Eesti Maaülikool
Estonian University of Life Sciences

# THE EFFECT OF COVER CROPS ON BIOMASS AND NITROGEN ACCUMULATION AND ON CROP YIELD

# VAHEKULTUURIDE BIOMASSI MOODUSTAMISE JA LÄMMASTIKU SIDUMISE VÕIME JA MÕJU JÄRELKULTUURI SAAGILE

**MERILI TOOM**

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

Väitekiri
filosoofiadoktori kraadi taotlemiseks
põllumajanduse erialal

Tartu 2021

**Eesti Maaülikooli doktoritööd**

**Doctoral Theses of the**
**Estonian University of Life Sciences**

Eesti Maaülikool
Estonian University of Life Sciences

# THE EFFECT OF COVER CROPS ON BIOMASS AND NITROGEN ACCUMULATION AND ON CROP YIELD

## VAHEKULTUURIDE BIOMASSI MOODUSTAMISE JA LÄMMASTIKU SIDUMISE VÕIME JA MÕJU JÄRELKULTUURI SAAGILE

**MERILI TOOM**

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

Väitekiri
filosoofiadoktori kraadi taotlemiseks
põllumajanduse erialal

Tartu 2021

Institute of Agricultural and Environmental Sciences

Estonian University of Life Sciences

According to verdict No 6-14/9-2, of May 5th 2021, the Doctoral Committee of the Agricultural Sciences of the Estonian University of Life Sciences has accepted this thesis for the defence of the degree of doctor of Philosophy in Agriculture

Opponent: Prof. dr. **Vaclovas Bogužas**
Institute of Agroecosystems and Soil Sciences
Agriculture Academy of Vytautas Magnus University

Supervisors: Associate Prof. **Enn Lauringson**, PhD,
Estonian University of Life Sciences

Associate Prof. **Liina Talgre**, PhD,
Estonian University of Life Sciences

Senior Researcher **Andres Mäe**, PhD,
Estonian Crop Research Institute

Defence of the thesis:
Estonian University of Life Sciences, F.R. Kreutzwaldi 5,
Tartu on June 16th, 2021 at 14.15

The English language was edited by Andrus Lauringson
The Estonian language was edited by Ülle Tamm

ISSN 2382-7076
ISBN 978-9949-698-86-8 (trükis)
ISBN 978-9949-698-87-5 (pdf)

# CONTENTS

# LIST OF ORIGINAL PUBLICATIONS

The present thesis is based on the following research papers, which are referred to by their Roman numerals.

**I** **Toom, M.**, Talgre, L., Mäe, A., Tamm, S., Narits, L., Edesi, L., Haljak, M., Lauringson, E. 2019. Selecting winter cover crop species for northern climatic conditions. Biological Agriculture and Horticulture, 35(4), 263–274.

**II** **Toom, M.**, Tamm, S., Talgre, L., Tamm, I., Tamm, Ü., Narits, L., Hiiesalu, I., Edesi, L., Talve, T., Mäe, A., Lauringson, E. 2021. The effect of sowing date on biomass and nitrogen accumulation of five winter cover crop species. Agricultural Research and Technology, 25, 133–140.

**III** **Toom, M.**, Tamm, S., Talgre, L., Tamm, I., Tamm, Ü., Narits, L., Hiiesalu, I., Mäe, A., Lauringson, E. 2019. The effect of cover crops on the yield of spring barley in Estonia. Agriculture 9, 172.

The contribution of the authors to the papers

| | I | II | III |
|---|---|---|---|
| Idea and design | **MT**; EL; LT; AM; LN | **MT**; EL; LT; AM | **MT**; EL; LT; ÜT; ST |
| Field experiment | **MT**; EL; LT; LN; LE; MH | **MT**; EL, LT; LN; LE; TT; ÜT; IH | **MT**; EL; LT; AM; ÜT; IT; ST |
| Data analysis | ST; IT | ST; IT; IH | ST; IT |
| Preparation of manuscript | All | All | All |

**MT - Merili Toom**; EL – Enn Lauringson; LT – Liina Talgre; AM – Andres Mäe; ST – Sirje Tamm; IT – Ilmar Tamm; ÜT – Ülle Tamm; LN – Lea Narits; LE – Liina Edesi; TT – Tiina Talve; MH – Merlin Haljak; IH – Inga Hiiesalu

# ABBREVIATIONS

| | |
|---|---|
| N | Nitrogen |
| CC | Cover crop |
| C | Carbon |
| C:N | Carbon to nitrogen ratio |
| DM | Dry matter |
| ETS | The sum of effective air temperatures |
| LTA | Long-term average |
| ANOVA | Analysis of variance |

# 1. INTRODUCTION

Over the past few decades, there has been increasing concerns about the negative impact of intensive agricultural practices, especially excessive chemical fertilizer and pesticide application that cause soil, air, and water pollution, greenhouse gas emissions, and decrease of biodiversity (Tilman et al., 2002; Wittwer et al., 2017). Crop production is limited primarily by the acquisition of soil resources (Lynch, 2013). Nitrogen (N) is a key nutrient for plant growth and therefore an efficient crop production relies on a high input of synthetic N fertilizers (Rütting et al., 2018). However, not all of the supplied N is utilized by the plants and the remaining part is susceptible to be lost through leaching or gaseous emissions (Robertson & Vitousek, 2009). Due to its mobility, nitrate is considered to be the primary form of N loss from agricultural systems, especially in autumn and winter under humid conditions in fallow fields. Excess nitrate in groundwater causes ecosystem eutrophication and water quality degradation with negative impact on human health (Daryanto et al., 2017; De Notaris et al., 2018; Acharya et al., 2019). Sustainable agricultural management practices are required to enhance and maintain productivity while reducing the reliance on synthetic inputs (Kleijn et al., 2019). Further, these practices may be increasingly important under the conditions of climate change that may cause a warmer winter period with higher precipitation, leading to increased nutrient leaching and water erosion of the fields without vegetation (Iivonen et al., 2017; Peltonen-Sainio, 2018). Replacing fallow periods with cover crops (CC) (also referred as catch crops) is recognized as an effective strategy that provides several agronomic and environmental benefits, including protecting the soil from loss of N and other nutrients and improving the nutrition of subsequent (cash) crop (Dabney et al., 2001; Zandvakili et al., 2017; Wittwer et al., 2017; Sharma et al., 2018; De Notaris et al., 2018; Antosh et al., 2020).

Biomass production potential is an important determinant of CC selection because it is positively correlated with provided ecosystem services, including N accumulation (Finney et al., 2016; Ruis et al., 2019; Antosh et al., 2020). Biomass yield depends on CC species, soil and weather conditions, and the length of the growing season (Lu et al., 2000). Sowing time as early as possible is important to maximize the growing season of CCs. In northern regions, the late establishment of CCs can result in insufficient biomass due to low temperature and moisture levels (Lawson et al., 2015; Iivonen et al., 2017).

The effect of CCs on subsequent crop yield can be variable, depending on factors such as CC species, biomass production and quality, environmental factors and management practices. The N supply of CC to the subsequent cash crop depends greatly on the chemical composition of crop residue and the rate of N mineralization during the residue decomposition (Campiglia et al., 2014). In general, the higher concentration of N and lower carbon (C) to N ratio (C:N) of legume CCs results in greater potential for improving yield, compared to non-legume CCs (Sainju & Singh, 1997; Vyn et al., 2000; Kumar & Goh, 2002; Campiglia et al., 2014; Mancinelli et al., 2019). The decomposition of mature grass CC residues may immobilize N because of the high C:N ratio (Sievers & Cook, 2018). CCs may also have a negative effect on the following crop because of their water consumption, particularly in water-limited regions (Martinez-Feria et al., 2016; Handlířová et al., 2017; Krstić et al., 2018; Meyer et al., 2020).

Although a lot of research on the effects of CCs on different regions and production systems has been conducted, the integration of winter CCs in Estonian cropping systems is recent. The selection of CCs for a given region requires knowledge to integrate suitable species into Estonian cropping systems to improve the economic and environmental sustainability of agricultural production, which is also the objective of Green Deal strategy set forth by the European Commission (European Commission 2020). This thesis aims to investigate the suitability of the winter CCs regarding biomass and N accumulation and their effects on the yield of subsequent spring barley.

Novelty of this research:

The selection of different CC species to use as cover crops, their winter hardiness, biomass production, N accumulation and the effect on yield of subsequent cereal.

# 2. REVIEW OF LITERATURE

## 2.1. Winter cover crops

Cover crops are integrated to the cropping system during periods between production of cash crops with the major goal of protecting soil from losses of N and other nutrients, and improve their availability for the following cash crop (Sarrantonio & Gallandt, 2003; Plaza-Bonilla et al., 2015; Sharma et al., 2018). In addition, CCs are reported to provide many other benefits to agroecosystems such as suppressing weeds (Schultz et al., 2013; Brust et al., 2014; Cordeau et al., 2015; Jabran et al., 2015; Madsen et al., 2016) and pests (Sarwar et al. 1998; Smolinska & Horbowicz 1999; Larkin & Griffin, 2007), attracting pollinators and other beneficial insects (Nicholls & Altieri, 2013), enhancing soil microbial population (Kim et al., 2020), soil physical and chemical properties (Liu et al., 2005), C sequestration and mitigation of greenhouse gas emissions (Poeplau & Don, 2015; Kaye & Quemada, 2017; Tribouillois et al., 2018). In temperate regions, a CC established following the main crop harvest in late summer or early fall and terminated into the soil in the spring is considered a winter CC (Weil & Kremen, 2007; Justes et al., 2012). Overwintering species protect the soil during winter and accumulate additional biomass and N in the following spring. CCs that are frost sensitive and accumulate a high amount of biomass and N before being destroyed by frost provide possibilities for CC use in reduced tillage or no-tillage organic farming systems, eliminating the need for CC termination with tillage or chemicals (Lawley et al., 2011; 2012; Hashemi et al., 2013; Storr et al., 2020). However, the disadvantage of winter-killed species is that N may mineralize in their decomposing residues during winter and early spring in the high leaching risk conditions (White et al., 2017; Gollner et al., 2020).

In addition to high biomass production ability, CCs have to be suitable for the rotation, not serve as hosts for cash crop disease pathogens, be easily terminated and economically rational (Adetunji et al., 2020). CC species are selected based on their adaption to local environmental conditions and the targeted agro-ecological functions (Bodner et al., 2010). Legume (*Leguminosae*) CCs are generally used for their biological N fixation ability (Gselman & Kramberger, 2008; Büchi et al., 2015), rapid mineralization, and release of N to the subsequent crop (Dabney et al., 2001; Acharya et al., 2019), thus reducing the need for external N fertilizer inputs (Campiglia et al., 2014; De Notaris et al., 2018; Zhou et al., 2019). While non-legumes, such as grass (*Graminaceae*) and brassica (*Brassicaceae*) species, are more effective at scavenging soil N and preventing nitrate leaching (Tosti et al., 2012; Tuulos et al., 2014).

## 2.2. Cover crop species used in the study

Winter turnip rape (*Brassica rapa* spp. *oleifera* L.) and winter rye (*Secale cereale* L.) are commonly used cash crops in Estonia and have been included in experiments as winter CCs recently (Madsen et al., 2016). Winter turnip rape is a winter hardy brassica CC that is effective for scavenging mineral N at low temperatures (Tuulos et al., 2014). Winter rye is widely used grass CC species because of its ability to germinate at low temperatures and tolerance to harsh winter conditions (Sarrantonio & Gallandt, 2003; Marcillo et al., 2019). It has a fibrous root system, accumulates high amount of soil N, increases soil organic matter content and is a good weed suppressor (Ruffo & Bollero, 2003; Hill et al., 2016; Appelgate et al., 2017).

The other species forage radish (*Raphanus sativus* L. var. *longipinnatus*), hairy vetch (*Vicia villosa* Roth), and berseem clover (*Trifolium alexandrinum* L.) were included in the study because these are used worldwide.

Forage radish is a brassica species that grows rapidly in fall producing a large taproot. It is winter-killed at air temperature below -4 °C, thus leaving the weed and residue free seedbed by the following spring without the use of chemical termination or tillage (Williams & Weil, 2004; Dean & Weil, 2009; White & Weil, 2010; Lawley et al., 2011, 2012; Wang et al., 2019).

Annual legume species hairy vetch and berseem clover are used as CCs because of their high biomass and N fixation ability. Hairy vetch has shown to be frost tolerant CC in many northern regions (Teasdale et al., 2004; Brandsæter et al., 2008; Mirsky et al., 2017), whereas berseem clover has poor winter hardiness and therefore it is used as winter-killed annual in colder regions (Lu et al., 2000; Clark et al., 2012; Anderson, 2017).

## 2.3. The effect of sowing date on cover crop biomass and nitrogen accumulation

The provision of ecosystem services is highly dependent on CC biomass production (Antosh et al., 2020; Finney et al., 2016; Ruis et al., 2019). This is in turn affected by the species, sowing and termination time, soil characteristics, and weather conditions during the growing period (Lu et al., 2000; Teasdale et al., 2004; Lawson et al., 2015; Mirsky et al., 2017; Zhou et al., 2019). Delayed sowing can result in a rapid reduction in N accumulation and therefore higher N loss through leaching (Hashemi et al., 2013). Moreover, it causes the reduction of rooting depth and N uptake from deeper soil layers (Thorup-Kristensen et al., 2003). Generally, legumes and brassicas tend to be more susceptible to delayed sowing, compared to grass species (Thorup-Kristensen et al., 2003; Gselman & Kramberger, 2008; Van Eerd, 2018; Zhou et al., 2019: Akbari et al., 2020).

Biomass production of over-wintering CCs is also affected by the time of termination (Ruffo & Bollero, 2003; Marcillo & Miguez, 2017), as later termination may partially compensate the growth lost by delayed sowing (Lawson et al., 2015; Mirsky et al., 2017; Teasdale et al., 2004). However, delaying the termination date of grass CCs may decrease residue N concentration, increase hemicellulose and lignin concentrations and C:N ratios, resulting in N immobilization (Lawson et al., 2015).

## 2.4. The effect of cover crops on the yield of the following cash crop

Cover crops can improve crop production through soil water storage and availability, suppression of weeds, diseases and pests, and enhancement of soil quality (Fageria et al., 2005; Thapa et al., 2018). However, the influence of CCs on subsequent crop yield is mainly attributed to N availability (Fageria et al., 2005; Parr et al., 2011; Acharya et al., 2019).

The ability of CCs to provide N retention and supply has been extensively evaluated, while the results have shown a high level of variability, depending on region, soil type, CC species, the length of the growing season, production system, and succeeding main crop (Ruffo & Bollero 2003; Blanco-Canqui et al., 2015; Wittwer e al., 2017; Marcillo & Miguez., 2017; Ruis et al., 2019). Effective N contribution of a CC depends on the synchrony between N mineralization of CC and the demand of subsequent crop (Lawson et al., 2013).

The benefits of legume CCs have shown to increase with the higher amount of biomass (Lawson et al., 2015; Mirsky et al., 2017; Spargo et al., 2016; Teasdale et al., 2004). In northern climate, late termination of legume CC is often recommended allowing higher N accumulation in the biomass and better synchronization of the N uptake by the subsequent crop (Lawson et al., 2015; Mirsky et al., 2017). Although the low C:N ratio is maintained longer in legume species compared to non-legumes (Lawson et al., 2015), very late CC termination can reduce the yield potential of the following crop, particularly at northern latitudes, due to a shorter growing season (Mirsky et al., 2017). Moreover, late termination may also cause the risk of some species, such as hairy vetch, becoming weedy in subsequent crops because of seed dormancy (Mirsky et al., 2017), incomplete kill, and regrowth in reduced tillage systems (Hayden et al., 2015).

In conditions of high spring rainfall and soil with low water retention, rapid mineralization because of low C:N ratio of legume species can lead to nitrate leaching, and therefore the CC termination must be adapted to the sowing date of the following crop (Tosti et al., 2014; Sievers & Cook, 2018). Rapid decomposition of legume CC residues may also lead to losses of N as emissions of nitrous oxide ($N_2O$) (Basche et al., 2014). When the following crop is sown later, no-till strategy is preferable in order to slow down the mineralization process and reduce the risks of N loss (Radicetti et al., 2016).

Deep rooted brassica CC species, such as forage radish and winter turnip rape, have a rapid growth and great potential to capture large amounts of residual N from deeper soil layers, providing sufficient N to cash crop (Williams & Weil, 2004; Wang et al., 2008; Tuulos et al., 2014; Jahanzad et al., 2017). The improvement of cash crop yield with brassica CCs have also been associated with suppressive biofumigation effect to soilborne pests and pathogens caused by glucosinolate compounds in their tissues (Larkin & Griffin, 2007; Cottney et al., 2020). Winter-killed forage radish leaves deep root channels that can contribute to subsequent crop growth (Laweley et al., 2011; Wang et al., 2019). However, depending on the soil type and weather conditions in spring, there is a risk of N leaching in case of winter-killed CCs, although this can be reduced by establishing subsequent crop early in the spring (Storr et al., 2020; Dean & Weil, 2009; White et al., 2017).

The effect of grass CC species have shown to be variable depending on the amount of biomass, termination time and the type of succeeding crop (Blanco-Canqui et al., 2015; Pantoja et al., 2015). Grass CCs usually have higher C:N ratios than legume and brassica species, while it depends on plant physical characteristics and chemical composition at the time of termination (Poffenbarger et al., 2015). Rye has higher N concentration and low C:N ratio when termination occurs in vegetative growth stage early in the spring (Reiter et al., 2008), while the C:N ratio increases with plant maturity and may lead to N immobilization and reduction of N availability to the following crop (Dabney et al., 2001; Hill et al., 2016; Reiter et al., 2008; Martinez Feria 2016, Pantoja et al., 2015; Sievers & Cook, 2018). Early spring termination of grass CC may decrease the negative effect on yield while limiting the positive effects on erosion control and increasing soil organic C inputs (Reiter et al., 2008, Pantoja et al., 2015). Additionally, grass winter CC species have shown to reduce the yield of the cash crop because of the well-developed fibrous root system and high water consumption which occurs generally in dry regions or during dry years (Handlířová et al., 2017; Kristic et al., 2018).

To avoid the negative impacts of CCs on grain yield, using mixtures of legume and non-legume species has been proposed as a solution to enhance N management with CCs. It is due to the combined benefits of the species, more beneficial C:N ratio and better synchrony of N release with N demand of the succeeding cash crop (Poffenbarger et al., 2015; Lawson et al., 2015; Tribouillois et al., 2016; Abdalla et al., 2019). Furthermore, continuous cover cropping increases the level of soil organic matter, therefore enhancing soil physical, chemical and biological properties and leading to improved soil health and yield of the cash crops (Fageria et al., 2005; Doltra & Olesen, 2013; Bogužas et al., 2015; Büchi et al., 2018; Mancinelli et al., 2019).

# 3. AIMS AND HYPOTHESES OF THE STUDY

Winter CCs are used in many regions in the world, but it is a relatively new practice in Estonia. To integrate winter CCs into Estonian crop rotations, region-specific information about their performance is needed.

**The main aims of the thesis were:**

To assess the potential of different winter CC species to accumulate biomass and N (**I**).

To test winter hardiness of hairy vetch for Estonian climatic conditions (**I**).

To examine the effect of sowing date on biomass and N accumulation of CCs (**II**).

To evaluate the effect of CCs on the yield of subsequent spring barley (**III**).

**Hypotheses:**

CC biomass and N accumulation depend on species and sowing date.

Forage radish, hairy vetch, berseem clover, winter turnip rape and winter rye as winter CCs accumulate high biomass and N.

Hairy vetch has winter hardiness comparable to winter turnip rape and winter rye.

Frost sensitive forage radish and berseem clover accumulate high amount of biomass and N before winter-killed.

CCs increase the yield of the following spring barley.

# 4. MATERIALS AND METHODS

## 4.1. Experimental site, design and subjects

The research was carried out at the Estonian Crop Research Institute, Jõgeva (58° 44' 59.41" N, 26°24' 54.02" E) during three growing seasons (2016–2017; 2017–2018 and 2018–2019). The soil of the experimental site is classified as *Cambic Phaeozem* (Loamic) (IUSS 2015). The soil characteristics on average were as follows: $pH_{KCl}$ 6.5, P 102 mg $kg^{-1}$, K 188 mg $kg^{-1}$, $C_{org}$ 1.9% and $N_{tot}$ 0.14%. The trial, CCs and barley that followed (*Hordeum vulgare* L.) were managed without synthetic fertilizers and pesticides. The CCs were sown after winter wheat (*Triticum aestivum* L.) harvest on 3 August in 2016. In 2017 and 2018, CCs were sown on 3, 8, 14 and 18 August and 3, 8, 13, and 17 August, respectively. After disc-harrowing, CCs were sown with plot seed drill (row spacing 12.5 cm) to 4 × 6 m plots that were arranged in a randomized complete block design with four replications. Seeding rates for the CC were 10 kg $ha^{-1}$ for forage radish (Tillage radish®) and winter turnip rape (cv. 'Largo'), 50 kg $ha^{-1}$ for hairy vetch (cv. 'Villana'), 15 kg $ha^{-1}$ for berseem clover (cv. 'Akenaton'), 180 kg $ha^{-1}$ for winter rye (cv. 'Sangaste'). The control plot without CC was also included in the experiment.

## 4.2. Sampling, measurements and analyses

Cover crop above- and below-ground biomass samples were collected from 1 $m^2$ area in each plot at the end of October prior to frosts. The biomass of the over-wintered species (winter rye, winter turnip rape, and hairy vetch) was measured twice: in autumn and in the following spring before incorporating the CCs into the soil (on 4 May in 2017 and 7 May in 2018 and 2019, respectively), prior to the establishment of spring barley. The autumn and spring biomass is considered separately throughout the study.

The above-ground biomass was cut at the ground level and to measure the below-ground biomass, the soil within the squares was dug to a depth of 25 cm, and the roots were washed out of the soil on a sieve. Forage radish was collected by digging the whole plants from the soil, roots and shoots were separated and washed free from soil.

Cover crop biomass was incorporated into the soil by ploughing in the following spring, prior to the sowing of spring barley as a cash crop (cv. 'Maali', at 400 seeds $m^2$). Barley was harvested at physiological maturity with a plot combine (on 30 August 2017, 6 August 2018 and 15 August 2019). The grain yield of dried and cleaned seeds was standardized to 14% moisture level and expressed as kg $ha^{-1}$.

For CC biomass dry matter (DM) accumulation, plant samples were oven-dried to a constant weight at 65 °C, weighed and expressed as kg $ha^{-1}$. The biomass samples were milled for elemental analysis. The total N and C concentration in plant samples was analyzed by the Dumas Combustion method on a VarioMAX CNS elemental analyser (Elementar, Germany) in Soil Science and Agrochemistry laboratory at Estonian University of Life Sciences.

