatussüsteemi mõju umbrohtude biomassile ja arvukusele mõnevõrra erinevalt, siis kõikide külvikorra kultuuride keskmistena tuli usaldusväärne erinevus selgelt esile vaid tava- ja maheviljelussüsteemide vahel. Pikaajalistes rotatsioonides seostataksegi umbrohtumuse muutusi eelkõige erinevate kasvatussüsteemidega, mis muudavad umbrohtude kasvutingimusi. Tavasüsteemides esines herbitsiidide toimel statistiliselt usaldusväärselt väiksem umbrohtude arvukus ja biomass kui mahesüsteemides; sama tendents avaldus ka mitmekesisuses, eriti esimese rotatsiooni algul.

Toitainete poolest vaesunud mullaga Tava 0 süsteemi suurenenud umbrohtude arvukus rotatsiooni lõpus näitas mitmekesisemat umbrohtude koosseisu, mis viitab väetamata kultuurtaimede madalamale survetõrjele. Samas Tava II süsteemis osutus umbrohtude biomass kõrgemaks, kuid arvukus ja ka mitmekesisus madalamaks tõenäoliselt just tugeva väetamise tõttu, mis varustasid nii kultuur- kui umbrohutaimi toitainetega, soodustades sealjuures teatavate umbrohuliikide domineerimist. Mahesüsteemides kasutatud vahekultuurid (Mahe I) ja nende ning sõnniku koosmõju (Mahe II) ei avaldanud loodetud pärssivat mõju umbrohtude biomassile ja arvukusele.

Mahesüsteemide mitmekesisus oli tavasüsteemidest suurem ja rotatsiooni lõpuks kõrgeim vahekultuuridega Mahe I süsteemis, mis on ilmselt selgitatavad soodsamate kasvutingimuste, keemiliste häiringute puudumise ning paremate mullaomadustega mahesüsteemides. Umbrohtumus ei seostu alati suuremate saagi kadudega. On teada, et teatav umbrohupopulatsioon saab olla ökoloogiliselt põllukultuurile kasulik, kuna see pakub toitu ja elupaika paljudele kasulikele organismidele toetades põllu kui ökosüsteemi toimimist. Seega on vajalikud jätkuvad uuringud mahesüsteemides umbrohutõrjeks optimaalsete lahenduste leidmiseks.

Töö hüpotees leidis kinnituse, sest pikaajalises külvikorra katses võrreldes esimese rotatsiooniga umbrohtude biomass, arvukus ja mitmekesisus suurenesid sõltuvalt kultuurist ning kasvatussüsteemist, sealjuures oli viimase mõju usaldusväärsem.

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Huvide konflikt / *Conflict of interest*

Autorid kinnitavad artikliga seotud huvide konflikti puudumist.
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Autorite panused / *Authors contributions*

HM – proovide kogumine, käsikirja kirjutamine, käsikirja toimetamine, lõplik heakskiit / *sampling, drafting of manuscript, revision and approval the final version of manuscript*
VE – katseandmete statistiline analüüs / *statistical analysis*
EM – käsikirja toimetamine, inglise keele korrektuur / *revision and approval the final version of manuscript, English correction*
AL – katse korraldamine, käsikirja toimetamine, lõplik heakskiit / *study conception and design, revision and approval the final version of manuscript*
LT – katse korraldamine, proovide kogumine, käsikirja toimetamine, lõplik heakskiit / *study conception and design, sampling, revision and approval the final version of manuscript*

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Changes in weed biomass, density and diversity in long-term crop rotation experiment during second rotation

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Summary

Although the cropping systems had different effects on weed biomass, density and abundance within the specific crops, the main significant difference as an average of all rotation crops was revealed between conventional (Conv) and organic (Org) cropping systems. Changes in weediness during long-term rotations are often associated with different cultivation systems as they affect the growing conditions in the field (Saulic *et al*., 2022). In conventional systems the herbicides had an effect on the abundance and biomass of weeds, which as a result were statistically significantly lower than in organic system treatments and the same tendency appeared in diversity, especially at the beginning of the rotation. Nevertheless, there were some differences due to the crop.