### 4.3. Weather conditions

The average air temperature during the CC main growing period from August until the end of October was similar in 2016 and 2017 (10.5 and 10.8 °C, respectively) and higher in 2018 (12.7 °C), compared to the long-term average (LTA) (10.4 °C) of these months. The sum of effective air temperatures (> +5 °C) (ETS) from August until the end of October was 566, 597, and 747 °C in 2016, 2017 and 2018, respectively. The LTA amount of precipitation from August until the end of October (74 mm) was similar to 2018 (75 mm) and higher in 2016 (84 mm) and 2017 (92 mm). In 2018, the soil was extremely dry at CC establishment because of very low amount of precipitation in July (15 mm), compared to the LTA of this month (79 mm). Rainfall in late autumn compensated the lack of soil moisture, since the average amount of precipitation by the end of October (75 mm) was similar to the LTA.

The average temperature during the main growing period in April was lower in 2017 (2.8 °C) and higher in 2018 and 2019 (6.2 and 6.6 °C, respectively) than the LTA average of this month (3.8 °C). ETS from March until the CC termination was 40, 113, and 127 °C in 2017, 2018 and 2019, respectively. Precipitation in April 2017 (51 mm) was above the LTA (36 mm); it was somewhat lower than the average in 2018 (21 mm) and significantly lower in 2019 (4 mm).

### 4.4. Statistical analyses

One-way analysis of variance (ANOVA) was used to test the differences of all measured characteristics within trial years in **I–III** and **thesis**. Two-way ANOVA was used to determine the effects of CC species, year and their interactions on measured characteristics in 2016/17–2017/18 **(I)** and in 2016/17–2018/19 **(thesis)**. To test the effect of CC species, sowing date and their interaction on biomass and N accumulation of CCs, analysis of two-way variance (ANOVA) was performed **(II)**. Two-way ANOVA was used also to study the effect of CC, year and their interactions on the yield of spring barley in 2017–2018 **(III)** and 2017–2019 **(thesis)**. The significance of differences between individual characteristics were calculated using the post hoc Fisher's Least Significant Difference (LSD) test for all trials. Statistical analyses were carried out using the statistical software package Agrobase (Agronomix Software, Inc., Winnipeg, Manitoba, CA, USA).

# 5. RESULTS

## 5.1. Biomass and N accumulation of cover crops at the earliest sowing date (I)

### 5.1.1. Biomass and N accumulation at the earliest sowing date in autumn of 2016–2018

According to the ANOVA results, the variation in biomass yield and N accumulation was significantly influenced by species, years and their interaction in autumn ($p < 0.001$). In 2016, the total biomass and N accumulation were lower than in 2017 and 2018. Berseem clover that had the lowest values in 2018 instead was an exception in that respect.

The highest autumn total biomass and N accumulation in all trial years were measured in forage radish (2515–3841 and 69–126 kg ha$^{-1}$, respectively) (Table 1). Forage radish also had the highest below ground biomass (1406–1857 kg ha$^{-1}$) and proportion of roots, accounting for 45–56% of the total DM. The other brassica species, winter turnip rape, accumulated lower total biomass and N (1169–2178 and 29–74 kg ha$^{-1}$, respectively), with the root percentage of 25–35%.

**Table 1.** The biomass accumulation (DM kg ha$^{-1}$), amount of nitrogen (kg ha$^{-1}$) and C:N ratio of cover crops in autumn of 2016–2018. Mean values with different lowercase letters (as an average of each trial year), capital letters (as an average of all the years) and numbers (as an average of species) are significantly different ($p < 0.05$; ANOVA, Fisher LSD test).

| | Biomass | | | Nitrogen | | | C:N ratio | | |
|---|---|---|---|---|---|---|---|---|---|
| | above ground | below ground | total | above ground | below ground | total | above ground | below ground | total |
| 2016 | | | | | | | | | |
| Winter turnip rape | 758$^{c}$ | 411$^{b}$ | 1169$^{c}$ | 21$^{d}$ | 8$^{b}$ | 29$^{c}$ | 15 | 21 | 16 |
| Forage radish | 1109$^{b}$ | 1406$^{a}$ | 2515$^{a}$ | 37$^{b}$ | 32$^{a}$ | 69$^{a}$ | 12 | 18 | 14 |
| Winter rye | 484$^{d}$ | 183$^{d}$ | 667$^{d}$ | 14$^{e}$ | 2$^{c}$ | 16$^{d}$ | 15 | 30 | 17 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Berseem clover | $1231^{a}$ | $184^{d}$ | $1415^{b}$ | $30^{c}$ | $3^{c}$ | $33^{c}$ | 17 | 26 | 18 |
| Hairy vetch | $1110^{b}$ | $312^{c}$ | $1422^{b}$ | $42^{a}$ | $10^{b}$ | $52^{b}$ | 11 | 12 | 11 |
| 2017 | | | | | | | | | |
| Winter turnip rape | $1308^{bc}$ | $444^{b}$ | $1752^{b}$ | $50^{b}$ | $13^{b}$ | $63^{b}$ | 10 | 12 | 11 |
| Forage radish | $1984^{a}$ | $1857^{a}$ | $3841^{a}$ | $65^{a}$ | $37^{a}$ | $102^{a}$ | 12 | 19 | 14 |
| Winter rye | $748^{d}$ | $440^{b}$ | $1188^{d}$ | $23^{d}$ | $5^{c}$ | $28^{e}$ | 13 | 37 | 17 |
| Berseem clover | $1320^{b}$ | $236^{c}$ | $1556^{bc}$ | $39^{c}$ | $4^{c}$ | $42^{d}$ | 14 | 29 | 15 |
| Hairy vetch | $1084^{c}$ | $278^{c}$ | $1362^{cd}$ | $45^{bc}$ | $8^{c}$ | $53^{c}$ | 10 | 14 | 10 |
| 2018 | | | | | | | | | |
| Winter turnip rape | $1524^{c}$ | $654^{b}$ | $2178^{b}$ | $56^{c}$ | $18^{b}$ | $74^{c}$ | 11 | 14 | 12 |
| Forage radish | $1976^{a}$ | $1605^{a}$ | $3581^{a}$ | $81^{b}$ | $45^{a}$ | $126^{a}$ | 9 | 14 | 11 |
| Winter rye | $993^{d}$ | $493^{c}$ | $1486^{c}$ | $29^{d}$ | $7^{d}$ | $36^{d}$ | 14 | 26 | 16 |
| Berseem clover | $687^{e}$ | $133^{d}$ | $820^{d}$ | $23^{d}$ | $3^{e}$ | $26^{e}$ | 12 | 17 | 12 |
| Hairy vetch | $1801^{b}$ | $443^{c}$ | $2244^{b}$ | $90^{a}$ | $12^{c}$ | $102^{b}$ | 9 | 15 | 9 |
| Average of years (2016–2018) | | | | | | | | | |
| Winter turnip rape | $1197^{C}$ | $503^{B}$ | $1700^{B}$ | $42^{B}$ | $13^{B}$ | $56^{C}$ | 12 | 16 | 13 |
| Forage radish | $1690^{A}$ | $1623^{A}$ | $3313^{A}$ | $61^{A}$ | $38^{A}$ | $99^{A}$ | 11 | 17 | 13 |
| Winter rye | $742^{E}$ | $372^{C}$ | 1114e | $22^{D}$ | $5^{D}$ | $27^{E}$ | 14 | 31 | 17 |
| Berseem clover | $1079^{D}$ | $184^{D}$ | 1263d | $31^{C}$ | $3^{E}$ | $34^{D}$ | 14 | 24 | 15 |
| Hairy vetch | $1332^{B}$ | $344^{C}$ | 1676c | $59^{A}$ | $10^{C}$ | $69^{B}$ | 10 | 14 | 10 |
| Average of species | | | | | | | | | |
| 2016 | $938^{3}$ | $499^{2}$ | $1438^{2}$ | $29^{3}$ | $11^{3}$ | $40^{3}$ | 14 | 22 | 15 |
| 2017 | $1289^{2}$ | $651^{1}$ | $1940^{1}$ | $44^{2}$ | $13^{2}$ | $58^{2}$ | 12 | 22 | 14 |
| 2018 | $1396^{1}$ | $665^{1}$ | $2062^{1}$ | $56^{1}$ | $17^{1}$ | $73^{1}$ | 11 | 18 | 12 |

Among legume species, hairy vetch had higher total biomass and N accumulation (1362–2244 and 52–102 kg ha$^{-1}$, respectively) than berseem clover (820–1556 and 26–42 kg ha$^{-1}$). Furthermore, hairy vetch had greater proportion of roots (20–22%) compared to berseem clover (13–16%). Winter rye accumulated the lowest total biomass and N (667–1486 and 16–36 kg ha$^{-1}$, respectively) with 27–37% of biomass consisting of roots.

### 5.1.2. Biomass and N accumulation of cover crops at the earliest sowing date in following springs of 2017–2019

Hairy vetch, winter turnip rape and winter rye overwintered well in both trial years. Berseem clover was killed by the first frosts in autumn, whereas forage radish was more cold tolerant and decomposed by the end of April. ANOVA results showed significant differences in biomass and accumulated N between species and trial years ($p < 0.001$). The interaction of these characteristics remained non-significant for biomass, but was significant for accumulated N ($p < 0.01$).

Hairy vetch accumulated the highest spring biomass and N in all trial years (1731–3231 and 62–112 kg ha$^{-1}$, respectively) (Table 2), while it had lower amount of roots (19–25%) compared to winter rye and winter turnip rape (34–37 and 36–44%, respectively).

**Table 2.** The biomass accumulation (DM kg ha$^{-1}$), amount of nitrogen (kg ha$^{-1}$) and C:N ratio of cover crops in spring of 2017–2019. Mean values with different lowercase letters (as average of each trial year), capital letters (as average of all the years) and numbers (as average of species) are significantly different ($p < 0.05$; ANOVA, Fisher LSD test).

| | Biomass | | | Nitrogen | | | C:N ratio | | |
|---|---|---|---|---|---|---|---|---|---|
| | above | below | total | above | below | total | above | below | total |
| | ground | | | ground | | | ground | | |
| 2017 | | | | | | | | | |
| Winter rye | 635$^{b}$ | 374$^{b}$ | 1009$^{b}$ | 25$^{b}$ | 6$^{c}$ | 31$^{c}$ | 11 | 25 | 14 |
| Winter turnip rape | 861$^{b}$ | 670$^{a}$ | 1531$^{a}$ | 34$^{b}$ | 13$^{b}$ | 48$^{b}$ | 10 | 20 | 13 |
| Hairy vetch | 1300$^{a}$ | 430$^{b}$ | 1731$^{a}$ | 47$^{a}$ | 16$^{a}$ | 62$^{a}$ | 11 | 11 | 11 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2018 | | | | | | | | | |
| Winter rye | 1361$^{b}$ | 725$^{b}$ | 2086$^{c}$ | 42$^{b}$ | 8$^{b}$ | 50$^{c}$ | 14 | 35 | 17 |
| Winter turnip rape | 1474$^{b}$ | 898$^{a}$ | 2372$^{b}$ | 43$^{b}$ | 19$^{a}$ | 62$^{b}$ | 14 | 19 | 16 |
| Hairy vetch | 2058$^{a}$ | 631$^{b}$ | 2689$^{a}$ | 65$^{a}$ | 18$^{a}$ | 83$^{a}$ | 13 | 14 | 13 |
| 2019 | | | | | | | | | |
| Winter rye | 1554$^{c}$ | 796$^{b}$ | 2350$^{b}$ | 48$^{c}$ | 10$^{b}$ | 58$^{c}$ | 13 | 32 | 17 |
| Winter turnip rape | 1998$^{b}$ | 1125$^{a}$ | 3123$^{a}$ | 60$^{b}$ | 21$^{a}$ | 81$^{b}$ | 14 | 22 | 16 |
| Hairy vetch | 2615$^{a}$ | 616$^{b}$ | 3231$^{a}$ | 99$^{a}$ | 12$^{b}$ | 111$^{a}$ | 10 | 20 | 11 |
| Average of years (2017–2019) | | | | | | | | | |
| Winter rye | 1183$^{C}$ | 632$^{B}$ | 1815$^{C}$ | 38$^{C}$ | 9$^{C}$ | 47$^{C}$ | 13 | 30 | 16 |
| Winter turnip rape | 1445$^{B}$ | 898$^{A}$ | 2342$^{B}$ | 46$^{B}$ | 18$^{AB}$ | 64$^{B}$ | 13 | 20 | 15 |
| Hairy vetch | 1991$^{A}$ | 560$^{B}$ | 2550$^{A}$ | 70$^{A}$ | 15$^{B}$ | 86$^{A}$ | 11 | 15 | 12 |
| Average of species | | | | | | | | | |
| 2017 | 932$^{3}$ | 491$^{2}$ | 1424$^{3}$ | 35$^{3}$ | 12$^{2}$ | 47$^{3}$ | 11 | 19 | 13 |
| 2018 | 1631$^{2}$ | 751$^{1}$ | 2382$^{2}$ | 50$^{2}$ | 16$^{1}$ | 65$^{2}$ | 13 | 23 | 15 |
| 2019 | 2056$^{1}$ | 846$^{1}$ | 2901$^{1}$ | 69$^{1}$ | 15$^{1}$ | 84$^{1}$ | 12 | 24 | 15 |

The biomass and N accumulated by winter turnip rape was 1531–3123 and 48–81 kg ha$^{-1}$, respectively. Winter rye had the lowest average spring biomass and N (1009–2350 and 31–59 kg ha$^{-1}$, respectively).

In the spring of 2017, biomass was 300–360 kg ha$^{-1}$ higher compared to the previous autumn. In 2018 it increased from 620 kg ha$^{-1}$ (winter turnip rape) to 1327 kg ha$^{-1}$ (hairy vetch) and in 2019 from 864 (winter rye) to 987 kg ha$^{-1}$ (hairy vetch). The N accumulation in spring was higher compared to autumn in 2017 from 10 kg ha$^{-1}$ (hairy vetch) to 19 kg ha$^{-1}$ (winter tunip rape). In 2018 it increased from 23 kg ha$^{-1}$ (hairy vetch) to 30 kg ha$^{-1}$ (winter rye) and in 2019 from 6 kg ha$^{-1}$ (winter turnip rape) to 22 kg ha$^{-1}$ (winter rye).

### 5.2. The effect of sowing date on cover crop biomass and nitrogen accumulation (II)

According to ANOVA, there were significant differences in biomass and N accumulation by different CC species as an average of sowing dates in both trial years, measured in autumn and spring. In autumn of both years, forage radish had the highest biomass and N accumulation and berseem clover the lowest. Among the overwintering CC species of both trial years, winter turnip rape and hairy vetch produced higher biomass than the following spring's winter rye. In both trial years, hairy vetch accumulated the highest amount of N in the following spring (**II** Tables 2–5).

The average biomass and N of CC species measured in autumn as well in spring were significantly affected by the sowing date in both trial years (**II** Tables 2–5). In general, biomass and N decreased at later sowing dates. As an exception, there was no significant decrease in the 1st (3 Aug) and 2nd (8 Aug) sowing date of the second trial year.

The variation of biomass and N depended significantly on the interaction between CC species and sowing date in both trial years, measured in autumn and spring (**II** Tables 2–5). According to the autumn measurements, the total biomass and N accumulation of winter rye were least affected by the sowing date, varying between 1188 kg ha$^{-1}$ (1st sowing date) to 873 kg ha$^{-1}$ (the last, 4th sowing date) and 28 kg ha$^{-1}$ (1st sowing date) to 22 kg ha$^{-1}$ (last (4th) sowing date) respectively in the first trial year and between 1486–1070 and 36–28 kg ha$^{-1}$, respectively, in the second trial year.

The highest decrease of biomass and N accumulation between the 1st and the last (4th) sowing dates in 2017 was found in berseem clover (1556–285 kg ha$^{-1}$ and 42–9 kg ha$^{-1}$, respectively). In 2018 the highest reduction occurred in hairy vetch (2243–1016 kg ha$^{-1}$ and 102–37 kg ha$^{-1}$, respectively).

Among tested CC species, forage radish accumulated the significantly highest amount of biomass and N in all sowing dates in both trial years despite of considerable reduction of biomass and N in the delayed sowing dates. In the first trial year, the biomass decreased from 3841 kg ha$^{-1}$ (1st sowing date) to 1164 kg ha$^{-1}$ (last (4th) sowing date) and N decreased from 103 kg ha$^{-1}$ (1st sowing date) to 43 kg ha$^{-1}$ (last (4th) sowing date). In the second trial year, the reduction of biomass was from 3581 to 2020 kg ha$^{-1}$ and the reduction of N from 126 to 71 kg ha$^{-1}$, respectively.

According to the spring measurements, overall biomass and N decrease caused by delayed sowing were lower than in autumn (**II** Tables 2–5). Among overwintering CC species, winter rye had the lowest overall biomass and N decrease due to delayed sowing date. In earlier sowing dates, the biomass of winter rye was lower compared to other species. In later sowing dates, however, winter rye's biomass reached the level of biomass from other CCs, except for winter turnip rape which had the highest biomass in the variant with most delayed sowing date in spring 2019.

Hairy vetch accumulated the highest amount of N across all the sowing dates, despite the highest overall decrease in N in case of delayed sowing. As an exception, the amount of N accumulated by hairy vetch and winter turnip rape increased significantly in the 2nd sowing date compared to the 1st sowing date in the first trial year.

## 5.3. The effect of cover crops on the yield of the following spring barley (III)

According to the ANOVA results, the spring barley yield depended significantly on CC species ($p = 0.022$) and year ($p < 0.001$), but the interaction of the two factors remained nonsignificant. Barley yield level was lower in 2018 (2693–3223 kg ha$^{-1}$) compared to 2017 and 2019 (3659–3884 kg ha$^{-1}$ and 3393–3656 kg ha$^{-1}$, respectively) (Figure 1). In 2018 forage radish and hairy vetch significantly increased barley yield. The differences remained nonsignificant in 2017 and 2019, while there was tendency for barley yield to increase in the same variants.

On average over the three years, forage radish and hairy vetch significantly increased (289 and 274 kg ha$^{-1}$, respectively) the yield of subsequent barley. The level of grain yield of barley following other CC species (winter turnip rape, winter rye, and berseem clover) were similar to the control.

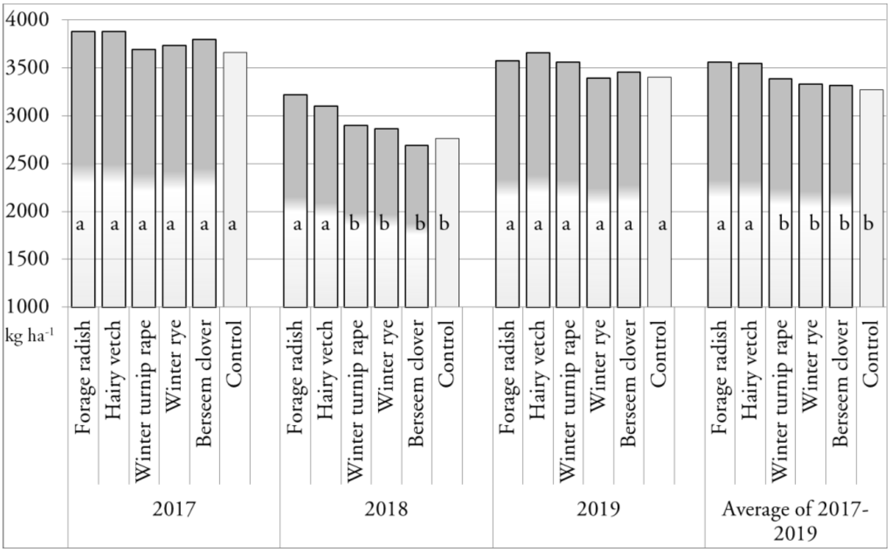


**Figure 1.** The yield of spring barley (kg ha$^{-1}$) in 2017, 2018, and 2019, and the average of these years compared to control (without cover crop). Within years, different lowercase letters are significantly different ($p < 0.05$; ANOVA, Fisher LSD test)

# 6. DISCUSSION

## 6.1. Biomass and N accumulation at the earliest sowing date (I)

### 6.1.1. Biomass and N accumulation of cover crops at the earliest sowing date in autumns of 2016–2018

Cover crop biomass and N accumulation have shown to be influenced mainly on species and the weather conditions in growing season (Talgre et al., 2011; Handlířová et al., 2017; De Notaris et al., 2018). In the present study, higher ETS from August until the end of October contributed to the higher biomass yield of all species (except berseem clover) in 2017 and 2018 compared to 2016.

Forage radish accumulated the highest biomass and N in the current study. It can be attributed to the high proportion of root biomass as concluded by many authors (Thorup-Kristensen, 2001; Lawley et al., 2011; Wang et al., 2019). The majority of studies reported high biomass of forage radish, while low biomass (277 kg ha$^{-1}$) found by Iivonen et al. (2017) was apparently caused by allelopathic effect of the preceding broccoli crop (*Brassica oleracea var. italica* L.) that inhibited seed germination. Brassica crops are also known to be the hosts of the pathogen *Plasmodiphora brassicae*, which causes the disease clubroot in some brassica species (Howard et al., 2010), suggesting that CC species should not belong to the same family with the cash crops in the rotation.

Compared to forage radish, winter turnip rape has generally lower level of biomass and N in autumn as indicated also in our study. However, after over-wintering, it is able to regrow and accumulate additional biomass and N until termination in spring (Tuulos et al., 2014).

The low biomass of winter rye found in our experiment has been also reported by others (Madsen et al., 2016; Handlířová et al., 2017), whereas some studies have found rye to have higher biomass compared to other species (Poffenbarger et al., 2015; Hill et al., 2016). In the present study, the lowest biomass in 2016 may have been caused by infection of leaf rust (*Puccinia recondita*). Furthermore, the cultivar ('Sangaste') used in the experiment has a rather low tillering capacity (Tupits, 2009). However, even with low biomass, rye has shown to be an effective weed suppressor (Madsen et al., 2016) that is often related to allelopathic properties (Jabran et al., 2015). As grass CCs are sensitive to the lack of N in the soil, the approach to support crop growth and nutrient accumulation is the integration of the manure application with CCs (Singer et al., 2008; Hashemi et al., 2013; Thilakarathna et al., 2015; Akbari et al., 2020; Cottney et al., 2020).

Due to additional N fixation from the atmosphere, legumes are less dependent on soil nutrient availability (Büchi et al., 2018), whilst the biomass and N accumulation differs between legume species (Parr et al., 2011). In the present experiment, hairy vetch had higher biomass and N compared to berseem clover. In 2018 hairy vetch had the greatest amount of biomass of all the trial years, while berseem clover had the lowest. It was probably caused by its susceptibility to drought conditions occurring before CC establishment. Due to small tap root, berseem clover can be more sensitive to water shortage compared to CCs with larger root system (Clark et al., 2012).

### 6.1.2. Biomass and N accumulation of cover crops at the earliest sowing date in following springs of 2017–2019

Many factors can reduce plant winter survival, including prolonged exposure to low temperatures, waterlogging, ice encasement, soil heaving, lack of snow cover, and plant pathogens (Waalen et al., 2013; Wiering et al., 2018). The reduction of winter survival is especially caused by a combination of such unfavourable conditions when occurring together or succeeding each other (Peltonen-Sainio et al., 2011).

Due to their winter hardiness, winter rye and winter turnip rape are commonly grown cash crop species in Estonia (Narits et al., 2017; Tupits et al., 2020). Winter turnip rape is considered to be more susceptible to wind and frost damage than small grain cereals because its apical meristem is well above the ground level. However, it is less sensitive to damages caused by weather and pests than winter oilseed rape, which additionally has hypocotyl partly above ground level (Mäkelä et al., 2011; Narits et al., 2017).

Although hairy vetch is considered more winter hardy than other winter annual legume species, it may not reliably overwinter in northern regions, depending on sowing time and the developmental stage reached before the onset of winter (Teasdale et al., 2004; Brandsæter et al., 2008; Hayden et al., 2015). Overall, the selection of CC cultivars adapted to the specific winter conditions is important (Brandsæter et al., 2008; Waalen et al., 2013; Van Eerd, 2018; Zhou et al., 2019).

Hairy vetch, winter turnip rape, and winter rye over-wintered at all experimental years in our study due to favourable conditions during winter. The plants were protected by snow cover in the periods with the coldest temperatures (below -20 °C) occurring in January of 2017 and 2019 and in February of 2018.

Our observation that CC biomass and N accumulation in the spring was influenced by the weather conditions in growing period was in accordance with other studies (Lawson et al., 2015; Mirsky et al., 2017; Van Eerd, 2018; Akbari et al., 2019). The greater autumn biomass and the higher ETS in the spring (from March until the CC termination) in 2018 and 2019 (113 and 127 °C, respectively) compared to 2017 (40 °C) resulted in higher final CC biomass and N accumulation.

In the current study, hairy vetch accumulated higher spring biomass and N in all trial years, which is in agreement with other studies, showing the superior N accumulation of legume species. For instance, Campiglia et al. (2014) found that hairy vetch accumulated over twice as much biomass and N (7131 and 340 kg ha$^{-1}$, respectively) as oilseed rape and oat. Caporali et al. (2004) reported that despite the similar amount of biomass of hairy vetch and ryegrass, hairy vetch accumulated significantly higher amount of N (197 kg ha$^{-1}$) than ryegrass (56 kg ha$^{-1}$) due to higher N content.

## 6.2. The effect of sowing date on cover crop biomass and nitrogen accumulation (II)

The autumnal decrease of average CC biomass and N accumulation at all sowing dates was higher in the first trial year (from 1940 kg ha$^{-1}$ at 1st to 710 kg ha$^{-1}$ at last sowing date, compared to the second trial year (from 2062 kg ha$^{-1}$ at the 1st sowing date to 1156 kg ha$^{-1}$ at the last sowing date. The main reason for lower biomass and N accumulation in 2017 was probably the sowing dates' lower ETS (574, 515, 438 and 393 °C), compared to the next year's sowing dates' ETS (706, 633, 577 and 513 °C).

The biomass and N accumulation of CCs in general decreased due to delayed sowing. Due to insufficient precipitation during CC establishment in the second trial year, CCs sown on 1st (3 Aug) and 2nd (8 Aug) sowing date emerged at the same time and accumulated similar amount of biomass and N. In current study, the influence of sowing date on tested species was different, as found by several authors (Thorup-Kristensen et al., 2003; Gselman & Kramberger, 2008; Van Eerd, 2018; Zhou et al., 2019: Akbari et al., 2020). Autumn measurements indicated that forage radish accumulated the highest amount of biomass and N in case of all sowing dates, despite considerable decrease (up to 70 and 58% by the last sowing date in 2017 and 2018, respectively). Brassica species are reported to have high biomass due to rapid emergence (Brust et al., 2014). Like forage radish, commonly used CC in Estonia, white mustard has shown higher biomass production, compared to many other species in case of delayed sowing (Toom et al., 2019). Forage radish has more extensive root system (Brust et al., 2014) that ensures sufficient water and nutrient uptake for CC growth (Bodner et al., 2010), and plants with deep roots are able to scavenge N from deeper soil layers (Sapkota et al., 2012).

The lowest biomass and N accumulation of berseem clover in the current study was probably caused by susceptibility to cooler temperatures and also drought conditions that occurred during crop establishment in the second trial year. In accordance with our observations, Anderson (2017) found berseem clover to be sensitive to drought, suggesting that for reduced or no-tillage management systems in which winter-killed CC species are advantageous, the legume species with higher biomass production capacity and drought tolerance should be selected. For instance, other annual clovers such as crimson clover (*Trifolium incarnatum*) or Persian clover (*Trifolium resupinatum*) (Mueller & Thorup-Kristensen, 2001). Faba bean and field pea have also shown high biomass and N accumulation in Northern climate (Etemadi et al., 2018; Toom et al., 2019). Previous studies conducted in Estonia indicate that spring sown berseem clover can accumulate high amount of biomass and N, thus being suitable pre-crop to winter cereals (Tamm et al., 2016).

The present study showed that although winter rye had relatively low biomass and N accumulation, it was least affected by the delayed sowing dates. According to autumn measurements the biomass and N of winter rye decreased up to 28 and 22%, respectively by the last sowing date. Van Eerd (2018) and Zhou et al. (2019) also found that rye had lowest biomass decrease, compared to other species in case of delayed sowing.

Among overwintering species, the biomass and accumulated N of winter rye decreased the least due to delayed sowing dates (up to 21 and 26%, respectively) in the spring. Despite considerable decrease (up to 39 and 42%, respectively), hairy vetch accumulated the highest amount of N across all sowing dates in the spring.

## 6.3. The effect of cover crops on the yield of the following spring barley (III)

The grain yield of barley increased significantly after hairy vetch and forage radish in 2018 when the overall yield level was lowest due to drought conditions and as an average of three trial years (2017–2019). However, there was a tendency of yield increase after same species also in other trial years, while the extra yields of barley remained nonsignificant compared to control. Accordingly, Madsen et al. (2016) found that the effect of green manures was highest in unfavourable, dry weather conditions; that could be associated with the increased water-holding capacity in the soil caused by CCs (Hill et al., 2016).

The evidence that the positive effect of the CCs depends on the quantity and quality of biomass was confirmed in the present study, in which forage radish and hairy vetch accumulated the highest biomass and N in autumn and spring, respectively.

Numerous experiments have indicated that N fixing legumes with high residue quality have a positive effect on the following crop (Kumar & Goh, 2002; Van Eerd, 2018; Akbari et al., 2019; Yang et al., 2019; Carciochi et al., 2021; Ghahremani et al., 2021). For example, a study by Kumar & Goh (2002) observed higher grain yield of the succeeding winter wheat with leguminous CCs being white clover and field pea that provided more N (223 and 141 kg ha$^{-1,}$ respectively), than with non-leguminous ryegrass and wheat as CCs (64 and 72 kg ha$^{-1}$, respectively). Yang et al. (2019) reported that hairy vetch and red clover accumulated

240 and 199 kg $ha^{-1}$ N and provided similar corn grain yields as conventional control with synthetic fertilizers and more than organic control without CCs. In a no-tillage management systems, Teasdale et al. (2004) suggest that hairy vetch biomass production of at least 4000 kg $ha^{-1}$ is required to supply a sufficient amount of N for corn and tomato. Spargo et al. (2016) showed that hairy vetch provided higher corn yield when over 4000 kg $ha^{-1}$ biomass was produced. Parr et al. (2011) found in the no-tillage organic farming system that the highest corn yields were achieved when hairy vetch biomass exceeded 4500 kg $ha^{-1}$. The previously mentioned biomass values were higher than those we observed, probably because of more favourable growing conditions and later termination, compared to our study. In Estonia, the later termination time for CCs to accumulate more biomass and N could also be possible in the case of later planted cash crop (e.g. vegetables), while is not an option in cereal production.

In agreement with our results, many studies reported the positive effect of forage radish on the yield of different cash crops, such as soybean (Weil & Kremen et al., 2006), silage corn (Wang et al., 2019), potato (Jahanzad et al., 2017) and barley (Sapkota et al., 2012; Munkholm & Hansen, 2012). Rutan & Steinke (2019) found that winter-killed forage radish and oat CCs sequestered effectively soil nitrate in the autumn, whereas quickly decomposed CC residues were not synchronized with N availability for cash crop. It is not known how much N from forage radish remained available to the barley in our study because N loss was not measured.

In the current experiment, all CCs including rye had a narrow C:N ratio (9–18:1) at the time of termination, which is reported to reduce the potential for N immobilization (Dabney et al., 2001; Lawson et al., 2013). Similarly to our study, Jahanzad et al. (2017) found no negative effect of rye CC on the following crop (potato) due to early termination and therefore low biomass of rye. While many studies have shown that usually grass CCs are not a significant source of available N for subsequent cash crops and may even cause yield reduction. For instance, Sigdel & Chatterjee (2020) found in a pot experiment that rye CC had a negative effect on subsequent spring wheat yield, possibly because of the high C:N ratio that caused N immobilization and also because of the allelopathic effect. In the same study, legume species Austrian pea showed efficient N recycling and increased wheat yield. Pantoja et al.

(2015) reported that rye CC did not affect soybean yield, whereas it caused a 6% reduction in corn yield. Hill et al. (2016) reported that the negative impact of rye CC on following dry bean increased with higher rye biomass and C:N ratio. While Basche et al. (2016) observed that the long-term use of a winter rye CC improved soil physical properties without negatively affecting yields in maize-soybean crop rotations.

The present short-term study indicates that CCs had no negative effect on cash crop in Estonian conditions and some species even caused a yield increase. However, the rather low effect of CCs on barley yield in our study indicates the need for long-term use of CCs, which leads to improved soil properties including higher soil organic matter formation (Kauer et al., 2015). Furthermore, the inclusion of other nutrient sources in the low input system should be used. For instance, it has been shown that combining CCs with other organic amendments such as animal manure can contribute to the yield increase of the following crop (Doltra & Olesen, 2013; Madsen et al., 2016). Moreover, the use of CCs in combination with reduced or no-tillage practices is more efficient in increasing soil organic matter content, leading to increased crop productivity in the long-term as stated by Bogužas et al (2015).

# CONCLUSIONS

Cover crop biomass and N accumulation depended on species and growing conditions. In autumn, all species except berseem clover accumulated higher biomass and N in 2017 and 2018 compared to 2016. Frost sensitive forage radish accumulated the highest amount of biomass and N in autumn, whereas berseem clover accumulated low amount of biomass and N, especially in the year with drought conditions before the establishment.

As hypothesized, hairy vetch over-wintered similarly to winter turnip rape and winter rye in all trial years. In this study, hairy vetch and winter turnip rape accumulated higher amount of biomass and N in the spring than winter rye, which may be partly related to characteristics of the used winter rye variety.

Cover crop biomass and N accumulation decreased with delayed sowing dates, while the influence of sowing date on cover crop species was different. Forage radish produced the highest amount of biomass and N at all sowing dates. Although the biomass of rye was relatively low, the reduction at delayed sowing dates was lowest compared to other species. Among over-wintering CCs, hairy vetch as a legume species accumulated the highest amount of N in the spring. It can be concluded that in Estonia, CCs require sowing in early August to enable maximum biomass and N accumulation. It is possible to delay the sowing of over-wintering species if the following cash crop is sown later.

The results partly provide support for the hypothesis that CCs have a positive effect on the yield of subsequent barley. As an average over the three years, only forage radish and hairy vetch significantly increased the yield of subsequent barley, probably because of the N contribution. None of the CCs had negative effect on barley, as the yield level following winter turnip rape, winter rye, and berseem clover were similar to the control.

## Issues requiring further research

Compared to monocultures, mixture of CC species could provide enhanced ecosystem services such as producing higher biomass, providing more effective nitrate leaching and improved N supply to the subsequent crop. Therefore, further studies should include CC mixtures.

The CC biomass production and N supply to a following cash crop is influenced not only by sowing, but also the termination time. Continued research is necessary to determine how termination timing affects CC biomass and nutrient accumulation. It would be also useful to study how different sowing and termination times of CCs affect the yield of the following crop.

Part of the N accumulated by CCs may be lost by leaching or volatilization. Thus, additional research is essential to determine the level of N loss.

Since no-tillage and reduced tillage farming systems are getting more popular, continued research is needed to evaluate CC management under these conditions.

The application of manure or other fertilizers could be a valuable strategy to increase CC biomass and nutrient accumulation.

The present study evaluated short term effect of CCs on the cash crop yield. Improvement of soil quality, primarily soil organic matter content is a long-term process. CC impacts on the cash crop yield can be measurable in the long term, therefore long-term studies with CCs in the crop rotations are required in order to assess their effects on cash crop yield.

Cost-benefit analyses would be valuable to provide information on the economic sustainability of cover cropping.

## Application of the research results

The results of this research will help promoting CC adoption into cropping systems in Estonia and other regions with similar climate to improve the agronomical and environmental sustainability of farming systems.

# REFERENCES

[IUSS] Working Group WRB. World Reference Base for Soil Resources 2014, Update 2015 International Soil Classification System for Naming Soils and Creating Legends for Soil Maps; World Soil Resources Reports No. 106; FAO: Rome, Italy, 2015.

Abdalla, M., Hastings, A., Cheng, K., Yue, Q., Chadwick, D., Espenberg, M., Truu, J., Rees, R. M., & Smith, P. (2019). A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity. Global Change Biology, 25(8), 2530–2543. https://doi.org/10.1111/gcb.14644.

Acharya, B. S., Dodla, S., Gaston, L. A., Darapuneni, M., Wang, J. J., Sepat, S., & Bohara, H. (2019). Winter cover crops effect on soil moisture and soybean growth and yield under different tillage systems. Soil and Tillage Research, 195(1), 104430. https://doi.org/10.1016/j.still.2019.104430.

Adetunji, A. T., Ncube, B., Mulidzi, R., & Lewu, F. B. (2020). Management impact and benefit of cover crops on soil quality: A review. Soil and Tillage Research, 204, 104717. https://doi.org/10.1016/j.still.2020.104717.

Akbari, P., Herbert, S. J., Hashemi, M., Barker, A. V., & Zandvakili, O. R. (2019). Role of cover crops and planting dates for improved weed suppression and nitrogen recovery in no till systems. Communications in Soil Science and Plant Analysis, 50(14), 1722–1731. https://doi.org/10.1080/00103624.2019.1631338.

Akbari, P., Herbert, S., Hashemi, M., Barker, A., Zandvakili, O. R., & Bistgani, Z. E. (2020). Winter annual rye seeding date influence on nitrogen recovery and ammonia volatilization from late fall surface-applied manure. Agronomy, 10(7), 1–12. https://doi.org/10.3390/agronomy10070931.

Anderson, R. L. (2017). Interseeding berseem clover in winter wheat. Renewable Agriculture and Food Systems, 32(6), 573–575. https://doi.org/10.1017/S1742170517000023.

Antosh, E., Idowu, J., Schutte, B., & Lehnhoff, E. (2020). Winter cover crops effects on soil properties and sweet corn yield in semi-arid irrigated systems. Agronomy Journal, 112(1), 92–106. https://doi.org/10.1002/agj2.20055.

Appelgate, S. R., Lenssen, A. W., Wiedenhoeft, M. H., & Kaspar, T. C. (2017). Cover crop options and mixes for upper midwest corn–soybean systems. Agronomy Journal, 109(3), 968–984. https://doi.org/10.2134/agronj2016.08.0453.

Basche AD, Miguez FE, Kaspar TC, Castellano MJ.(2014) Do cover crops increase or decrease nitrous oxide emissions ? A meta-analysis. Journal of Soil and Water Conservation 69, 471–482. https://doi.org/ 10.2489/jswc.69.6.471.

Basche, A. D., Kaspar, T. C., Archontoulis, S. V., Jaynes, D. B., Sauer, T. J., Parkin, T. B., & Miguez, F. E. (2016). Soil water improvements with the long-term use of a winter rye cover crop. Agricultural Water Management, 172, 40–50. https://doi.org/10.1016/j.agwat.2016.04.006.

Blanco-Canqui, H., Shaver, T. M., Lindquist, J. L., Shapiro, C. A., Elmore, R. W., Francis, C. A., & Hergert, G. W. (2015). Cover crops and ecosystem services: Insights from studies in temperate soils. Agronomy Journal, 107(6), 2449–2474. https://doi.org/10.2134/agronj15.0086.

Bodner, G., Himmelbauer, M., Loiskandl, W., & Kaul, H. P. (2010). Improved evaluation of cover crop species by growth and root factors. Agronomy for Sustainable Development, 30(2), 455–464. https://doi.org/10.1051/agro/2009029.

Bogužas, V., Mikučionienė, R., Šlepetienė, A., Sinkevičienė, A., Feiza, V., Steponavičienė, V., & Adamavičienė, A. (2015). Long-term effect of tillage systems, straw and green manure combinations on soil organic matter. Zemdirbyste, 102(3), 243–250. https://doi.org/10.13080/z-a.2015.102.031.

Brandsæter, L. O., Heggen, H., Riley, H., Stubhaug, E., & Henriksen, T. M. (2008). Winter survival, biomass accumulation and N mineralization of winter annual and biennial legumes sown at various times of year in Northern Temperate Regions. European Journal of Agronomy, 28(3), 437–448. https://doi.org/10.1016/j.eja.2007.11.013.

Brust, J., Claupein, W., Gerhards, R. (2014). Growth and weed suppression ability of common and new cover crops in Germany. Crop Protection, 63, 1–8. http://dx.doi.org/10.1016/j.cropro.2014.04.022

Büchi, L., Gebhard, C. A., Liebisch, F., Sinaj, S., Ramseier, H., & Charles, R. (2015). Accumulation of biologically fixed nitrogen by legumes cultivated as cover crops in Switzerland. Plant and Soil, 393(1–2), 163–175. https://doi.org/10.1007/s11104-015-2476-7

Büchi, L., Wendling, M., Amossé, C., Necpalova, M., & Charles, R. (2018). Importance of cover crops in alleviating negative effects of reduced soil tillage and promoting soil fertility in a winter wheat cropping system. Agriculture, Ecosystems and Environment, 256, 92–104. https://doi.org/10.1016/j.agee.2018.01.005.

Campiglia, E., Mancinelli, R., Di Felice, V., & Radicetti, E. (2014). Long-term residual effects of the management of cover crop biomass on soil nitrogen and yield of endive (Cichorium endivia L.) and savoy cabbage (Brassica oleracea var. sabauda). Soil and Tillage Research, 139, 1–7. https://doi.org/10.1016/j.still.2014.01.003.

Caporali, F., Campiglia, E., Mancinelli, R., & Paolini, R. (2004). Maize performances as influenced by winter cover crop green manuring. Italian Journal of Agronomy, 8(1), 37–45.

Carciochi, W. D., Crespo, C., Eliceche, M., & Barbieri, P. A. (2021). Nitrogen and sulfur recycling and diagnostic in cover crop-maize systems. Journal of Soil Science and Plant Nutrition, 21, 801–812. https://doi.org/10.1007/s42729-020-00402-y.

Clark A. (2012). Managing Cover Crop Profitably. In: Clark A (Ed). National SARE outreach handbook series book 9. 3rd ed. Beltsville (MD): Sustain. Agric. Netw; 248.

Cordeau, S., Guillemin, J. P., Reibel, C., and Chauvel, B. (2015). Weed species differ in their ability to emerge in no-till systems that include cover crops. Annals of Applied Biology. 166, 444–455.

Cottney, P., Black, L., White, E., & N. Williams, P. (2020). The correct cover crop species integrated with slurry can increase biomass, quality and nitrogen cycling to positively affect yields in a subsequent spring barley rotation. Agronomy, 10(11), 1760. https://doi.org/10.3390/agronomy10111760.

Dabney, S. M., Delgado, J. A., & Reeves, D. W. (2001). Using winter cover crops to improve soil and water quality. Communications in Soil Science and Plant Analysis, 32(7–8), 1221–1250. https://doi.org/10.1081/CSS-100104110.

Daryanto, S., Wang, L., & Jacinthe, P. A. (2017). Impacts of no-tillage management on nitrate loss from corn, soybean and wheat cultivation: A meta-analysis. Scientific Reports, 7(1), 1–9. https://doi.org/10.1038/s41598-017-12383-7.

De Notaris, C., Rasmussen, J., Sørensen, P., & Olesen, J. E. (2018). Nitrogen leaching: A crop rotation perspective on the effect of N surplus, field management and use of catch crops. Agriculture, Ecosystems and Environment, 255, 1–11. https://doi.org/10.1016/j.agee.2017.12.009.

Dean, J. E., & Weil, R. R. (2009). Brassica cover crops for nitrogen retention in the mid-atlantic coastal plain. Journal of Environmental Quality, 38(2), 520–528. https://doi.org/10.2134/jeq2008.0066.

Doltra, J., & Olesen, J. E. (2013). The role of catch crops in the ecological intensification of spring cereals in organic farming under Nordic climate. European Journal of Agronomy, 44, 98–108. https://doi.org/10.1016/j.eja.2012.03.006.

European Commission (2020). A European Green Deal. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en. (Accessed 11.03.2021).

Fageria, N. K., Baligar, V. C., & Bailey, B. A. (2005). Role of cover crops in improving soil and row crop productivity. Communications in Soil Science and Plant Analysis, 36(19–20), 2733–2757. https://doi.org/10.1080/00103620500303939.

Finney, D. M., White, C. M., & Kaye, J. P. (2016). Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. Agronomy Journal, 108(1), 39–52. https://doi.org/10.2134/agronj15.0182.

Ghahremani, S., Ebadi, A., Tobeh, A., Hashemi, M., Sedghi, M., Gholipoouri, A., & Barker, A. V. (2021). Short-term impact of monocultured and mixed cover crops on soil properties, weed suppression, and lettuce yield. Communications in Soil Science and Plant Analysis, 52(4), 1–10. https://doi.org/10.1080/00103624.2020.1854295.

Gollner, G., Fohrafellner, J., & Friedel, J. K. (2020). Winter-hardy vs. freeze-killed cover crop mixtures before maize in an organic farming system with reduced soil cultivation. Organic Agriculture, 10, 5–11. https://doi.org/10.1007/s13165-020-00294-3.