Barley and potato plots had the lowest weed biomass compared to other crops (Fig. 1 and 5). The weediness in potato plots was controlled mainly by mechanical intercropping and since potato was barley's pre-crop, it was probably affected by the aftereffect. Also, the chemical weed control and use of fertilizers kept the biomass and abundance of weeds in conventional barley systems significantly lower compared to organic systems (Fig. 1, Table 4). The use of winter cover crops in barley plots in Org I and Org II systems helped to increase the soil carbon content, which was accompanied by an increase in the activity of soil microorganisms (Kuht *et al*., 2022a, b), that resulted in

increase of abundance, biomass and species diversity of weeds in organic systems.

There was no significant difference in weed abundance in organic potato systems, but intercropping had a significantly positive effect on species diversity compared to conventional systems (Fig. 5, Table 4). The abundance of weeds turned out to be the highest in system Conv 0 – it was twice as high as in the Conv II system and, as a clear trend, higher than in the organic systems as well. This could have been resulted from the dominance of some weed species, the lower nutrient content in the soil due to the lack of mineral fertilizers and the herbicides used for weed control (De Cauwer *et al*., 2010; Rotchés-Ribalta *et al*., 2017; Rotchés-Ribalta *et al*., 2020). Weed diversity based on the S-W index was the lowest at the beginning of the rotation, while there was an increase of the index by the end of the rotation (Table 4). Many authors have highlighted that the use of herbicides affects the balance between species in communities, reducing the diversity of herbicide-sensitive species while favouring the resistant species (Bàrberi *et al*., 1998; Squire *et al*., 2000; Robinson, Sutherland, 2002; Hawes *et al*., 2010; Ryan *et al*., 2010; José-María, Sans, 2011; Rotchés-Ribalta *et al*., 2017).

Clover does not grow well with large mineral N fertilization rates and that emptied the areas for weeds in Conv II. In winter wheat plots the biomass of weeds was significantly lower in conventional systems than in all of the organic systems. Abundance of weeds was significantly higher in Org 0 and there was a slight weed oppressing due to the aftereffect of winter cover crops in Org I and Org II.

In winter wheat the system Conv 0 had higher abundance and lower diversity of weeds at the beginning of the rotation (Fig. 3, Table 4), which indicates the dominance of certain species. During the rotation, the diversity increased in both conventional systems, but remained lower than that of organic systems. In their paper Woźniac and Soroka (2022) mentioned that crop rotation favours the biodiversity and reduces the dominant weed species in the field, thus promoting the growth of cultivated crops. Weed biomass in organic systems reliably exceeded that of the conventional systems, while the abundance of weeds also tended to be higher. By the end of the rotation, all organic system winter wheat plots exceeded conventional systems in diversity. Red clover had beneficial effects on the soil properties in organic systems (Kuht *et al*., 2020) and this provided better nutritional conditions for weeds as well. Soil activity was inhibited with pesticides in conventional systems (Luik *et al*., 2017), hence the nutrients essential to plants were not released as fast. Also, the increased soil acidity reduced their uptake.

Among all the rotational crops – the pea plots had the highest weed biomass, abundance and diversity in all systems. Pea, as a legume crop, enriched the soil with nitrogen, which supported the growth of crop as well as weed plants. As pea is not a weed suppressive crop, all organic systems had significantly higher weed biomass than conventional ones. However, slight tendencies showed that systems with cover crops (Org I and Org II) had decreased abundance and diversity of weeds at the end of the rotation.

The higher abundance and diversity of weeds in system Conv 0 (Fig. 7), where the soil was depleted of nutrients, indicates that the weed supression effect by crop plants was low. Several studies have found that certain types of weeds may adapt to soil with lower nutrient content and pesticides (De Cauwer *et al*., 2010; Rotchés-Ribalta *et al*., 2017; Rotchés-Ribalta *et al*., 2020). In system Conv II the biomass of weeds was higher, but the abundance and diversity were lower, probably due to high fertilization rates, which supplied both cultivated and weed plants with nutrients, while certain weed species, for which the conditions were not suitable, were suppressed (Fig. 6, 7). Although it has been found that the diversification of the crop rotation (e.g. winter cover crops), regulates the weediness (Weisberger *et al*., 2019), the expected inhibitory effect of the intercrops used in organic systems (Org I) and their interaction with manure (Org II) was not manifested on the biomass and abundance of weeds. However, the diversity was higher in organic systems than in conventional systems and at the end of the rotation it was the highest in system with winter cover crops (Org I; Fig. 7). The aforementioned effect could be explained by the more favourable growing conditions in organic systems, where there were no chemical disturbances, and the soil properties were better than in conventional systems. Soils in organic systems had higher total nitrogen and organic carbon content, lower acidity and better water permeability than in conventional systems (Luik *et al*., 2014; Talgre *et al*., 2019; Kuht *et al*., 2022 a, b). Weeds are not always associated with higher yield losses (Cooper e*t al*., 2016). It is known that a certain weed population can be ecologically beneficial to a crop as it provides food and habitat for many organisms supporting the functioning of the field as an ecosystem (Marshall *et al*. 2003, Bretagnolle, Gaba, 2015; Eraud *et al*., 2015; Rollin *et al*., 2016).