Gselman, A., & Kramberger, B. (2008). Benefits of winter legume cover crops require early sowing. Australian Journal of Agricultural Research, 59(12), 1156–1163. https://doi.org/10.1071/AR08015.

Handlířová, M., Lukas, V., & Smutný, V. (2017). Yield and soil coverage of catch crops and their impact on the yield of spring barley. Plant, Soil and Environment, 63(5), 195–200. https://doi.org/10.17221/801/2016-PSE.

Hashemi, M., Farsad, A., Sadeghpour, A., Weis, S. A., & Herbert, S. J. (2013). Cover-crop seeding-date influence on fall nitrogen recovery. Journal of Plant Nutrition and Soil Science, 176(1), 69–75. https://doi.org/10.1002/jpln.201200062.

Hayden, Z. D., Ngouajio, M., & Brainard, D. C. (2015). Planting date and staggered seeding of rye-vetch mixtures: Biomass, nitrogen, and legume winter survival. Agronomy Journal, 107(1), 33–40. https://doi.org/10.2134/agronj14.0237.

Hill, E. C., Renner, K. A., & Sprague, C. L. (2016). Cover crop impact on nitrogen availability and dry bean in an organic system. Agronomy Journal, 108(1), 329–341. https://doi.org/10.2134/agronj2015.0164.

Howard, R. J., Strelkov, S. E., & Harding, M. W. (2010). Clubroot of cruciferous crops - New perspectives on an old disease. Canadian Journal of Plant Pathology, 32(1), 43–57. https://doi.org/10.1080/07060661003621761

Iivonen, S., Kivijärvi, P., Suojala-Ahlfors, T. (2017). Characteristics of various catch crops in the organic vegetable production in northern climate conditions – Results from and on-farm study. Reports 165. University of Helsinki, Ruralia Institute. http://hdl. handle.net/10138/229443 (accessed 11.11.2020)

Jabran, K., Mahajan, G., Sardana, V., & Chauhan, B. S. (2015). Allelopathy for weed control in agricultural systems. Crop Protection, 72, 57–65. https://doi.org/10.1016/j.cropro.2015.03.004.

Jahanzad, E., Barker, A. V., Hashemi, M., Sadeghpour, A., Eaton, T., & Park, Y. (2017). Improving yield and mineral nutrient concentration of potato tubers through cover cropping. Field Crops Research, 212, 45–51. https://doi.org/10.1016/j.fcr.2017.06.023.

Justes, E., Beaudoin, N., Bertuzzi, P., Charles, R., Constantin, J., Dürr, C., Hermon, C., Joannon, A., Le Bas, C., Mary, B., Mignolet, C., Montfort, F., Ruiz, L., Sarthou, J.P., Souchère, V., Tournebize, J., Savini, I., Réchauchère, O. (2012). The use of cover crops to reduce nitrate leaching: Effect on the water and nitrogen balance and other ecosystem services. Synopsis of the study report INRA (France), 68 p.

Kauer, K., Tein, B., Sanchez de Cima, D., Talgre, L., Eremeev, V., Loit, E., Luik, A. (2015). Soil carbon dynamics estimation and dependence on farming system in a temperate climate. Soil and Tillage Research, 154, 53–63. https://doi.org/10.1016/j.still.2015.06.010.

Kaye, J. P., & Quemada, M. (2017). Using cover crops to mitigate and adapt to climate change. A review. Agronomy for Sustainable Development, 37, 4. https://doi.org/10.1007/s13593-016-0410-x.

Kim, N., Zabaloy, M. C., Guan, K., & Villamil, M. B. (2020). Do cover crops benefit soil microbiome? A meta-analysis of current research. Soil Biology and Biochemistry, 142, 107701. https://doi.org/10.1016/j.soilbio.2019.107701

Kleijn, D., Bommarco, R., Fijen, T. P. M., Garibaldi, L. A., Potts, S. G., & van der Putten, W. H. (2019). Ecological Intensification: Bridging the Gap between Science and Practice. Trends in Ecology and Evolution, 34(2), 154–166. https://doi.org/10.1016/j.tree.2018.11.002.

Krstić, D., Vujić, S., Jaćimović, G., D'Ottavio, P., Radanović, Z., Erić, P., & Ćupina, B. (2018). The effect of cover crops on soil water balance in rain-fed conditions. Atmosphere, 9(12). https://doi.org/10.3390/atmos9120492.

Kumar, K., & Goh, K. M. (2002). Management practices of antecedent leguminous and non-leguminous crop residues in relation to winter wheat yields, nitrogen uptake, soil nitrogen mineralization and simple nitrogen balance. European Journal of Agronomy, 16(4), 295–308. https://doi.org/10.1016/S1161-0301(01)00133-2.

Larkin, R. P., & Griffin, T. S. (2007). Control of soilborne potato diseases using Brassica green manures. Crop Protection, 26(7), 1067–1077. https://doi.org/10.1016/j.cropro.2006.10.004.

Lawley, Y. E., Teasdale, J. R., & Weil, R. R. (2012). The mechanism for weed suppression by a forage radish cover crop. Agronomy Journal, 104(2), 205–214. https://doi.org/10.2134/agronj2011.0128.

Lawley, Y. E., Weil, R. R., & Teasdale, J. R. (2011). Forage radish cover crop suppresses winter annual weeds in fall and before corn planting.

Agronomy Journal, 103(1), 137–144. https://doi.org/10.2134/agronj2010.0187.

Lawson, A., Cogger, C., Bary, A., & Fortuna, A. M. (2015). Influence of seeding ratio, planting date, and termination date on rye-hairy vetch cover crop mixture performance under organic management. PLoS ONE, 10(6), 1–19. https://doi.org/10.1371/journal.pone.0129597.

Lawson, A., Fortuna, A. M., Cogger, C., Bary, A., & Stubbs, T. (2013). Nitrogen contribution of rye-hairy vetch cover crop mixtures to organically grown sweet corn. Renewable Agriculture and Food Systems,28(1),59–69.https://doi.org/10.1017/S1742170512000014.

Liu, A., Ma, B. L., & Bomke, A. A. (2005). Effects of cover crops on soil aggregate stability, total organic carbon, and polysaccharides. Soil Science Society of America Journal. 69(6), 2041–2048. https://doi.org/10.2136/sssaj2005.0032

Lu, Y. C., Watkins, K. B., Teasdale, J. R., & Abdul-Baki, A. A. (2000). Cover crops in sustainable food production. Food Reviews International, 16(2), 121–157. https://doi.org/10.1081/FRI-100100285.

Lynch, J. P. (2013). Steep, cheap and deep: An ideotype to optimize water and N acquisition by maize root systems. Annals of Botany, 112(2), 347–357. https://doi.org/10.1093/aob/mcs293.

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 and Horticulture, 32(3), 182–191. https://doi.org/10.1080/01448765.2016.1138141.

Mäkelä, P. S. A., Tuulos, A., Turakainen, M., Santanen, A., & Stoddard, F. L. (2011). Revitalizing the winter turnip rape crop in the northern latitudes. Acta Agriculturae Scandinavica Section B: Soil and Plant Science, 61(3), 195–201. https://doi.org/10.1080/09064711003747470.

Mancinelli, R., Muleo, R., Marinari, S., & Radicetti, E. (2019). How soil ecological intensification by means of cover crops affects nitrogen use efficiency in pepper cultivation. Agriculture (Switzerland), 9(7), 145. https://doi.org/10.3390/agriculture9070145

Marcillo, G. S., & Miguez, F. E. (2017). Corn yield response to winter cover crops: An updated meta-analysis. Journal of Soil and Water Conservation, 72(3), 226–239. https://doi.org/10.2489/jswc.72.3.226.

Marcillo, Guillermo S., Carlson, S., Filbert, M., Kaspar, T., Plastina, A., & Miguez, F. E. (2019). Maize system impacts of cover crop management decisions: A simulation analysis of rye biomass response to planting populations in Iowa, U.S.A. Agricultural Systems, 176, 102651. https://doi.org/10.1016/j.agsy.2019.102651.

Martinez-Feria, R. A., Dietzel, R., Liebman, M., Helmers, M. J., & Archontoulis, S. V. (2016). Rye cover crop effects on maize: A system-level analysis. Field Crops Research, 196, 145–159. https://doi.org/10.1016/j.fcr.2016.06.016.

Meyer, N., Bergez, J. E., Constantin, J., Belleville, P., & Justes, E. (2020). Cover crops reduce drainage but not always soil water content due to interactions between rainfall distribution and management. Agricultural Water Management, 231, 105998. https://doi.org/10.1016/j.agwat.2019.105998.

Mirsky, S. B., Ackroyd, V. J., Cordeau, S., Curran, W. S., Hashemi, M., Reberg-Horton, S. C., Ryan, M. R., & Spargo, J. T. (2017). Hairy vetch biomass across the eastern united states: Effects of latitude, seeding rate and date, and termination timing. Agronomy Journal, 109(4), 1510–1519. https://doi.org/10.2134/agronj2016.09.0556.

Mueller, T., & Thorup-Kristensen, K. (2001). N-fixation of selected green manure plants in an organic crop rotation. Biological Agriculture and Horticulture, 18(4), 345–363. https://doi.org/10.1080/01448765.2001.9754897.

Munkholm, L. J., & Hansen, E. M. (2012). Catch crop biomass production, nitrogen uptake and root development under different tillage systems. Soil Use and Management, 28(4), 517–529. https://doi.org/10.1111/sum.12001.

Narits, L., & Keppart, L. (2017). The impact of winter conditions on winter oilseed rape and winter turnip rape in Jõgeva at vegetation periods of 2005/2006–2015/2016. Taimekasvatus Eestis 2017. (Ed) Tupits, I., Tamm, S., Tamm, Ü., Toe, A. AS Rebellis, Saku, 99– 106. (In Estonian).

Nicholls C. I & Altieri M. A. (2013). Plant biodiversity enhances bees and other insect pollinators in agroecosystems. A review. Agronomy for Sustainable Development 33, 257–274. https://doi.org/10.1007/s13593-012-0092-y

Pantoja, J. L., Woli, K. P., Sawyer, J. E., & Barker, D. W. (2015). Corn Nitrogen Fertilization Requirement and Corn-Soybean Productivity with a Rye Cover Crop. Soil Science Society of America Journal, 79(5), 1482–1495. https://doi.org/10.2136/sssaj2015.02.0084.

Parr, M., Grossman, J. M., Brinton, C., & Crozier, C. (2011). Nitrogen delivery from legume cover crops in no-till organic corn production. Organic Agriculture and Agroecology, 103(6), 1578-1590. https://doi.org/10.2134/agronj2011.0007.

Peltonen-Sainio, P. (2018). Warming autumns at high latitudes of Europe : an opportunity to lose or gain in cereal production. Regional Environmental Change 18, 1453–1465. https://doi.org 10.1007/s10113-017-1275-5

Peltonen-Sainio, P., Hakala, K., & Jauhiainen, L. (2011). Climate-induced overwintering challenges for wheat and rye in northern agriculture. Acta Agriculturae Scandinavica Section B: Soil and Plant Science, 61(1), 75–83. https://doi.org/10.1080/09064710903535977.

Plaza-Bonilla, D., Nolot, J. M., Raffaillac, D., & Justes, E. (2015). Cover crops mitigate nitrate leaching in cropping systems including grain legumes: Field evidence and model simulations. Agriculture, Ecosystems and Environment, 212, 1–12. https://doi.org/10.1016/j.agee.2015.06.014.

Poeplau, C. & Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops - A meta-analysis. Agriculture, Ecosystems and Environment, 200, 33–41. http://dx.doi.org/10.1016/j.agee.2014.10.024

Poffenbarger, H. J., Mirsky, S. B., Weil, R. R., Maul, J. E., Kramer, M., Spargo, J. T., & Cavigelli, M. A. (2015). Biomass and nitrogen content of hairy vetch-cereal rye cover crop mixtures as influenced by species proportions. Agronomy Journal, 107(6), 2069–2082. https://doi.org/10.2134/agronj14.0462.

Radicetti, E., Mancinelli, R., Moscetti, R., & Campiglia, E. (2016). Management of winter cover crop residues under different tillage conditions affects nitrogen utilization efficiency and yield of eggplant (Solanum melanogena L.) in Mediterranean environment. Soil and Tillage Research, 9(1), 1237–1243. https://doi.org/10.1016/j.still.2015.09.004

Reiter, M. S., Reeves, D. W., Burmester, C. H., & Torbert, H. A. (2008). Cotton nitrogen management in a high-residue conservation system: cover crop fertilization. Soil Science Society of America Journal, 72(5), 1321–1329. https://doi.org/10.2136/sssaj2007.0313.

Robertson, G. P., & Vitousek, P. M. (2009). Nitrogen in agriculture: Balancing the cost of an essential resource. Annual Review of Environment and Resources, 34, 97–125. https://doi.org/10.1146/annurev.environ.032108.105046.

Ruffo, M. L., & Bollero, G. A. (2003). Modeling rye and hairy vetch residue decomposition as a function of degree-days and decomposition-days. Agronomy Journal, 95(4), 900–907. https://doi.org/10.2134/agronj2003.9000.

Ruis, S. J., Blanco-Canqui, H., Creech, C. F., Koehler-Cole, K., Elmore, R. W., & Francis, C. A. (2019). Cover crop biomass production in temperate agroecozones. Agronomy Journal, 111(4), 1535–1551. https://doi.org/10.2134/agronj2018.08.0535.

Rutan, J., & Steinke, K. (2019). Corn nitrogen management following daikon radish and forage oat cover crops. Soil Science Society of America Journal, 83(1), 181–189. https://doi.org/10.2136/sssaj2018.07.0269.

Rütting, T., Aronsson, H., & Delin, S. (2018). Efficient use of nitrogen in agriculture. Nutrient Cycling in Agroecosystems, 110(1), 1–5. https://doi.org/10.1007/s10705-017-9900-8.

Sainju, U. M., & Singh, B. P. (1997). Winter cover crops for sustainable agricultural systems: Influence on soil properties, water quality, and crop yields. HortScience, 32(1), 21–28. https://doi.org/10.21273/hortsci.32.1.21.

Sapkota, T. B., Askegaard, M., Lægdsmand, M., & Olesen, J. E. (2012). Effects of catch crop type and root depth on nitrogen leaching and yield of spring barley. Field Crops Research, 125, 129–138. https://doi.org/10.1016/j.fcr.2011.09.009.

Sarrantonio, M., & Gallandt, E. (2003). The Role of Cover Crops in North American Cropping Systems. Journal of Crop Production, 8(1–2), 53–74. https://doi.org/10.1300/J144v08n01_04.

Sarwar, M., Kirkegaard, J. A., Wong, P. T. W., & Desmachelier, J. M. (1998). Biofumigation potential of brassicas. Plant Soil 201, 103–112.

Schulz, M.; Marocco, A.; Tabaglio, V.; Macias, F. A.; Molinillo, J. M. G. (2013). Benzoxazinoids in Rye Allelopathy - From Discovery to Application in Sustainable Weed Control and Organic Farming. Journal of Chemical Ecology, 39, 154–174 https://doi.org/10.1007/s10886-013-0235-x.

Sharma, P., Singh, A., Kahlon, C. S., Brar, A. S., Grover, K. K., Dia, M., & Steiner, R. L. (2018). The Role of Cover Crops towards Sustainable Soil Health and Agriculture—A Review Paper. American Journal of Plant Sciences, 09(09), 1935–1951. https://doi.org/10.4236/ajps.2018.99140.

Sievers, T., & Cook, R. L. (2018). Aboveground and Root Decomposition of Cereal Rye and Hairy Vetch Cover Crops. Soil Science Society of America Journal, 82(1), 147–155. https://doi.org/10.2136/sssaj2017.05.0139.

Sigdel, S., & Chatterjee, A. (2020). Do cover crop and soil-mediated legacy influence succeeding wheat production? Communications in Soil Science and Plant Analysis, 51(11), 1514–1524. https://doi.org/10.1080/00103624.2020.1784923.

Singer, J. W., Cambardella, C. A., & Moorman, T. B. (2008). Enhancing nutrient cycling by coupling cover crops with manure injection. Agronomy Journal, 100(6), 1735–1739. https://doi.org/10.2134/agronj2008.0013x.

Smolinska, U., & Horbowicz, M. (1999). Fungicidal activity of volatiles from selected cruciferous plants against resting propagules of soil-borne fungal pathogens. Journal of Phytopathology, 147, 119–124. https://doi.org/10.1046/j.1439-0434.1999.147002119.x

Spargo, J. T., Cavigelli, M. A., Mirsky, S. B., Meisinger, J. J., & Ackroyd, V. J. (2016). Organic supplemental nitrogen sources for field corn production after a hairy vetch cover crop. Agronomy Journal, 108(5), 1992–2002. https://doi.org/10.2134/agronj2015.0485.

Storr, T., Simmons, R. W., & Hannam, J. A. (2020). Using frost-sensitive cover crops for timely nitrogen mineralization and soil moisture management. Soil Use and Management, June, 1–9. https://doi.org/10.1111/sum.12619.

Talgre, L., Lauringson, E., Makke, A., & Lauk, R. (2011). Biomass production and nutrient binding of catch crops. Zemdirbyste, 98(3), 251–258.

Tamm, I., Tamm, Ü., Ingver, A., Koppel, R., Tupits, I., Bender, A., Tamm, S., Narits, L. & Koppel, M. (2016). Different leguminous pre-crops increased yield of succeeding cereals in two consecutive years. Acta Agriculturae Scandinavica, Section B - Soil & Plant Science, 66 (7), 593–601. https://doi.org/10.1080/09064710.2016.1205125

Teasdale, J. R., Devine, T. E., Mosjidis, J. A., Bellinder, R. R., & Beste, C. E. (2004). Growth and development of hairy vetch cultivars in the northeastern United States as influenced by planting and harvesting date. Agronomy Journal, 96(5), 1266–1271. https://doi.org/10.2134/agronj2004.1266.

Thapa, R., Mirsky, S. B., & Tully, K. L. (2018). Cover crops reduce nitrate leaching in agroecosystems: a global meta-analysis. Journal of Environmental Quality, 47(6), 1400–1411. https://doi.org/10.2134/jeq2018.03.0107.

Thilakarathna, M. S., Serran, S., Lauzon, J., Janovicek, K., & Deen, B. (2015). Management of manure nitrogen using cover crops. Agronomy Journal, 107(4), 1595–1607. https://doi.org/10.2134/agronj14.0634.

Thorup-Kristensen, K. (2001). Are differences in root growth of nitrogen catch crops important for their ability to reduce soil nitrate-N content, and how can this be measured? Plant and Soil, 230(2), 185–195. https://doi.org/10.1023/A:1010306425468.

Thorup-Kristensen, K., Magid, J., & Jensen, L.S. (2003). Catch crops and green manures as biological tools in nitrogen management in temperate zones. Advances in Agronomy. 51, 227–302. https://doi.org/10.1016/S0065-2113(02)79005-6.

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., & Polasky, S. (2002). Agricultural sustainability and intensive production practices. Nature, 418, 671–677. https://doi.org/10.1038/nature01014.

Toom, M., Talgre, L., Pechter, P., Narits, L., Tamm, S., & Lauringson, E. (2019). The effect of sowing date on cover crop biomass and nitrogen accumulation. Agronomy Research 17(4), 1779–1787. https://doi.org/10.15159/ar.19.164.

Tosti, G., Benincasa, P., Farneselli, M., Pace, R., Tei, F., Guiducci, M., & Thorup-Kristensen, K. (2012). Green manuring effect of pure and mixed barley - hairy vetch winter cover crops on maize and processing tomato N nutrition. European Journal of Agronomy, 43, 136–146. https://doi.org/10.1016/j.eja.2012.06.004.

Tosti, G., Benincasa, P., Farneselli, M., Tei, F., & Guiducci, M. (2014). Barley–hairy vetch mixture as cover crop for green manuring and the mitigation of N leaching risk. European Journal of Agronomy 54, 34–39. https://doi.org/10.1016/j.eja.2013.11.012.

Tribouillois, H., Cohan, J. P., & Justes, E. (2016). Cover crop mixtures including legume produce ecosystem services of nitrate capture and green manuring: assessment combining experimentation and modelling. Plant Soil. 401(1–2), 347–64. https://doi.org/10.1007/s11104-015-2734-8.

Tribouillois, H., Constantin, J., & Justes E. (2018). Cover crops mitigate greenhouse gases balance but reduce drainage under climate change scenarios in temperate climate with dry summers. Global Change Biology, 24(6), 2513–2529. https://doi.org/10.1111/gcb.14091.

Tupits, I. (2009). The effect of sowing and seeding rate on grain yield of winter rye. Crop varieties, characteristics and recommendations for cultivation. OÜ Vali Press, Jõgeva, 30–35 (In Estonian).

Tupits, I. (2020). Growing winter rye in conventional and organic farming. Agronoomia 2020. (Ed) Alaru, M. OÜ Vali Press, Jõgeva, 117−122. (In Estonian).

Tuulos, A., Yli-Halla, M., Stoddard, F., & Mäkelä, P. (2014). Winter turnip rape as a soil N scavenging catch crop in a cool humid climate. Agronomy for Sustainable Development, 35(1), 359–366. https://doi.org/10.1007/s13593-014-0229-2.

Van Eerd, L. L. (2018). Nitrogen dynamics and yields of fresh bean and sweet corn with different cover crops and planting dates. Nutrient Cycling in Agroecosystems, 111(1), 33–46. https://doi.org/10.1007/s10705-018-9914-x.

Vyn, T. J., Faber, J. G., Janovicek, K. J., & Beauchamp, E. G. (2000). Cover crop effects on nitrogen availability to corn following wheat. Agronomy Journal, 92(5), 915–924. https://doi.org/10.2134/agronj2000.925915x.

Waalen, W., Øvergaard, S. I., Åssveen, M., Eltun, R., & Gusta, L. V. (2013). Winter survival of winter rapeseed and winter turnip rapeseed in field trials, as explained by PPLS regression. European Journal of Agronomy, 51, 81–90. https://doi.org/10.1016/j.eja.2013.06.004.

Wang, F., Weil, R. R., Han, L., Zhang, M., Sun, Z., & Nan, X. (2019). Subsequent nitrogen utilisation and soil water distribution as affected by forage radish cover crop and nitrogen fertiliser in a corn silage production system. Acta Agriculturae Scandinavica Section B: Soil and Plant Science, 69(1), 52–61. https://doi.org/10.1080/09064710.2018.1498911.

Wang, G., Ngouajio, M., & Warncke, D. D. (2008). Nutrient cycling, weed suppression, and onion yield following Brassica and Sorghum sudangrass cover crops. HortTechnology, 18(1), 68–74. https://doi.org/10.21273/horttech.18.1.68.

Weil, R., & Kremen, A. (2007). Thinking across and beyond disciplines to make cover crops pay Journal of the Science of Food and Agriculture, 87(4) 551-557 https:// doi.org/10.1002/jsfa.2742.

White, C. M., & Weil, R. R. (2010). Forage radish and cereal rye cover crop effects on mycorrhizal fungus colonization of maize roots. Plant and Soil, 328(1), 507–521. https://doi.org/10.1007/s11104-009-0131-x.

White, C. M., DuPont, S. T., Hautau, M., Hartman, D., Finney, D. M., Bradley, B., LaChance, J. C., & Kaye, J. P. (2017). Managing the trade off between nitrogen supply and retention with cover crop mixtures. Agriculture, Ecosystems and Environment, 237, 121–133. https://doi.org/10.1016/j.agee.2016.12.016.

Wiering, N. P., Flavin, C., Sheaffer, C. C., Heineck, G. C., Sadok, W., & Ehlke, N. J. (2018). Winter hardiness and freezing tolerance in a hairy vetch collection. Crop Science, 58(4), 1594–1604. https://doi.org/10.2135/cropsci2017.12.0748.

Williams, S. M., & Weil, R. R. (2004). Crop cover root channels may alleviate soil compaction effects on soybean crop. Soil Science Society of America Journal, 68(4), 1403–1409. https://doi.org/10.2136/sssaj2004.1403.

Wittwer, R. A., Dorn, B., Jossi, W., & Van Der Heijden, M. G. A. (2017). Cover crops support ecological intensification of arable cropping systems. Scientific Reports, 7, 1–12. https://doi.org/10.1038/srep41911.

Yang, X. M., Drury, C. F., Reynolds, W. D., & Reeb, M. D. (2019). Legume cover crops provide nitrogen to corn during a three-year transition to organic cropping. Agronomy Journal, 111(6), 3253–3264. https://doi.org/10.2134/agronj2018.10.0652.

Zandvakili, O. R., Ebrahimi, E., Hashemi, M., Barker, A. V., & Akbari, P. (2017). The potential of green manure mixtures to provide nutrients to a subsequent lettuce crop. Communications in Soil Science and Plant Analysis, 48(19), 2246–2255. https://doi.org/10.1080/00103624.2017.1408819

Zhou, Y., Roosendaal, L., & Van Eerd, L. L. (2019). Increased nitrogen retention by cover crops: implications of planting date on soil and plant nitrogen dynamics. Renewable Agriculture and Food Systems, 1–10.

# SUMMARY IN ESTONIAN

## Vahekultuuride biomassi moodustamise ja lämmastiku sidumise võime ja mõju järelkultuuri saagile

Intensiivse põllumajandustootmisega kaasneb sageli liigne sünteetiliste väetiste ja taimekaitsevahendite kasutamine, mis põhjustab õhu ja vee saastumist, kasvuhoonegaaside teket ja bioloogilise mitmekesisuse vähenemist (Tilman et al., 2002; Wittwer et al., 2017). Lämmastik (N) on taimede kasvuks kõige olulisem toiteelement, mistõttu efektiivne taimekasvatus sõltub sageli suurest lämmastikväetiste sisendist (Rütting et al., 2018). Põllukultuuride poolt kasutamata jäänud N võib aga leostumise või lendumise teel mullast kaduma minna (Robertson & Vitousek, 2009). Suurimaks probleemiks on nitraatide leostumine, eriti sügis-talvisel perioodil taimkatteta põllul. Sattudes põhjavette, põhjustavad nitraadid veekogude eutrofeerumist ja veekvaliteedi halvenemist, kujutades ohtu ka inimese tervisele (Daryanto et al., 2017; De Notaris et al., 2018; Acharya et al., 2019). Kliimamuutuste tingimustes võib soojem talveperiood ja suurem sademete hulk suurendada toitainete leostumist ja taimikuta põldude vee-erosiooni (Iivonen et al., 2017; Peltonen-Sainio, 2018).

Vahekultuuride kasvatamist põhikultuuride vahelisel perioodil peetakse efektiivseks agrotehniliseks võtteks, mis tagab pinnakaetuse põhikultuurideta perioodil, kaitstes mulda N ja teiste toitainete kao eest ning parandades järgneva kultuuri varustatust toitainetega (Dabney et al., 2001; Wittwer et al., 2017; De Notaris et al., 2018; Sharma et al., 2018; Antosh et al., 2020). Vahekultuurid täidavad lisaks teisigi funktsioone: vähendavad umbrohtumust (Schultz et al., 2013; Cordeau et al., 2015; Jabran et al., 2015) ja haigustekitajaid (Sarwar et al. 1998; Smolinska & Horbowicz 1999; Larkin & Griffin, 2007), soodustavad tolmeldajate ja teiste kasulike putukate levikut (Nicholls & Altieri, 2013), mulla mikrobioloogilist mitmekesisust (Kim et al., 2020), parandavad mulla füüsikalisi ja keemilisi omadusi (Liu et al., 2005) ning soodustavad süsiniku sidumist vähendades seeläbi kasvuhoonegaaside teket (Poeplau & Don, 2015; Kaye & Quemada, 2017; Tribouillois et al., 2018).

Mõõduka kliimaga piirkondades käsitletakse talvise vahekultuurina liike, mis külvatakse hilissuvel või sügisel pärast põhikultuuri koristust ja viiakse mulda kevadel enne põhikultuuri külvi (Weil & Kremen, 2007; Justes et al., 2012). Talvituvad liigid tagavad pinnakaetuse sügis-talvisel perioodil ja moodustavad täiendava biomassi ning seovad lämmastikku ka järgneval kevadel. Mittetalvituvatest kultuuridest kasutatakse vahekultuuridena liike, mis moodustavad sügisel suure biomassi ja lagunevad enne järgmise kultuuri külvamist, võimaldades keskkonnasäästlikku kasutamist ka otsekülvi tingimustes (Lawley et al., 2011; 2012; Hashemi et al., 2013; Storr et al., 2020). Mittetalvituvate vahekultuuride puhul võib nende lagunemise tõttu N kadu olla aga tõenäolisem võrreldes talvituvate liikidega (White et al., 2017; Gollner et al., 2020).

Liblikõielised vahekultuurid seovad mügarbakterite abil õhulämmastikku (Gselman & Kramberger, 2008; Büchi et al., 2015), nende kitsas C:N suhe tagab kiire lagunemise mullas ja kättesaadavuse järgnevale kultuurile (Dabney et al., 2001; Acharya et al., 2019), vähendades N väetiste kasutamise vajadust (Campiglia et al., 2014; De Notaris et al., 2018; Zhou et al., 2019). Teised liigid, näiteks kõrrelised ja ristõielised, on aga efektiivsemad mulla N sidujad ja leostumise vähendajad (Tosti et al., 2012; Tuulos et al., 2014). Vahekultuuride liikide valikul arvestatakse eelkõige sobivust kohalikes kliimatingimustes kasvatamiseks (Bodner et al., 2010).

Vahekultuuride biomassi moodustamise võimest sõltub nende efektiivsus, sealhulgas N sidumise võime (Finney et al., 2016; Ruis et al., 2019; Antosh et al., 2020). Biomassi suurus sõltub vahekultuuri liigist, mulla- ja ilmastikutingimustest ning kasvuperioodi pikkusest (Lu et al., 2000). Põhjamaistes kliimatingimustes on oluline võimalikult varajane külviaeg, sest madal temperatuur ja niiskustase võivad biomassi vähendada (Lawson et al., 2015; Iivonen et al., 2017).

Vahekultuuride mõju järgneva põhikultuuri saagile võib sõltuda liigist, biomassi suurusest ja kvaliteedist, keskkonnateguritest ja kasutatavast agrotehnikast. N kättesaadavus järgnevale põhikultuurile sõltub peamiselt vahekultuuride keemilisest koostisest ja N mineraliseerumisest taimede lagunemisel (Campiglia et al., 2014). Kõrgema N sisalduse ja kitsama C:N suhte tõttu on liblikõielistel enamasti suurem positiivne mõju järgnevale kultuurile võrreldes teiste liikidega (Sainju & Singh, 1997; Vyn et al., 2000; Campiglia et al., 2014; Mancinelli et al., 2019). Vahekultuuride negatiivne mõju võib avalduda N immobilisatsiooni tõttu biomassi lagunemise ajal. See võib olla tingitud liiga laiast C:N suhtest, näiteks kõrrelistel vahekultuuridel hilises kasvufaasis (Sievers & Cook, 2018). Kuivades piirkondades võib negatiivne mõju olla põhjustatud ka vahekultuuride suurest veetarbimisest (Martinez-Feria et al., 2016; Handlířová et al., 2017; Krstić et al., 2018; Meyer et al., 2020).

Maailmas on talviste vahekultuuride kasvatamine muutunud järjest populaarsemaks, kuid Eesti tingimustes on see vähetuntud praktika. Samas võib see olla üheks võimaluseks aidata täita Euroopa komisjoni sätestatud Euroopa rohelise kokkuleppe strateegiat, mille põhieesmärgid on kliimamuutuste leevendamine ja majanduse keskkonnasäästlikumaks muutmine. Eesti tingimustesse sobivate vahekultuuride valikuks on vajalikud teadmised erinevate liikide kohta. Uurimistöö eesmärk oli uurida sügistalviste vahekultuuride biomassi moodustamise ja lämmastiku sidumise võimet ning hinnata vahekultuuride mõju järgnevale suviodra saagile.

## Doktoritöö eesmärgid

Võrrelda erinevate sügistalvisel perioodil kasvatatavate vahekultuuri liikide biomassi moodustamise ja N sidumise võimet (I).

Välja selgitada taliviki sobivus talvekindlaks vahekultuuriks Eesti tingimustes (I).

Hinnata külviaja mõju vahekultuuride biomassile ja N sidumisele (II).

Hinnata vahekultuuride mõju järgneva suviodra saagile (III).

## Eesmärkidest lähtuvalt püstitati järgmised hüpoteesid

Kesaredis, talivikk, talirüps, talirukis ja aleksandria ristik on Eesti tingimustes suure biomassi ja N sidumise võimega.

Talivikk on sarnaselt talirüpsile ja talirukkile Eesti kliimatingimustes talvituv vahekultuur.

Kesaredis ja aleksandria ristik kui mitte-talvituvad vahekultuurid on hea biomassi ja N sidumise võimega sügisel.

Vahekultuuride biomass ja N sidumine sõltuvad taimeliigist, külviajast ja ilmastikutingimustest kasvuperioodil.

Vahekultuuridel on positiivne mõju järgneva suviodra saagile.

## Metoodika

Põldkatsed viidi läbi katseaastatel 2016/2017, 2017/2018 ja 2018/2019 Eesti Taimekasvatuse Instituudis. Vahekultuurid (talirukis, talirüps, kesaredis, aleksandria ristik ja talivikk) külvati pärast talinisu koristust 2016. aastal 3. augustil ja 2017. aastal 3., 8., 14. ja 18. augustil ning 2018. aastal 3., 8., 13. ja 17. augustil. Vahekultuuride maapealne ja -alune biomass määrati sügisel vegetatsiooniperioodi (oktoobri) lõpus ning talvitunud liikidel (talirukis, taliraps ja talivikk) ka kevadel, vahetult enne vahekultuuride sissekündi ja suviodra külvi (4. mail 2017. aastal ja 7. mail 2018. ning 2019. aastal) ning väljendati kuivaines kg ha$^{-1}$. Oder koristati füsioloogilises küpsuses (30. augustil 2017, 6. augustil 2018 ja 15. augustil 2019). Kuivatatud ja sorteeritud terasaak väljendati 14% niiskustaseme juures kg ha$^{-1}$. Taimede süsiniku ja N üldsisaldus määrati Dumas kuivpõletusmeetodil CNS elementanalüsaatoriga Eesti Maaülikooli mullateaduse ja agrokeemia laboris.

Uuritud näitajate vahelist erinevust ($p < 0{,}05$) analüüsiti dispersioonanalüüsi meetodil statistikatarkvaraga Agrobase Generation II SQL (Agronomix Software, Inc., Winnipeg, Manitoba, CA, USA).

## Tulemused

Uurimistöö tulemusel selgus, et vahekultuuride biomass ja N sidumine nii sügisel kui ka kevadel sõltusid liigist, kasvuperioodi pikkusest ja ilmastikutingimustest, eelkõige efektiivsete temperatuuride summast. Vahekultuurid moodustasid 2017. ja 2018. aasta sügisel 2016. aastaga võrreldes suurema biomassi. Kesaredis ei talvitunud, kuid moodustas sügisel nii suurima maapealse kui ka juurte biomassi ja sidus kõige rohkem lämmastikku. Aleksandria ristik, mis samuti ei talvitunud, moodustas aga väikseima biomassi ja sidus väikseima koguse N. Aleksandria ristik oli ka põuatundlik, moodustades väikseima biomassi 2018. aastal, kui vahekultuuride külvile eelnes kuiv periood.

Lisaks talirukkile ja talirüpsile talvitus mõlemal aastal ka talivikk, mis oli suurima biomassi ja N sidumise võimega kevadel.

Kahel katseaastal läbiviidud vahekultuuride külviaegade katse näitas, et vahekultuuride biomass ja N kogus vähenesid külviaja hilinemisel ning vähenemine sõltus vahekultuuri liigist. Kõikidel külviaegadel oli suurima biomassi ja N sidumise võimega kesaredis. Kuigi talirukki biomass oli katses küllaltki madal, oli külviaja hilinedes biomassi vähenemine kõige väiksem.

Aastate keskmisena suurendasid vaid kesaredis ja talivikk usutavalt järgneva suviodra saaki. Teiste vahekultuuride puhul oli suviodra saak sarnane kontrollvariandile.

## Edasist uurimist vajavad teemad

Lisaks vahekultuuride üksikliikidele on vaja uurida vahekultuuri segus kasvatamist. Segude eelisteks võib olla suurem biomass, tõhusam N leostumise vähendamine ja parem N tagamine järgnevale kultuurile.

Vahekultuuride biomass ja N sidumine sõltuvad lisaks külviajale ka mulda viimise ajast, mistõttu on oluline uurida biomassi moodustamise ja N sidumise võimet ning mõju järelkultuuri saagile erinevate mulda viimise aegade korral.

Vahekultuuride poolt seotud lämmastikust võib osa leostumise ja lendumise tõttu kaduma minna. Seega on vaja uurida N kadu vahekultuuride kasvatamisel.

Minimeeritud mullaharimise ja otsekülvi tehnoloogia on muutunud järjest populaarsemaks, mistõttu on edaspidi oluline hinnata vahekultuuride kasvatamist nendes tingimustes.

Suurema biomassi ja N sidumise tagamiseks on vaja uurida vahekultuuride väetamise võimalusi sõnniku või teiste väetistega.

Vajalik on uurida vahekultuuride pikaajalist mõju mulla omadustele ja põhikultuuri saagile.

Vahekultuuride kasvatamise tasuvuse hindamiseks on vaja teha majanduslik analüüs.

Uurimistöö tulemused annavad olulist informatsiooni vahekultuuride sobivusest Eestis tingimustes, kuid ka teistes põhjamaistes piirkondades kasvatamisel, aidates kaasa keskkonnasäästliku põllumajandussüsteemi arendamisele.

# ACKNOWLEDGEMENTS

This PhD thesis would have never been accomplished without the support and assistance that I received from many people. I would like to express my gratitude to my supervisors, Dr Enn Lauringson, Dr Liina Talgre, and Dr Andres Mäe for their expertise, guidance and support throughout my PhD study.

My sincere gratitude is extended to all co-authors for their substantial contribution to publications presented in this research.

I am grateful to Karin Kauer for peer-reviewing the manuscript of my theses and providing valuable recommendations.

I would like to thank my colleagues from Estonian Crop Research Institute for their help. I greatly admire them all for being exceptionally passionate about their work. I am extremely grateful to Sirje Tamm for being always available; her positive attitude and invaluable contribution were essential for the success of this research. I wish to thank Anu Toe, Liina Kann and Terje Tähtjärv for being by my side and and supporting me. My sincere gratitude to Ilmar Tamm, whose help was always readily available, providing assistance with many aspects of my research. I would like to express gratitude to Lea Narits for the support and suggestions provided during my research and for the good company on conference trips. I wish to thank Anne Ingver for her professional advice, encouragement, and corrections that enhanced the value of the theses. I also acknowledge the valuable assistance with field operations provided by Oat, Barley, and Legume team members.

I am grateful to Andrus Lauringson for English language editing and Ülle Tamm for Estonian language editing of the thesis.

I greatly appreciate the support received from my friends. Special thanks to Liis Nurm for her constant support, laughs, and encouragement. I am thankful to my family for believing in me and encouraging me while working toward this achievement.

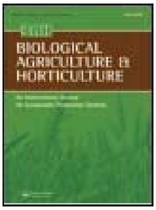
The research was supported by Estonian Ministry of Rural Affairs' project *Varieties suitable for organic cultivation in Estonia* (10.1-2/430 p.4;

PA1-RUP-026) and by *Designing of an agrotechnical system including evaluation of suitable catch crop species, their seed mixtures and their cultivation methods* (T170143PKTM).

# I

# ORIGINAL PUBLICATIONS

**Toom, M.**, Talgre, L., Mäe, A., Tamm, S., Narits, L., Edesi, L., Haljak, M., Lauringson, E. 2019. Selecting winter cover crop species for northern climatic conditions. Biological Agriculture and Horticulture, 35(4), 263–274.



Biological Agriculture & Horticulture
An International Journal for Sustainable Production Systems

ISSN: 0144-8765 (Print) 2165-0616 (Online) Journal homepage: https://www.tandfonline.com/loi/tbah20

# Selecting winter cover crop species for northern climatic conditions

Merili Toom, Liina Talgre, Andres Mäe, Sirje Tamm, Lea Narits, Liina Edesi, Merlin Haljak & Enn Lauringson

**To cite this article:** Merili Toom, Liina Talgre, Andres Mäe, Sirje Tamm, Lea Narits, Liina Edesi, Merlin Haljak & Enn Lauringson (2019): Selecting winter cover crop species for northern climatic conditions, Biological Agriculture & Horticulture, DOI: 10.1080/01448765.2019.1627908

**To link to this article:** https://doi.org/10.1080/01448765.2019.1627908

BIOLOGICAL AGRICULTURE & HORTICULTURE
https://doi.org/10.1080/01448765.2019.1627908

# Selecting winter cover crop species for northern climatic conditions

Merili Toom[a,b], Liina Talgre[b], Andres Mäe[c], Sirje Tamm[a], Lea Narits[a], Liina Edesi[d], Merlin Haljak[a] and Enn Lauringson[b]

[a]Department of Plant Breeding, Estonian Crop Research Institute, Jõgeva, Estonia; [b]Chair of Crop Science and Plant Biology Institute of Agricultural and Environmental Sciences, Estonian University of Life Sciences, Tartu, Estonia; [c]Department of Plant Protection, Estonian Crop Research Institute, Jõgeva, Estonia; [d]Department of Agrotechnology, Estonian Crop Research Institute, Jõgeva, Estonia

**ABSTRACT**

The use of cover crops in crop rotations provides a wide range of ecosystem services including protection of the soil from nutrient loss. The objective of this study was to determine the suitability of winter cover crop species for Estonian conditions. Field trials with cover crop species winter rye (*Secale cereale* L), winter turnip rape (*Brassica rapa* spp. *oleifera* L.), forage radish (*Raphanus sativus* L. var. longipinnatus), hairy vetch (*Vicia villosa* Roth) and berseem clover (*Trifolium alexandrinum* L.) were carried out during the period 2016–2018 at the Estonian Crop Research Institute. Biomass production, nitrogen (N), phosphorous (P), potassium (K), calcium (Ca) and magnesium (Mg) accumulation were evaluated. The results under northern European conditions indicated that together with winter rye and winter turnip rape, hairy vetch survived the winters. By the spring, hairy vetch had produced the most biomass and accumulated the highest amount of N, compared with the other species. Winter turnip rape showed the greatest uptake of P, K and Ca in the spring. In both years, forage radish presented the highest biomass and nutrient accumulation in the autumn. After winterkill and decomposition in the spring, the forage radish left holes in the ground, which could be a beneficial characteristic, particularly in no-tillage farming systems. Berseem clover did not produce remarkable biomass in the autumn and was killed by the first frosts and was therefore considered unsuitable as an overwintering cover crop for northern latitudes.

**ARTICLE HISTORY**
Received 25 June 2018
Accepted 3 June 2019

**KEYWORDS**
Winter cover cropping; northern climate; biomass production; nutrient uptake

## Introduction

The inclusion of cover crops into crop rotations is considered a promising option for sustainable agricultural production (Robačer et al. 2016). Cover crops (also called catch crops) are cultivated between periods of cash crop production, and they can protect the soil from loss of nutrients (Dabney et al. 2001; Thorup-Kristensen et al. 2003). In addition, cover crops can positively influence beneficial soil organisms, like earthworms (Roarty et al. 2017), and are often associated with greater soil microbial biomass and activity (Piotrowska-Długosz and Wilczewski 2014; Chavarría et al. 2016). The beneficial effects also include the suppression of weeds (Madsen et al. 2016) and the control of soilborne plant pathogens (Sarwar et al. 1998; Smolinska and Horbowicz 1999). Cover crops also increase soil organic matter (Ding et al. 2006) and soil organic carbon levels or reduce their rate of depletion (Kuo et al. 1997). Studies have shown that cover

**CONTACT** Merili Toom merili.toom@etki.ee Estonian Crop Research Institute, Jõgeva 48309, Estonia

crops can significantly affect physical soil properties in terms of improved soil structure (Chen and Weil 2010) and increased aggregate stability (Liu et al. 2005).

Leguminous cover crops can supply additional N through biological nitrogen fixation from the atmosphere (Askegaard and Eriksen 2008; Büchi et al. 2015; Li et al. 2015), whereas non-leguminous species have been found to be very effective in taking up mineral N from the soil (Kramberger et al. 2010). After incorporation into the soil, major parts of the nutrients accumulated by the cover crops can be reused by the subsequent cash crop (Thorup-Kristensen et al. 2003). Due to their usually higher N concentrations and lower C: N ratios, legumes are expected to make N available more rapidly after their incorporation to the soil (Li et al. 2015). Nutrient input by cover crops is especially important in organic farming systems where the use of synthetic fertilisers is not allowed. As organic production in Estonia has grown in recent years, the interest in growing cover crops has also increased. The use of short-term cover crops that are sown in the autumn after main crop harvest is considered to be an effective strategy to maintain soil fertility. In this way, the cover crops can be used in rotations more frequently and at a lower cost compared with green manures that are grown during the whole growing season (Thorup-Kristensen et al. 2012). For sufficient nutrient accumulation, in northern regions with short autumns, it is important to choose species that are capable of producing high amounts of biomass in the short period between the cash crops.