All in all, further research is necessary to find optimal solutions for weed control in organic systems. The hypothesis of the work was confirmed, because in the long-term crop rotation experiment compared to the first rotation, the biomass, abundance, and diversity of weeds increased depending on the crop and the cultivation system, while the effect of the latter was more significant.

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2021	PRG1260 *Correlation of farming systems and gene expression in crops*

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2023–2027	101084084 *Agroecological strategies for sustainable weed management in key European crops*
2021	PRG1260 *Viljelusviisi ja geenide ekspressiooni seosed põllumajandustaimedes*

2017–2021	13-6/315 *Põhikultuuride järel vahekultuurina kasvatamiseks sobivate liikide ja segude ning nende viljelemiseks sobiva agrotehnika väljatöötamine*
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2015, 25th NJF Congress	Ettekande "In organic crop rotation winter cover crops improve soil, weed suppression and crop yields" eest parima noorteadlase sektsiooni auhind

LIST OF PUBLICATIONS

Scholarly articles indexed by Web of Science (1.1)

Madsen H, Luik A, Eremeev V, Mäeorg E, Talgre L (2023) Changes in weed biomass, density and diversity in long-term crop rotation experiment during second rotation. Agraarteadus, 34 (1), 18–30. DOI: 10.15159/jas.23.05.

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Madsen H, Talgre L, Kuht J, Alaru M, Eremeev V, Mäeorg E, Loit E, Luik A (2020) Organic Cropping Systems do not Increase Weed Seed Numbers but do Increase Weed Diversity. Agricultural Research & Technology Open Access Journal, 23 (4). DOI: 10.19080/ARTOAJ.2020.23.556244.

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PÕLLUMAJANDUSE ÕPPEKAVA VIIMASEID KAITSMISI

PEETER LÄÄNISTE
RISTÕIELISTE KULTUURIDE SOBIVUS VAHEKULTUURINA, NENDE VASTUPIDAVUS HAIGUSTELE NING OPTIMEERITUD KASVATUSTEHNOLOOGIATE MÕJU TALVITUMISELE JA SAAGIKUSELE
SUITABILITY OF CRUCIFEROUS OILSEEDS AS COVER CROPS, THEIR DISEASE RESISTANCE AND OPTIMIZED CULTIVATION TECHNOLOGIES FOR IMPROVED OVERWINTERING AND YIELD
Dotsent Eve Runno-Paurson, professor Ülo Niinemets
31. detsember 2024

GIOVANNI MARCONE
LAMMASTE HEAOLU VÕRDLEV HINDAMINE ERINEVATES PIDAMISSÜSTEEMIDES
COMPARATIVE WELFARE EVALUATION OF SHEEP PRODUCTION SYSTEMS
Professor David Arney, lektor Peep Piirsalu
9. jaanuar 2025

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FACTORS AFFECTING BEEKEEPING SUSTAINABILITY: PATHOGEN SPREAD, DIAGNOSTICS AND QUEEN BREEDING
Professor Marika Mänd, kaasprofessor Reet Karise
11. veebruar 2025

BRITT PUIDET
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PHENOTYPIC TRAITS INFLUENCING CHANGES IN POTATO LATE BLIGHT PATHOGEN *PHYTOPHTHORA INFESTANS* POPULATIONS IN EUROPE
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21.veebruar 2025

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PARASIITSETE IMIUSSIDE JA KALADEST PEREMEESTE GENEETILINE MITMEKESISUS JA STRUKTUUR ERI TASANDITEL: ÜKSIKISENDITEST POPULATSIOONIDE JA KOOSLUSTENI
POPULATION GENETICS OF FISH HOST AND DIPLOSTOMID PARASITES AT DIFFERENT SCALES: FROM INDIVIDUALS TO POPULATIONS AND COMMUNITIES
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