Estonia is located in Northern Europe, on the eastern coast of the Baltic Sea, in the transition zone between maritime and continental climate. Mild and moist maritime, and cold and dry continental air masses are alternating during a whole cold season and therefore, a great variability of weather conditions in the winter is typical for the region (Jaagus 1997). The growth period of cover crops after cash crop harvest remains short; therefore, the selection of species is limited. Most of the research in Estonia has focused on autumn cover crops that are sown after the harvest of the cash crop in early autumn and then incorporated in the soil before the frosts (Talgre et al. 2011). Growing over wintering cover crops is a relatively new practice in Estonia. The only experiments with over wintering crops in the region have been conducted with winter rye (*Secale cereale* L.), winter oilseed rape (*Brassica napus* L. var. *oleifera*) and ryegrass (*Lolium perenne* L.). They focused on understanding whether these species were good for weed suppression or could enhance soil physical and chemical properties and cash crop yield (Sánchez de Cima et al. 2015; Madsen et al. 2016; Sánchez de Cima 2016).

Forage radish (*Raphanus sativus* L. var. *longipinnatus)*, hairy vetch (*Vicia villosa* Roth), berseem clover (*Trifolium alexandrinum* L.), turnip rape *(Brassica rapa spp. oleifera* L.) and winter rye are cover crop species that have been used worldwide. To integrate these species as cover crops into Estonian crop rotations, region-specific information about their performance is needed. Winter turnip rape and winter rye are both adapted to a cold climate (Lepajõe 1982; Mäkelä et al. 2011). The primary benefit of rye is its rapid growth in cool weather and deep fibrous root system, which provides soil cover and protection against erosion (Sarrantonio and Gallandt 2003). Winter turnip rape is a suitable crop for low-input production and considered to be less sensitive to damage caused by weather and pests compared with winter oilseed rape (Mäkelä et al. 2011).

Forage radish has received attention due to its large root system. It is a widely studied cover crop grown in different parts of the USA and has been observed to successfully suppress weeds (Lawley et al. 2011; 2012), increase soil phosphorous levels (White and Weil 2010) and alleviate soil compaction (Chen and Weil 2010). Forage radish has a potential for mitigating against soil C depletion through enhancement of soil organic matter (Wang et al. 2017). Research has also shown yield increase of the succeeding cash crop (Jahanzad et al. 2017).

Hairy vetch is considered as one of the few annual legumes with characteristics that include cold tolerance, fast growth and high N fixation capacity (Wilke and Snapp 2008). Brandsæter et al. (2008) reported hairy vetch to be suitable in northern climatic conditions and pointed out that for maximum winter survival it is important to choose winter hardy cultivars.

Berseem clover is grown as a summer annual or winter annual legume. Spring seeded berseem clover has shown to have good forage potential (Fraser et al. 2004; Ross et al. 2009) and proved to be suitable pre-crop for winter cereals (Tamm et al. 2016). As berseem clover is frost sensitive, it has also been used as a winterkilled cover crop before nitrogen-demanding cash crops (Clark 2007).

The aim of the present research was to evaluate the biomass production and nutrient accumulation of different cover crop species in Estonian conditions. In addition to nitrogen (N) and phosphorous (P) that are commonly studied, the uptake of potassium (K), calcium (Ca) and magnesium (Mg) was also included. These three elements carry essential functions in plants, such as stomatal regulation by K, chlorophyll synthesis by Mg and root extension by Ca (Wendling et al. 2016).

## Materials and methods

A field experiment was conducted at Estonian Crop Research Institute, located in the eastern part of Estonia (58° 44′ 59.41″ N, 26°24′ 54.02″ E) during the period of 2016–2018. The trial site is situated in a climate zone with an average annual temperature of 5.3°C and precipitation of 670 mm (Estonian weather service 2018). The soil type in the experimental area was Cambic Phaeozem (Loamic) soil (IUSS 2015). The soil characteristics were as follows: $pH_{KCl}$, 6.9; P, 104 mg $kg^{-1}$; K, 195 mg $kg^{-1}$; Ca, 3700 mg $kg^{-1}$; Mg, 510 mg $kg^{-1}$; $C_{org}$, 2.1%; and $N_{tot}$, 0.16%. The organic carbon concentration ($C_{org}$) was determined by the Tjurin method (Tjurin 1937). Total nitrogen ($N_{tot}$) was measured after Kjeldahl digestion (van Reeuwijk 2002). The concentrations of the plant-available P, K, Ca, and Mg in the soil were extracted by the ammonium lactate (AL) method (Egnér et al. 1960). The trial was not conducted in a certified organic area, but the land was managed using organic practices without synthetic fertilisers and pesticides. The preceding crop of this trial was winter wheat. Before the winter wheat, a summer cover crop mixture of buckwheat (*Fagopyrum esculentum* Moench), phacelia (*Phacelia tanacetifolia* Benth) and field pea (*Pisum sativum* L.) was incorporated into the soil to provide fertilisation. Precipitation and air temperature were measured daily at a meteorological station located near the field trial site.

The cover crops were sown on August 3 in both years, immediately, after harvest of winter wheat *(Triticum aestivum* L.*)*. The soil was disc-harrowed before sowing the cover crops. Cover crops were sown with Hege 80 plot seed drill (row spacing 12.5 cm). The seeds of the leguminous species, berseem clover and hairy vetch, were not inoculated with specific bacteria. The seeding rates for the cover crops were 10 kg $ha^{-1}$ for forage radish (Tillage radish®) and winter turnip rape (cv. 'Largo'), 50 kg $ha^{-1}$ for hairy vetch (cv. 'Villana'), 15 kg $ha^{-1}$ for berseem clover (cv. 'Akenaton'), 180 kg $ha^{-1}$ for cereal rye (cv. 'Sangaste'). Plots were arranged in a randomised complete block design with four replications, each plot with an area of 4 × 6 m.

Cover crop above- and below-ground biomass samples were collected from four randomly placed squares of 0.25 $m^2$ in each plot on 17 and 24 October in 2016 and 2017, respectively. The biomass of the over-wintered species was measured also in the following spring before incorporating the cover crops into the soil (on 4 and 7 May in 2017 and 2018, respectively), prior to the establishment of spring barley. For assessment, the above-ground biomass was cut at the ground level, and to measure the below-ground biomass, the soil within the squares was dug to a depth of 25 cm, and the roots were washed on a sieve (mesh size 0.5 mm). Above- and below-ground biomass values were added for assessment of total biomass production. For the forage radish, whole plants were dug from the soil, after which the roots were separated from shoots and washed free from soil. A mould-board plough (Kverneland) was used to incorporate the cover crops into the soil.

Dry matter (DM) yield was determined after drying the material at 65°C to a constant weight. The samples were milled for elemental analysis. Nutrient concentrations of the biomass were determined in Soil Science and Agrochemistry laboratory at the Estonian University of Life Sciences. Plant total N concentration was analysed by the Dumas Combustion method on a VarioMAX CNS elemental analyser ('Elementar', Germany). Acid digestion by sulphuric acid solution (van Reeuwijk 2002) was used to determine the total P, K, Ca and Mg concentration in plant material.

Statistical analyses were carried out by statistical package Agrobase $20^{TM}$. One-way analysis of variance (ANOVA) was used to test the differences of biomass, N, P, K, Ca and Mg accumulation.

The two-way ANOVA was used for calculations of biomass, N, P, K, Ca and Mg accumulation. Least significant differences were calculated for biomass, N, P, K, Ca and Mg accumulation, in order to evaluate the statistical significance of differences. All characteristics of cover crops were calculated as the average of four replications. Cover crop species, years, and blocks were considered as fixed effects.

## Results and discussion

### Weather conditions

The weather conditions data is presented in Table 1. In 2016, the period of temperatures below 0°C started on 1 November (22 days earlier than average) and ended on 15 March (9 days earlier than average). The average temperature in the winter months (November–March) 2016/2017 was −1.5°C. The lowest temperature in trial area was recorded on 7 January (−21.8°C) with only a thin cover of snow.

In the winter 2017/18 the average daily air temperature dropped below 0°C on 7 of January (44 days later than average) and temperature increased again above 0°C on 1 April (9 days later than average). The coldest period in Estonia was from 21 February to 5 April. In the trial area, the lowest registered temperature was −24.3°C. During this period the plants were protected by snow cover (about 15 cm) which melted by 5 April. The average temperature of winter 2017–2018 was −2.6°C. Both winters were warmer than the long-term average (−3.9°C).

### Biomass production and nutrient accumulation in the autumn

The growing period for the cover crops in the autumn 2016 was 68 days with the sum of effective temperatures (ETS) 546°C (Table 1). In 2017 there were 77 days with an ETS of 570°C. In the autumn, the variation in biomass and nutrient accumulation was significantly influenced by species, years and

Table 1. Average air temperature and precipitation per month, monthly sums of effective air temperatures > +5 °C (ETS) during the experimental period and long-term average (1922–2017).

| Month | Average air temperature per month (°C) | Long-term average temperature per month (°C) | Precipitation per month (mm) | Long-term average precipitation per month (mm) | ETS per month (°C) | Long-term average ETS per month (°C) |
|---|---|---|---|---|---|---|
| **2016/2017** | | | | | | |
| August | 15.7 | 15.3 | 180 | 89 | 332.3 | 320.4 |
| September | 11.9 | 10.6 | 20 | 66 | 207.9 | 176.9 |
| October | 3.9 | 5.3 | 52 | 66 | 25.9 | 60.4 |
| November | −1.2 | 0.3 | 83 | 56 | 1.9 | 8.0 |
| December | −0.3 | −3.7 | 26 | 47 | 0.8 | 1.0 |
| January | −3.5 | −6.5 | 33 | 41 | 0 | 0.066 |
| February | −3.2 | −6.8 | 31 | 31 | 0 | 0.2 |
| March | 1.0 | −3.0 | 37 | 31 | 2.7 | 2.9 |
| April | 2.8 | 3.8 | 52 | 36 | 24.0 | 46.2 |
| May | 9.6 | 10.4 | 8 | 50 | 13.0[a] | |
| **2017/2018** | | | | | | |
| August | 15.9 | 15.3 | 83 | 89 | 337.0 | 320.4 |
| September | 11.8 | 10.6 | 86 | 66 | 205.9 | 176.9 |
| October | 4.8 | 5.3 | 107 | 66 | 53.4 | 60.4 |
| November | 2.1 | 0.3 | 47 | 56 | 4.8 | 8.0 |
| December | 0.1 | −3.7 | 80 | 47 | 0 | 1.0 |
| January | −2.4 | −6.5 | 35 | 41 | 0 | 0.066 |
| February | −8.7 | −6.8 | 25 | 31 | 0 | 0.2 |
| March | −4.3 | −3.0 | 21 | 31 | 0 | 2.9 |
| April | 6.2 | 3.8 | 52 | 36 | 73.5 | 46.2 |
| May | 14.5 | 10.4 | 17 | 50 | 39.3[a] | |

Notes: [a]ETS until ploughing cover crops into the soil

**Table 2.** Analyses of variance for biomass and nutrient accumulation depending on species, year and their interaction during the autumn.

| Characteristic | Source of variation | df | SS | MS | *F* | *p* |
|---|---|---|---|---|---|---|
| Biomass | Species | 4 | 23,837,346.850 | 5,959,336.713 | 125.18 | 0.001 *** |
| | Year | 1 | 2,522,550.625 | 2,522,550.625 | 52.99 | 0.001 *** |
| | Species x year | 4 | 2,262,263.250 | 565,565.813 | 11.88 | 0.001 *** |
| Nitrogen | Species | 4 | 17,698.269 | 4424.567 | 106.58 | 0.001 *** |
| | Year | 1 | 3301.489 | 3301.489 | 79.53 | 0.001 *** |
| | Species x year | 4 | 1886.884 | 471.721 | 11.36 | 0.001 *** |
| Phosphorous | Species | 4 | 780.584 | 195.146 | 174.27 | 0.001 *** |
| | Year | 1 | 127.449 | 127.449 | 113.81 | 0.001 *** |
| | Species x year | 4 | 85.959 | 21.490 | 19.19 | 0.001 *** |
| Potassium | Species | 4 | 50,682.204 | 12,670.551 | 187.45 | 0.001 *** |
| | Year | 1 | 4562.496 | 4562.496 | 67.50 | 0.001 *** |
| | Species x year | 4 | 9032.887 | 2258.222 | 33.41 | 0.001 *** |
| Calcium | Species | 4 | 10,234.139 | 2558.535 | 214.66 | 0.001 *** |
| | Year | 1 | 509.796 | 509.796 | 42.77 | 0.001 *** |
| | Species x year | 4 | 946.827 | 236.707 | 19.86 | 0.001 *** |
| Magnesium | Species | 4 | 131.424 | 32.856 | 100.80 | 0.001 *** |
| | Year | 1 | 119.025 | 119.025 | 365.15 | 0.001 *** |
| | Species x year | 4 | 58.513 | 14.628 | 44.88 | 0.001 *** |

Notes: df – degrees of freedom; SS – sums of squares; MS – mean squares.
*F* – treatment mean square/error mean square.
*p* – significance probability value.
*** – significant at $p < 0.001$.

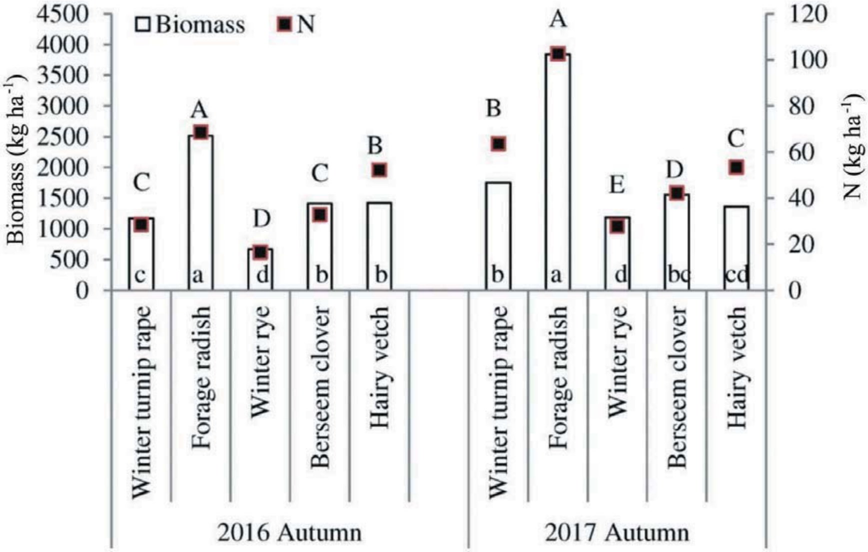


**Figure 1.** Biomass (above- and below ground) and nitrogen content of cover crops (kg ha$^{-1}$, dry matter) in the autumn 2016 and 2017. Within years, bars marked with different letters are significantly different ($p < 0.05$; ANOVA, Fisher LSD test) (lowercase letter – biomass; capital letter – N).

their interaction (Table 2). By the end of the growing season in the autumn (end of October), forage radish produced the highest DM yield (Figure 1). In 2016 it was 2515 kg ha$^{-1}$ (56% as roots), and in 2017 it was 3841 kg ha$^{-1}$ (48% as roots). Wang et al. (2017) reported similar root percentage (36–55%)

of forage radish cover crop. The biomass of winter turnip rape was 1169 kg ha$^{-1}$ (35% roots) and 1752 (25% roots) in 2016 and 2017, respectively.

Winter rye had the lowest biomass (667 kg ha$^{-1}$) in 2016, principally due to infection by leaf rust (*Puccinia recondita)*, which caused leaf loss. Although in 2017 winter rye still had the lowest biomass (1188 kg ha$^{-1}$) compared with other species, it was higher than in the previous year and had greater proportion of roots (37% compared to 27% in 2016). De Baets et al. (2011) noted that fibrous roots of grass cover crops were especially effective for protecting the topsoil against water erosion. The higher biomass yields in 2017 were likely associated with warmer temperatures during two weeks after cover crop emergence. Another reason was that in 2016 the vegetation period ended with the first night frosts on 5 October, whereas in 2017 vegetation period continued until 20 October.

According to the assessment in the autumn, the biomass production of legume species was less influenced by differences in weather conditions in 2016 and 2017. The biomass of hairy vetch was 1422 kg ha$^{-1}$ in 2016 and 1362 kg ha$^{-1}$ in 2017. The biomass of berseem clover was 1415 kg ha$^{-1}$ in 2016 and 1556 kg ha$^{-1}$ in 2017. Visual observations, registered desiccation of berseem clover plants when air temperature dropped below 0°C. Forage radish was more resistant to the cold; the shoots were frost damaged when air temperature was persistently below −4°C, but the roots were not damaged.

The nutrient values of a cover crop depend on the total amount of biomass produced and the nutrient concentration (accumulation) in the plant tissue. Several researchers found non-leguminous cover crops to be very effective in taking up mineral N from the soil during the autumn-winter period (Thorup-Kristensen 2001; Kramberger et al. 2010). In the autumn of both 2016 and 2017, forage radish accumulated the highest amount of N (70 and 103 kg ha$^{-1}$, respectively) compared with the other species. (Figure 1). As forage radish is winter-killed, some of the nutrients, especially N, may be leached (Thomsen et al. 2016). To prevent N leaching, forage radish has been recommended as a suitable cover crop before early-sown subsequent summer crops. The accumulation of N differed between the legume species. Hairy vetch contained significantly more N (52 kg ha$^{-1}$ and 53 kg ha$^{-1}$ in 2016 and 2017, respectively) than berseem clover (33 kg ha$^{-1}$ and 42 kg ha$^{-1}$ in 2016 and 2017, respectively) (Figure 1). Studies have indicated that cover crops are able to utilise moderately labile P and enhance the proportion of labile P fractions in the soil (Soltangheisi et al. 2018). In the study reported here, forage radish accumulated the most P by the autumn; 11 kg ha$^{-1}$ and 19 kg ha$^{-1}$ in 2016 and 2017, respectively (Figure 2). Pavinato et al. (2008) reported that radish with higher concentrations of malic acid and P was the most efficient of the cover crop species tested under conditions of increased availability of soil P. White and Weil (2010) reported that after three years of forage radish cover crop cultivation in no-till cropping system, soil P concentration increased at the site where forage radish cycled large quantities of P. They found that the soil surrounding radish root holes had greater soil P values than the soil without radish.

In the autumn, forage radish presented the highest accumulation of K, Ca and Mg. In 2016, it had accumulated 83 kg ha$^{-1}$ K, 39 kg ha$^{-1}$ Ca, 3 kg ha$^{-1}$ Mg. In 2017, the nutrient accumulation was 161 kg ha$^{-1}$ K, 64 kg ha$^{-1}$ Ca and 11 kg ha$^{-1}$ Mg. In both years, berseem clover showed higher accumulation of K (42–44 kg ha$^{-1}$) (significant in 2016 only) and Ca (19 kg ha$^{-1}$) compared with hairy vetch (33–35 kg ha$^{-1}$ K; 10–12 kg ha$^{-1}$ Ca).

### *Biomass and nutrient accumulation in the following spring*

The cover crops that survived the winters in the experimental period were hairy vetch, winter turnip rape and winter rye. In both years, majority of the forage radish roots had decomposed by the end of April and left holes in the soil surface. Chen and Weil (2010) reported that the channels created by the roots can improve water infiltration, surface drainage and soil warming. Due to the rapid biomass production in the autumn and rapid residue decomposition in the spring, forage radish can be recommended for farmers who want to take advantage of autumn cover crops and avoid excessive spring crop residues. It has also been recommended for organic farmers who are using reduced pre-plant tillage (Lawley et al. 2011; Laweley et al. 2012).

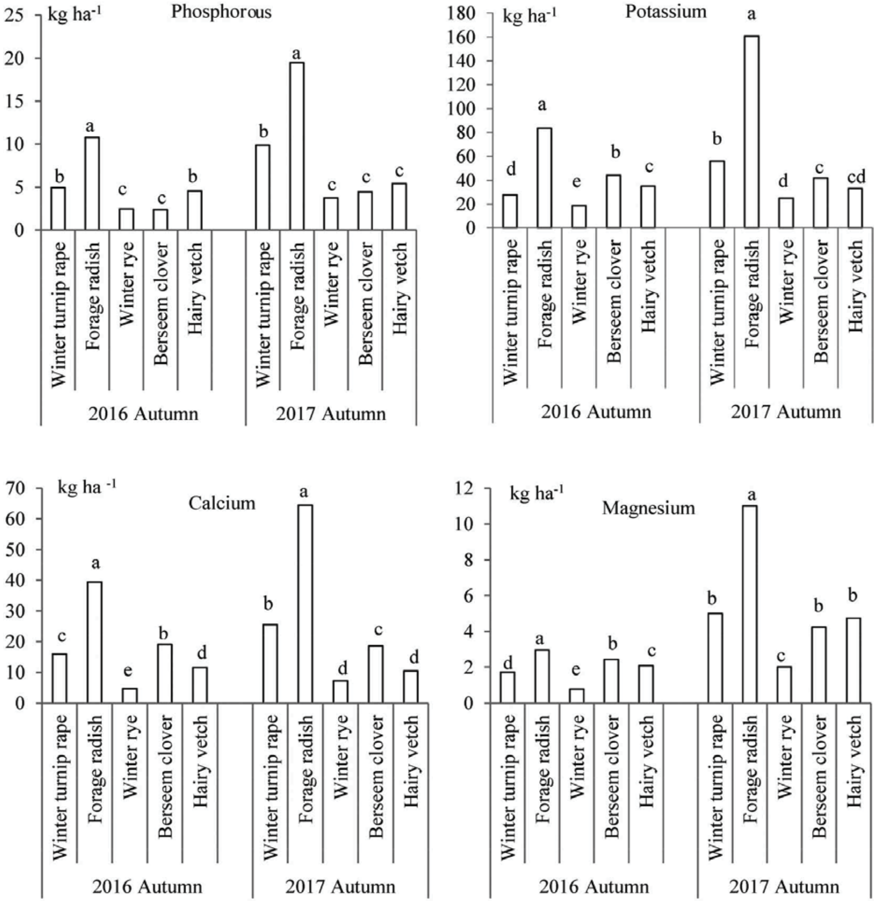


**Figure 2.** The nutrient (P, K, Ca, Mg) content of cover crops (kg ha$^{-1}$, dry matter) in the autumn 2016 and 2017. Within years, bars marked with different letters are significantly different ($p < 0.05$; ANOVA, Fisher LSD test).

The influence of species for biomass and nutrient accumulation was significant. Species and year interaction remained non-significant for biomass and was significant for most of the nutrients, except nitrogen (Table 3). Biomass yields in the spring of 2017 were much lower compared with those in the spring 2018, probably because the sum of effective temperatures for cover crop growth in the spring 2017 (39°C) was much lower than that in 2018 (112.8°C). The plant vegetation period (average daily temperature permanently > +5 °C) in the spring 2017 started on the 1 May, which was 9 days later than long-term average (1922–2015). As an average of two years, hairy vetch was the best accumulator of biomass in the spring (Figure 3). The biomass of hairy vetch, winter turnip rape and winter rye in 2017 was 1731 kg ha$^{-1}$, 1531 kg ha$^{-1}$ and 1009 kg ha$^{-1}$, respectively, which was about 300 kg ha$^{-1}$ higher than in that in the autumn.

In the spring 2018, with favourable growing conditions, cover crops produced greater amounts of biomass compared with that in the autumn. Hairy vetch had rapid regrowth and produced the largest amount of biomass of 2689 kg ha$^{-1}$, which was 1327 kg ha$^{-1}$ more than in the previous

**Table 3.** Analyses of variance for biomass and nutrient accumulation depending on species, year and their interaction in the spring.

| Characteristic | Source of variation | df | SS | MS | *F* | *p* |
|---|---|---|---|---|---|---|
| Biomass | Species | 2 | 1,783,399.693 | 891,699.847 | 20.64 | 0.001 *** |
| | Year | 1 | 5,513,483.760 | 5,513,483.760 | 127.64 | 0.001 *** |
| | Species x year | 2 | 55,743.960 | 27,871.980 | 0.65 | 0.5385 ns |
| Nitrogen | Species | 2 | 4146.318 | 2073.159 | 47.80 | 0.001 *** |
| | Year | 1 | 2042.415 | 2042.415 | 47.09 | 0.001 *** |
| | Species x year | 2 | 54.768 | 27.384 | 0.63 | 0.5454 ns |
| Phosphorous | Species | 2 | 49.291 | 24.645 | 34.08 | 0.001 *** |
| | Year | 1 | 54.000 | 54.000 | 74.67 | 0.001 *** |
| | Species x year | 2 | 7.458 | 3.729 | 5.16 | 0.0198 *** |
| Potassium | Species | 2 | 2559.198 | 1279.599 | 47.41 | 0.001 *** |
| | Year | 1 | 8709.660 | 8709.660 | 322.72 | 0.001 *** |
| | Species x year | 2 | 1118.373 | 559.186 | 20.72 | 0.001 *** |
| Calcium | Species | 2 | 1035.548 | 517.774 | 146.60 | 0.001 *** |
| | Year | 1 | 1501.002 | 1501.002 | 425.00 | 0.001 *** |
| | Species x year | 2 | 296.781 | 148.390 | 42.02 | 0.001 *** |
| Magnesium | Species | 2 | 46.923 | 23.462 | 90.67 | 0.001 *** |
| | Year | 1 | 132.070 | 132.070 | 510.42 | 0.001 *** |
| | Species x year | 2 | 29.543 | 14.772 | 57.09 | 0.001 *** |

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

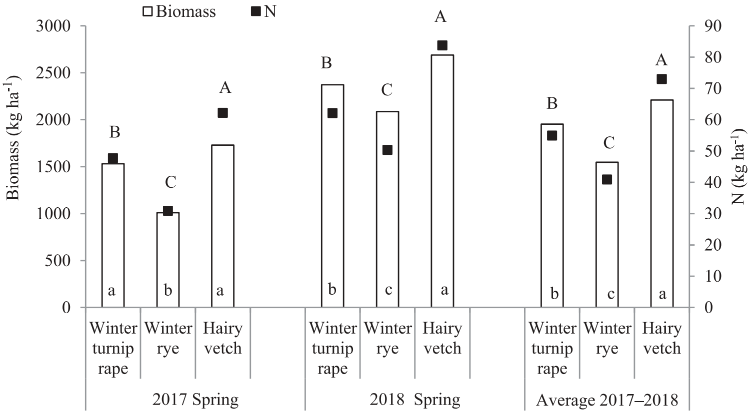


**Figure 3.** Biomass and nitrogen content of cover crops (kg ha$^{-1}$, dry matter) in the spring 2017 and 2018 and the averages of the two years. Within years, bars marked with different letters are statistically significantly different ($p < 0.05$; ANOVA, Fisher LSD test) (lowercase letter – biomass; capital letter – N).

autumn. The biomass of winter turnip rape was 2372 kg ha$^{-1}$ (620 kg ha$^{-1}$ higher than in the autumn). The biomass of winter rye was 2086 kg ha$^{-1}$ (898 kg ha$^{-1}$ more compared with that in the autumn). In the springs of 2017 and 2018, hairy vetch accumulated more N than non-leguminous species due to greater biomass and N concentration (62 kg ha$^{-1}$ and 84 kg ha$^{-1}$ N, respectively). Studies have found hairy vetch to accumulate much more biomass and N, if allowed to grow longer and be terminated later in the spring. However, very late termination of the cover crop may reduce the yield of the following crop, particularly in northern climatic conditions with the short growing season. In Estonia, spring cereals such as barley are commonly sown at the end of April or in early May; therefore, preceding cover crops have short time for biomass production.

To provide sufficient available N for a high N demanding crop, such as corn, a hairy vetch cover crop would need to produce at least 4000–4500 kg ha$^{-1}$ (Teasdale et al. 2004; Mirsky et al. 2017). Mirsky et al. (2017) concluded that in northern cropping systems, hairy vetch may not be the best choice as a source of N for corn, but they recommended it for systems where the cash crops are planted later e.g. vegetables. The benefits of cover crops in vegetable systems have been confirmed by many authors (Wang et al. 2008; Robačer et al. 2016).

Winter turnip rape accumulated great amounts of N in both years; 48 kg ha$^{-1}$ and 62 kg ha$^{-1}$ in 2017 and 2018, respectively. Studies in Finland confirmed that a winter turnip rape cover crop was effective for scavenging mineral nitrogen from the soil in a cold and humid climate (Tuulos et al. 2015). The N accumulation by rye was the lowest; 31 kg ha$^{-1}$ and 50 kg ha$^{-1}$ in 2017 and 2018, respectively. Due to high C: N ratio and the threat of subsequent crop yield loss due to N immobilisation, rye has been recommended to be used in mixture with hairy vetch (Sainju et al. 2005).

The P uptake by cover crops in the spring 2017 ranged from 5 kg ha$^{-1}$ for winter rye to 7 kg ha$^{-1}$ for winter turnip rape. K, Ca and Mg accumulation were lower for winter rye, whereas the accumulation of nutrients by winter turnip rape and hairy vetch did not differ significantly (Figure 4).

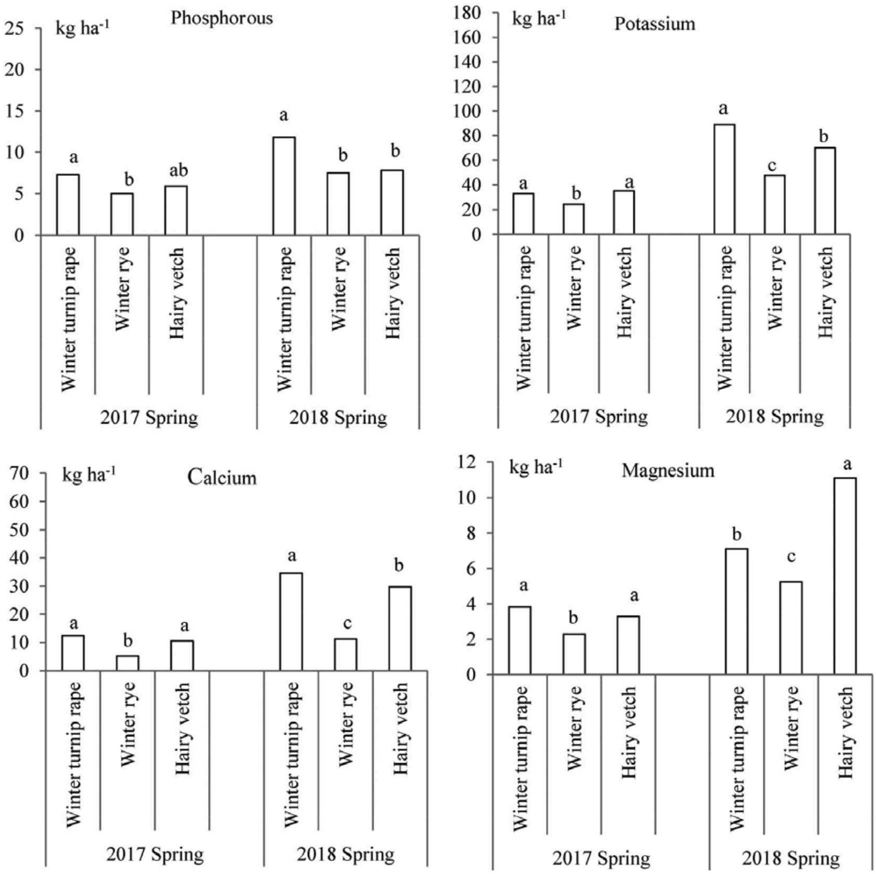


**Figure 4.** The nutrient (P, K, Ca, Mg) content of cover crops (kg ha$^{-1}$, dry matter) in 2017 and 2018 spring. Within years, bars marked with different letters are statistically significantly different ($p < 0.05$; ANOVA, Fisher LSD test).

As an average of two years, winter turnip rape proved to be the best accumulator of P, K and Ca, due to higher concentrations of these nutrients in the biomass (Figure 4). Compared with the other species, hairy vetch accumulated, as an average over the two years, higher amounts of Mg.

## Conclusion

It was concluded that all of the species tested, except berseem clover, could successfully be used as winter cover crops in northern climatic conditions. By the spring, hairy vetch had accumulated the most biomass and N. The other leguminous crop, berseem clover, was killed in the autumn by the first frosts. Although forage radish was killed in the winter, it produced the largest biomass and accumulated the highest amounts of nutrients in the autumn. Winter turnip rape was the most efficient cover crop in terms of binding P, K and Ca in the spring. However, in the autumn, the values for biomass production and nutrient accumulation by the winter turnip rape were lower than those for forage radish. Winter hardy species, such as winter turnip rape, hairy vetch and winter rye, continue to capture nutrients until they are terminated in the spring and are therefore recommended to be more suitable for cultivation before cash crops that are established later in the spring.

## Disclosure statement

No potential conflict of interest was reported by the authors.

## Funding

This work was supported by the Estonian Ministry of Rural Affairs [T170143PKTM];

## References

Askegaard M, Eriksen J. 2008. Residual effect and leaching of N and K in cropping systems with clover and ryegrass catch crops on a coarse sand. Agric Ecosyst Environ. 123:99–108.

Brandsæter LO, Heggen H, Riley H, Stubhaug E, Henriksen TM. 2008. Winter survival, biomass accumulation and N mineralization of winter annual and biennial legumes sown at various times of year in northern temperate regions. Eur J Agron. 28:437–448.

Büchi L, Gebhard CA, Liebisch F, Sinaj S, Ramseier H, Charles R. 2015. Accumulation of biologically fixed nitrogen by legumes cultivated as cover crops in Switzerland. Plant Soil. 393:163–175.

Chavarría DN, Verdenelli RA, Serri DL, Restovich SB, Andriulo AE, Meriles JM, Vargas-Gil S. 2016. Effect of cover crops on microbial community structure and related enzyme activities and macronutrient availability. Eur J Soil Biol. 76:74–82.

Chen G, Weil RR. 2010. Penetration of cover crop roots through compacted soils. Plant Soil. 331:31–43.

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

Dabney SM, Delgado JA, Reeves DW. 2001. Using winter cover crops to improve soil and water quality. Commun Soil Sci Plant Anal. 32:1221–1250.

De Baets S, Poesen J, Meersmans J, Serlet L. 2011. Cover crops and their erosion-reducing effects during concentrated flow erosion. Catena. 85:37–244.

Ding G, Liu X, Herbert S, Novak J, Amarasiriwardena D, Xing B. 2006. Effect of cover crop management on soil organic matter. Geoderma. 130:229–239.

Egnér H, Riehm H, Domingo WR. 1960. Untersuchungen éber die chemische bodenanalyse als grundlage fér die Beurteilung des Nührstoffzustandes der Bäden. II. Chemische Extractionsmethoden zur Phosphor- und Kaliumbestimmung. Kungliga Lantbrukhägskolans Annaler. (in Germany).

Estonian weather service. 2018. Estonia (EE). [accessed 2018 Apr 4]. http://www.ilmateenistus.ee/kliima/kliimanormid/sademed/?lang=en.

Fraser J, McCartney D, Najda H, Mir Z. 2004. Yield potential and forage quality of annual forage legumes in Southern Alberta and northeast Saskatchewan. Can J Plant Sci. 84:143–155.

[IUSS] Working Group WRB. 2015. World reference base for soil resources 2014, update 2015 international soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. Rome: FAO.

Jaagus J. 1997. The impact of climate change on the snow cover pattern in Estonia. Clim Change. 36:65–77.

Jahanzad E, Barker AV, Hashemi M, Sadeghpour A, Eaton T, Park Y. 2017. Improving yield and mineral nutrient concentration of potato tubers through cover cropping. Field Crops Res. 212:45–51.

Kramberger B, Gselman A, Janzekovic M, Kaligaric M, Bracko B. 2010. Effects of cover crops on soil mineral nitrogen and on the yield and nitrogen content of maize. Eur J Agron. 31:103–109.

Kuo S, Sainju UM, Jellum EJ. 1997. Winter cover crop effects on soil organic carbon and carbohydrate in soil. Soil Sci Soc Am J. 61:145–152.

Laweley YE, Teasdale JR, Weil RR. 2012. The mechanism for weed suppression by a forage radish cover crop. Agron J. 104:205–214.

Lawley YE, Weil RR, Teasdale JR. 2011. Forage radish cover crop suppresses winter annual weeds in fall and before corn planting. Agron J. 103:137–144.

Lepajõe J 1982. Rukis. Rye. Tallinn, Valgus. Estonian.

Li X, Petersen SO, Sørensen P, Olesen JE. 2015. Effects of contrasting catch crops on nitrogen availability and nitrous oxide emissions in an organic cropping system. Agric Ecosyst Environ. 199:382–393.

Liu A, Ma BL, Bomke AA. 2005. Effects of cover crops on soil aggregate stability, total organic carbon, and polysaccharides. Soil Sci Soc Am J. 69:2041–2048.

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? Biol Agric Hortic. 32:182–191.

Mäkelä PSA, Tuulos A, Turakainen M, Stoddard FL. 2011. Revitalizing the winter turnip rape crop in the northern latitudes. Acta Agric Scand Sect B. 61:195–201.

Mirsky SB, Ackroyd VJ, Cordeau S, Curran WS, Hashemi M, Reberg-Horton S, Ryan M, Spargo JT. 2017. Hairy vetch biomass across the eastern United States: effects of latitude, seeding rate and date, and termination timing. Agron J. 109:1510–1519.

Pavinato PS, Merlin A, Rosolem CA. 2008. Organic compounds from plant extracts and their effect on soil phosphorus availability. Pesq Agropec Bras. 43:1379–1388.

Piotrowska-Długosz A, Wilczewski E. 2014. Changes in enzyme activities as affected by green-manure catch crops and mineral nitrogen fertilization. Zemdirbyste-Agriculture. 101:139–146.

Roarty S, Hackett RA, Schmidt O. 2017. Earthworm populations in twelve cover crop and weed management combinations. Appl Soil Ecol. 114:142–151.

Robačer M, Canali S, Kristensen HL, Bavec F, Mlakar SG, Jakop M, Bavec M. 2016. Cover crops in organic field vegetable production. Sci Hortic. 208:104–110.

Ross SM, King JR, Izaurralde RC, O'Donovan JT. 2009. The green manure value of seven clover species grown as annual crops on low and high fertility temperate soils. Can J Plant Sci. 89:469–476.

Sainju UM, Whitehead WF, Singh BP. 2005. Biculture legume–cereal cover crops for enhanced biomass yield and carbon and nitrogen. Agron J. 97:1403–1412.

Sánchez de Cima D. 2016. Organic farming and cover crops as an alternative to mineral fertilizers to improve soil physical properties. Int Agrophys. 29:405–412.

Sánchez de Cima D, Tein B, Eremeev V, Luik A, Kauer K, Reintam E, Kahu G. 2015. Winter cover crop effects on soil structural stability and microbiological activity in organic farming. Biol Agric Hortic. 32:170–181.

Sarrantonio M, Gallandt E. 2003. The role of cover crops in North American cropping systems. J Crop Prod. 8:53–74.

Sarwar M, Kirkegaard JA, Wong PTW, Desmachelier JM. 1998. Biofumigation potential of brassicas. Plant Soil. 201:103–112.

Smolinska U, Horbowicz M. 1999. Fungicidal activity of volatiles from selected cruciferous plants against resting propagules of soil-borne fungal pathogens. J Phytopathol. 147:119–124.

Soltangheisi A, Rodrigues M, Coelho MJA, Gasperini AM, Sartor LR, Pavinato PS. 2018. Changes in soil phosphorus lability promoted by phosphate sources and cover crops. Soil Tillage Res. 179:20–28.

Talgre L, Lauringson E, Makke A, Lauk R. 2011. Biomass production and nutrient binding of catch crops. Zemdirbyste-Agriculture. 98:251–258.

Tamm I, Tamm Ü, Ingver A, Koppel R, Tupits I, Bender A, Tamm S, Narits L, Koppel M. 2016. Different leguminous pre-crops increased yield of succeeding cereals in two consecutive years. Acta Agric Scand Sect B. 66(7):593–601.

Teasdale JR, Devine TE, Mosjidis JA, Bellinder RR, Beste CE. 2004. Growth and development of hairy vetch cultivars in the northeastern United States as influenced by planting and harvesting date. Agron J. 96:1266–1271.

Thomsen IK, Elsgaard L, Olesen JE, Christensen BT. 2016. Nitrogen release from differently aged Raphanus sativus L nitrate catch crops during mineralization at autumn temperatures. Soil Use Manag. 32:183–191.

Thorup-Kristensen K. 2001. Are differences in root growth of nitrogen catch crops important for their ability to reduce soil nitrate-N content, and how can this be measured? Plant Soil. 230:185–195.

Thorup-Kristensen K, Bodin Dresboll D, Kristensen HL. 2012. Crop yield, root growth, and nutrient dynamics in a conventional and three organic cropping systems with different levels of external inputs and N re-cycling through fertility building crops. Eur J Agron. 37:66–82.

Thorup-Kristensen K, Magid J, Jensen LS. 2003. Catch crops and green manures as biological tools in nitrogen management in temperate zones. Adv Agron. 51:227–302.

Tjurin IV. 1937. Soil organic matter and its role in pedogenesis and soil productivity. In: Study of soil humus. Moscow; p. 287. Selkhozgiz. Russian.

Tuulos A, Yli-Halla M, Stoddard F, Mäkelä P. 2015. Winter turnip rape as a soil N scavenging catch crop in a cool humid climate. Agron Sustainable Dev. 35:359–366.

van Reeuwijk LP. 2002. Procedures for soil analysis. 6th ed. Wageningen: International Soil Reference and Information Centre.

Wang F, Weil RR, Nan X. 2017. Total and permanganate-oxidizable organic carbon in the corn rooting zone of US coastal plain soils as affected by forage radish cover crops and N fertilizer. Soil Tillage Res. 165:247–257.

Wang G, Ngouajio M, Warncke DD. 2008. Nutrient cycling, weed suppression, and onion yield following brassica and sorghum sudangrass cover crops. Hort Technol. 18:68–74.

Wendling M, Büchi L, Amossé C, Sinaj S, Walter A, Charles R. 2016. Influence of root and leaf traits on the uptake of nutrients in cover crops. Plant Soil. 409:419–434.

White CM, Weil RR. 2010. Forage radish cover crops increase soil test phosphorus surrounding radish taproot holes. Soil Sci Soc Am J. 75:121–130.

Wilke BJ, Snapp SS. 2008. Winter cover crops for local ecosystems: linking plant traits and ecosystem function. J Sci Food Agric. 88:551–557.

# II

**Toom, M.**, Tamm, S., Talgre, L., Tamm, I., Tamm, Ü., Narits, L., Hiiesalu, I., Edesi, L., Talve, T., Mäe, A., Lauringson, E. 2021. The effect of sowing date on biomass and nitrogen accumulation of five winter cover crop species.
Agricultural Research and Technology, 25, 133–140.

Agricultural Research & Technology
Open Access Journal
ISSN: 2471-6774

Juniper PUBLISHERS
key to the Researchers

Research Article
Volume 25 Issue 3 - January 2021
DOI: 10.19080/ARTOAJ.2021.25.556308

Agri Res & Tech: Open Access J

# The Effect of Sowing Date on Biomass and Nitrogen Accumulation of Five Winter Cover Crop Species

**Merili Toom[1,2]*, Sirje Tamm[1]*, Liina Talgre[2], Ilmar Tamm[1], Ülle Tamm[1], Lea Narits[1], Inga Hiiesalu[3], Liina Edesi[1], Tiina Talve[1], Andres Mäe[1] and Enn Lauringson[2]**

[1]*Estonian Crop Research Institute, J Aamisepa 1, 48309 Jõgeva, Estonia*

[2]*Institute of Agricultural and Environmental Sciences, Estonian University of Life Sciences, Estonia*

[3]*Institute of Ecology and Earth Sciences, University of Tartu, Estonia*

**Submission**: January 20, 2021; **Published:** January 25, 2021

***Corresponding author:** Merili Toom, Estonian Crop Research Institute, Jõgeva, Estonia

**Abstract**

Winter cover crops are used to protect soil from nitrogen (N) loss in fallow periods of crop production. For sufficient N accumulation, it is essential to produce high amount of biomass, and therefore it is important to sow cover crop as early as possible after the main crop harvest. A two-year field experiment was carried out in northern climate to study the effect of sowing date on biomass and N accumulation of five winter cover crop species: winter rye (*Secale cereale L.*), winter turnip rape (*Brassica rapa spp. oleifera L.*), forage radish (*Raphanus sativus L. var. longipinnatus*), hairy vetch (*Vicia villosa* Roth), and berseem clover (*Trifolium alexandrinum L.*). Cover crops were sown during a two-week period at four different dates in late summer. Biomass and accumulated N were measured at the end of the vegetation period in autumn and for overwintered species also in the following spring. Results showed that the cover crops differed in biomass and N, measured in autumn and spring. Forage radish produced the highest and berseem clover the lowest biomass and N in autumn. Delayed sowing reduced biomass and N of cover crops, while the influence of sowing date on tested species was different. Notably, the biomass and N of forage radish remained the highest at all sowing dates as measured in autumn, despite considerable decrease by delayed sowing. Winter rye was least affected by delayed sowing, whereas berseem clover and hairy vetch were most affected. Despite considerable decrease, hairy vetch accumulated the highest amount of N across all sowing dates as measured in spring.

**Keywords:** Winter cover crops; Delayed sowing, Biomass; Accumulated N; Winter rye; Winter turnip rape; Forage radish; Hairy vetch; Berseem clover

## Introduction

Replacing fallow periods with cover crops provide many benefits to agroecosystems including reduced nitrogen (N) loss [1,2]. In northern temperate areas, the most common types of cover crops are winter annuals that are sown after the harvest of the cash crop in late summer and incorporated into the soil in the following spring. Overwintering species are valuable because they protect the soil during winter and accumulate additional biomass and N in the following spring. Cover crops that are not winter hardy, but accumulate high amount of biomass and N before the killing frost, are useful especially in reduced or no-tillage organic farming systems, eliminating the need for chemical or mechanical cover crop termination [3,4,5]. Hairy vetch is a commonly used winter annual legume, because of its winter hardiness, high biomass, and N fixation ability [6,7,8]. Similarly, berseem clover can accumulate high amount of biomass and N mostly in Southern regions, while it is winterkilled in northern latitudes [4,9]. Winter rye is a winter hardy cover crop species that accumulates high amount of biomass and soil N [10,11]. Likewise, brassica species such as a winter hardy winter turnip rape and winter-killed forage radish scavenge great amount of soil N with deep root system [12,13]. To maximize ecosystem services provided by cover crops, the major goal is the production of high biomass yield [14,15]. In northern regions with short autumns, there is often a narrow window of opportunity for establishing cover crops after harvesting a cash crop, which can result in low biomass [16]. Delayed sowing has shown to result in dramatic decrease in biomass and N accumulation [5], however, the reduction is dependent on cover crop species [17,18,19]. The biomass and N accumulation of overwintering species depends also on the termination time in spring [6,8,16,20]. In nordic latitudes cover crops are commonly sown after harvest of the cash crop in late summer and incorporated into the soil before frosts [21,22]. However, winter cover crops allow to maintain the fields covered throughout the winter season, preventing erosion of soils and loss of nutrients. This is important under changed climatic conditions, whereby temperatures are more often above freezing during recent years. Cover crops should be ideally sown early autumn, directly after harvest of early-ripening cash crops, such as winter cereals. However, delayed sowing of cover crops would allow to use them after later-ripening cash crop, such as spring cereals. Winter cover crops have been recently introduced to Estonia [23], but studies with delayed sowings have not been conducted. Therefore, this study aimed to investigate the effect of different sowing dates (during the period of two weeks) on biomass and N accumulation of five species of winter cover crops. We hypothesized that 1) winter cover crop species differ in their ability to produce biomass and accumulate N, while biomass and accumulated N will decrease with delayed sowing date; 3) biomass and N accumulation of some winter cover crop species will decrease less with delayed sowing than that of others.

## Materials and Methods

Field experiments were established in 2017 and 2018 at Estonian Crop Research Institute. The cover crops included winter turnip rape (cultivar (cv.) Largo 10 kg $ha^{-1}$), forage radish (Tillage radish® at 10 kg $ha^{-1}$), hairy vetch (cv. Villana at 50 kg $ha^{-1}$), berseem clover (cv. Akenaton at 15 kg $ha^{-1}$), and winter rye (cv. Sangaste at 180 kg $ha^{-1}$). Cover crops were sown on August 3, 8, 14 and 18 in 2017 and August 3, 8, 13, 17 in 2018, after winter wheat harvest (*Triticum aestivum L.*). Plots with an area of 24 $m^2$ (4 × 6 m) were laid out in a randomized complete block design with four replications. Biomass samples were collected from four squares of 0.25 $m^2$ in each plot at the end of vegetation period (October 20 and 23 in 2017 and 2018, respectively). Biomass of the overwintered species was determined again in spring, before the cover crops were ploughed into the soil (May 7 in 2018 and 2019). Above ground biomass was collected by cutting the shoots on the ground level. Roots were collected with a shovel to a depth of 25 cm and washed from soil on a sieve. The biomass samples were oven-dried at 65 °C until constant weight in order to determine dry weight and ground for elemental analysis. Shoot and root dry weight values were merged. Plant total N was determined by the Dumas Combustion method on a varioMAX CNS elemental analyser ('Elementar', Germany). Statistical analyses were carried out by statistical package Agrobase 20TM. To test the effect of cover crop species, sowing date and their interaction on biomass and N accumulation of cover crops, analysis of variance (ANOVA) was performed. Fisher's LSD was used to test the significance of differences between cover crop species within sowing dates and across sowing dates.

## Results

### Weather conditions

The average air temperature during the cover crops' main growing period from August until the end of October was similar in 2017 (10.8 °C) and higher in 2018 (12.7 °C) compared to the long-term average (LTA; 10.4 °C) of these months (Table 1). The average amount of precipitation from August until the end of October was higher in 2017 (92 mm) than the LTA (74 mm). In 2018, the soil was dry during cover crop establishment, because of very low amount of precipitation in July (15mm) compared to the LTA of this month (79 mm). The rainfall started from August 4 and the average amount of precipitation (75 mm) by the end of October was similar to the LTA. The average temperature during the main growing period in April was higher in 2018 and 2019 (6.2 and 6.6 °C, respectively) than the LTA of this month (3.8°C). Precipitation in April was 21 mm in 2018 and only 4 mm in 2019 which is lower compared to the LTA (36 mm).

**Table 1:** Average air temperature and precipitation per month, monthly sums of effective air temperatures > +5 °C (ETS) during the experimental period and long-term average (LTA; 1922–2017).

| Month | Average air temperature per month (°C) | LTA temperature per month (°C) | Precipitation per month (mm) | LTA precipitation per month (mm) | ETS per month (°C) | LTAETS per month (°C) |
|---|---|---|---|---|---|---|
| 2017/2018 | | | | | | |
| July | 14.9 | 16.8 | 57 | 79 | 308 | 365 |
| August | 15.9 | 15.3 | 83 | 89 | 337 | 320 |
| September | 11.8 | 10.6 | 86 | 66 | 206 | 177 |
| October | 4.8 | 5.3 | 107 | 66 | 53 | 60 |
| November | 2.1 | 0.3 | 47 | 56 | 4.8 | 8 |
| December | 0.1 | -3.7 | 80 | 47 | 0 | 1 |
| January | -2.4 | -6.5 | 35 | 41 | 0 | 0.06 |
| February | -8.7 | -6.8 | 25 | 31 | 0 | 0.2 |

| | | | | | | |
|---|---|---|---|---|---|---|
| March | -4.3 | -3 | 21 | 31 | 0 | 2.9 |
| April | 6.2 | 3.8 | 52 | 36 | 73.5 | 46 |
| May | 14.5 | 10.4 | 17 | 50 | 39.3* | |
| 2018/2019 | | | | | | |
| July | 20.2 | 16.8 | 15.5 | 79 | 474 | 365 |
| August | 17.9 | 15.3 | 76 | 89 | 401 | 320 |
| September | 13.6 | 10.6 | 72 | 66 | 260 | 177 |
| October | 6.5 | 5.3 | 78 | 66 | 86 | 60 |
| November | 2.2 | 0.3 | 22 | 56 | 18 | 8 |
| December | -2.8 | -3.7 | 37 | 47 | 0 | 1 |
| January | -6.7 | -6.5 | 39 | 41 | 0 | 0.06 |
| February | -0.7 | -6.8 | 34 | 31 | 0.4 | 0.2 |
| March | 4.3 | -3 | 49 | 31 | 7.6 | 2.9 |
| April | 6.6 | 3.8 | 4 | 36 | 108 | 46 |
| May | 10.6 | 10.4 | 50 | 50 | 11.5* | |

*ETS until ploughing cover crops into the soil.

## Biomass Accumulation

The ANOVA results showed that there were significant differences in biomass produced by different species of cover crops as an average of sowing dates in both trial years, measured in autumn as well in spring (Tables 2 & 3). Out of the five tested winter cover crop species forage radish produced the highest average biomass and berseem clover the lowest measured in autumn during both trial years. Among three overwintering cover crop species winter turnip rape and hairy vetch produced higher biomass compared to winter rye, as measured in the following spring, during both trial years. The amount of biomass as an average of cover crop species was significantly affected by the sowing date measured in autumn as well in spring in both trial years (Table 2 & Table 3). In general, cover crops in average produced lower biomass in case of later sowing date. As an exception, the biomass of cover crops sown in the 1st (Aug 3) and 2nd (Aug 8) sowing dates remained on the same level in the second trial year. The decrease of average biomass in autumn was higher in the first trial year, from 1940 kg ha$^{-1}$ as sown in the 1st sowing date on Aug 3 to 710 kg ha$^{-1}$ as sown in the last date on Aug 18 (Table 2). However, the decrease of average biomass was lower in the second trial year, from 2016 kg ha$^{-1}$ as sown in the 1st sowing date on Aug 3 to 1191 kg ha$^{-1}$ as sown in the last date on Aug 17 (Table 3). The average biomass of the overwintering cover crops measured in the following spring decreased much less compared to the biomass measured in autumn, from 2382 to 1609 kg ha$^{-1}$ in the first trial year and from 2901 to 2054 kg ha$^{-1}$ in the second trial year.

**Table 2:** Biomass production of cover crops (mean±standard error; dry matter kg ha$^{-1}$) depending on the date of sowing in the field experiment established in autumn 2017. The results of two-way analysis of variance (F-statistics and p-values) of the factors cover crop (Crop), sowing date (Date) and cover crop by sowing date interaction (Crop*Date) are also presented.

| Cover crop | 1st sowing date 8/3/2017 | 2nd sowing date 8/8/2017 | 3rd sowing date 8/14/2017 | 4th sowing date 8/18/2017 | Average of sowing dates |
|---|---|---|---|---|---|
| **Autumn 2017** | Crop: $F_{4,57}$=155, p<0.001; Date: $F_{3'57}$=196, p<0.001; Crop*Date: $F_{12,57}$=25, p<0.001 | | | | |
| Winter turnip rape | 1752±124$^{b/A}$ | 1321±72$^{b/B}$ | 1041±28$^{b/C}$ | 801±30$^{b/D}$ | 1229±97$^{b}$ |
| Forage radish | 3841 ±269$^{a/A}$ | 2146±78$^{a/B}$ | 1401±98$^{a/C}$ | 1164±74$^{a/D}$ | 2138±279$^{a}$ |
| Winter rye | 1188±32$^{d/B}$ | 1404±50$^{b/A}$ | 1191±57$^{b/B}$ | 873±58$^{b/C}$ | 1164±54$^{b}$ |
| Berseem clover | 1556±48$^{bc/A}$ | 737±53$^{c/B}$ | 440±24$^{d/C}$ | 285±35$^{c/C}$ | 754±128$^{d}$ |
| Hairy vetch | 1362±61$^{cd/A}$ | 1230±82$^{b/A}$ | 723±46$^{c/B}$ | 425±11$^{c/C}$ | 935±101$^{c}$ |
| Average of crops | 1940±229$^{A}$ | 1367±107$^{B}$ | 959±81$^{C}$ | 710±75$^{D}$ | |
| **Spring 2018** | Crop: $F_{2,33}$=39, p<0.001; Date: $F_{3,33}$=120, p<0.001; Crop*Date: $F_{6,33}$=5, p<0.001 | | | | |
| Winter rye | 2086±70$^{c/A}$ | 2116±35$^{c/A}$ | 1788±33$^{b/B}$ | 1646±41$^{a/C}$ | 1909±55$^{c}$ |
| Winter turnip rape | 2372±127$^{b/A}$ | 2294±44$^{b/A}$ | 1895±23$^{b/B}$ | 1531±31$^{a/C}$ | 2023±92$^{b}$ |

| | | | | | |
|---|---|---|---|---|---|
| Hairy vetch | 2689±107$^{a/A}$ | 2602±22$^{a/A}$ | 2107±42$^{a/B}$ | 1651±37$^{a/C}$ | 2262±111$^{a}$ |
| Average of crops | 2382±92$^{A}$ | 2337±63$^{A}$ | 1930±44$^{B}$ | 1609±25$^{C}$ | |

Mean values without common lowercase letters (a,b,c,d) within sowing dates (in columns) and mean values without common uppercase letters (A,B,C,D) within cover crops (in rows) are statistically significantly different ($p < 0.05$, Fisher LSD test).

**Table 3:** Biomass production of cover crops (mean±standard error; dry matter kg ha$^{-1}$) depending on the date of sowing in the field experiment established in autumn 2018. The results of two-way analysis of variance (F-statistics and p-values) of the factors cover crop (Crop), sowing date (Date) and cover crop by sowing date interaction (Crop*Date) are also presented.

| Cover crop | 1st sowing date 8/3/2018 | 2nd sowing date 8/8/2018 | 3rd sowing date 8/13/2018 | 4th sowing date 8/17/2018 | Average of sowing dates |
|---|---|---|---|---|---|
| **Autumn 2018** | Crop: $F_{4,57}$=493, p<0.001; Date: $F_{3,57}$=170, p<0.001; Crop*Date: $F_{12,57}$=13, p<0.001 | | | | |
| Winter turnip rape | 2178±65$^{b/A}$ | 2157±81$^{b/A}$ | 1834±60$^{b/B}$ | 1212±39$^{b/C}$ | 1845±105$^{b}$ |
| Forage radish | 3581±95$^{a/A}$ | 3661±98$^{a/A}$ | 2643±63$^{a/B}$ | 2020±107$^{a/C}$ | 2976±181$^{a}$ |
| Winter rye | 1486±75$^{c/A}$ | 1487±96$^{c/A}$ | 1404±73$^{c/A}$ | 1070±85$^{bc/B}$ | 1362±58$^{c}$ |
| Berseem clover | 820±47$^{d/A}$ | 879±51$^{d/A}$ | 642±57$^{d/B}$ | 463±29$^{d/C}$ | 701±47$^{d}$ |
| Hairy vetch | 2243±83$^{b/A}$ | 2267±90$^{b/A}$ | 1786±75$^{b/B}$ | 1016±29$^{c/C}$ | 1828±135$^{b}$ |
| Average of crops | 2062±213$^{A}$ | 2090±216$^{A}$ | 1662±152$^{B}$ | 1156±118$^{C}$ | |
| **Spring 2019** | Crop: $F_{2,33}$=74, p<0.001; Date: $F_{3,33}$=112, p<0.001; Crop*Date: $F_{6,33}$=9, p<0.001 | | | | |
| Winter rye | 2350±73$^{b/A}$ | 2472±89$^{b/A}$ | 2364±38$^{b/A}$ | 1928±46$^{b/B}$ | 2279±61$^{b}$ |
| Winter turnip rape | 3123±106$^{a/A}$ | 3147±126$^{a/A}$ | 2598±35$^{a/B}$ | 2270±49$^{a/C}$ | 2785±103$^{a}$ |
| Hairy vetch | 3231±38$^{a/A}$ | 3239±74$^{a/A}$ | 2706±55$^{a/B}$ | 1963±14$^{b/C}$ | 2785±136$^{a}$ |
| Average of crops | 2901±125$^{A}$ | 2953±115$^{A}$ | 2556±49$^{B}$ | 2054±51$^{C}$ | |

Mean values without common lowercase letters (a,b,c,d) within sowing dates (in columns) and mean values without common uppercase letters (A,B,C,D) within cover crops (in rows) are statistically significantly different ($p < 0.05$, Fisher LSD test).

The ANOVA results showed that the variation of biomass depended significantly on the interaction between cover crop species and sowing date in both trial years, measured in autumn as well as in spring (Table 2 & 3), meaning that there were differences in the degree of reduction in biomass of different cover crop species depending on the sowing date. According to the autumn measurements, the biomass of winter rye was least affected by the sowing date, varying between 1188–873 kg ha$^{-1}$ in the 1st trial year and between 1486–1070 kg ha$^{-1}$ in the 2nd trial year. In the 1st trial year the biomass of berseem clover decreased the most (1556–285 kg ha$^{-1}$), whereas in the 2nd trial year, biomass of hairy vetch decreased the most (2243–1116 kg ha$^{-1}$) between the first and the last sowing dates. Out of the five tested cover crop species forage radish produced significantly highest amount of biomass in all sowing dates in both trial years despite of considerably reduced biomass in the delayed sowing dates (3841 versus 1164 kg ha$^{-1}$ in the 1st and 3581 versus 2020 kg ha$^{-1}$ in the 2nd trial year).

According to the spring measurements, overall biomass decrease caused by delayed sowing was considerably lower than in autumn (Table 2 & 3). Among the three overwintering cover crop species winter rye was the most stable, with the lowest overall biomass decrease due to delayed sowing date. Specifically, in the earlier sowing dates, the biomass of winter rye was smaller compared to winter turnip rape and hairy vetch. However, in the later sowing dates the biomass of winter rye reached the same level than of the other two cover crops, except winter turnip rape which had the highest biomass as measured in spring 2019 from the variant of most delayed sowing date.

## N accumulation

The ANOVA results showed that there were significant differences in accumulated N by different species of cover crops as an average of sowing dates in both trial years, measured in autumn as well in spring (Table 4 & 5). Out of the five tested winter cover crop species forage radish accumulated the highest average N and berseem clover the lowest accumulated N measured in autumn during both trial years. Among the three overwintering cover crop species hairy vetch accumulated the highest amount of N, as measured in the following spring, during both trial years.

The accumulated N as an average of cover crop species was significantly affected by the sowing date as measured in autumn as well as in spring in both trial years (Table 4 & 5). In general, cover crops in average produced lower N in case of later sowing dates, however, in most cases the decrease of accumulated N was not significant in the 2nd sowing date compared to the 1st. When comparing the 1st and last sowing date, the overall decrease of average accumulated N in autumn was somewhat higher in the first trial year than in the second trial year. In the first trial year average N reduced from 58 kg ha$^{-1}$ to 25 kg ha$^{-1}$ and in the second trial year N reduced from 73 kg ha$^{-1}$ to 38 kg ha$^{-1}$ (Table 4 & 5). The average accumulated N of the overwintering cover crops measured in the following spring decreased less compared to the N measured in autumn – N in spring decreased from 65 to 46 kg ha$^{-1}$ in the first trial year and from 84 to 56 kg ha$^{-1}$ in the second trial year.

**Table 4:** Nitrogen accumulation of cover crops (mean±standard error; N kg ha$^{-1}$) depending on the date of sowing in the field experiment established in autumn 2017. The results of two-way analysis of variance (F-statistics and p-values) of the factors cover crop (Crop), sowing date (Date) and cover crop by sowing date interaction (Crop*Date) are also presented.

| Cover crop | 1st sowing date 8/3/2017 | 2nd sowing date 8/8/2017 | 3rd sowing date 8/14/2017 | 4th sowing date 8/18/2017 | Average of sowing dates |
|---|---|---|---|---|---|
| Autumn 2017 | Crop: $F_{4,57}$=186, p<0.001; Date: $F_{3,57}$=180, p<0.001; Crop*Date: $F_{12,57}$=16, p<0.001 | | | | |
| Winter turnip rape | 64±5$^{b/A}$ | 46±3$^{b/B}$ | 35±1$^{b/C}$ | 30±1$^{b/C}$ | 44±4$^{b}$ |
| Forage radish | 103±7$^{a/A}$ | 70±3$^{a/B}$ | 42±3$^{a/C}$ | 43±1$^{a/C}$ | 65±7$^{a}$ |
| Winter rye | 28±2$^{e/A}$ | 30±1$^{c/A}$ | 27±1$^{c/AB}$ | 22±1$^{c/B}$ | 27±1$^{d}$ |
| Berseem clover | 42±2$^{d/A}$ | 22±2$^{d/B}$ | 13±1$^{d/C}$ | 9±1$^{d/C}$ | 22±3$^{e}$ |
| Hairy vetch | 53±3$^{c/A}$ | 45±2$^{b/A}$ | 31±2$^{bc/C}$ | 21±1$^{c/D}$ | 38±3$^{c}$ |
| Average of crops | 58±6A | 43±4$^{B}$ | 30±2$^{C}$ | 25±3$^{D}$ | |
| **Spring 2018** | Crop: $F_{2,33}$=358, p<0.001; Date: $F_{3,33}$=131, p<0.001; Crop*Date: $F_{6,33}$=14, p<0.001 | | | | |
| Winter rye | 50±2$^{c/A}$ | 50±1$^{c/A}$ | 44±1$^{c/B}$ | 37±1$^{c/C}$ | 45±1$^{c}$ |
| Winter turnip rape | 61±3$^{b/B}$ | 67±1$^{b/A}$ | 57±1$^{b/C}$ | 46±1$^{b/D}$ | 58±2$^{b}$ |
| Hairy vetch | 83±4$^{a/B}$ | 94±1$^{a/A}$ | 70±2$^{a/C}$ | 54±1$^{a/D}$ | 75±4$^{a}$ |
| Average of crops | 65±4$^{B}$ | 70±6$^{A}$ | 57±3$^{C}$ | 46±2$^{D}$ | |

Mean values without common lowercase letters (a,b,c,d) within sowing dates (in columns) and mean values without common uppercase letters (A,B,C,D) within cover crops (in rows) are statistically significantly different ($p < 0.05$, Fisher LSD test).

**Table 5:** Nitrogen accumulation of cover crops (mean±standard error; N kg ha$^{-1}$) depending on the date of sowing in the field experiment established in autumn 2018. The results of two-way analysis of variance (F-statistics and p-values) of the factors cover crop (Crop), sowing date (Date) and cover crop by sowing date interaction (Crop*Date) are also presented.

| Cover crop | 1st sowing date 8/3/2018 | 2nd sowing date 8/8/2018 | 3rd sowing date 8/13/2018 | 4th sowing date 8/17/2018 | Average of sowing dates |
|---|---|---|---|---|---|
| Autumn 2018 | Crop: $F_{4,57}$=448, p<0.001; Date: $F_{3,57}$=140, p<0.001; Crop*Date: $F_{12,57}$=14, p<0.001 | | | | |
| Winter turnip rape | 75±2c$^{/A}$ | 76±4$^{c/A}$ | 62±2$^{b/B}$ | 41±2$^{b/C}$ | 64±4$^{c}$ |
| Forage radish | 126±6$^{a/A}$ | 127±6$^{a/A}$ | 95±3$^{a/B}$ | 71±4$^{a/C}$ | 105±6$^{a}$ |
| Winter rye | 36±2$^{d/A}$ | 35±3$^{d/A}$ | 35±2$^{c/A}$ | 28±2$^{c/B}$ | 34±1$^{d}$ |
| Berseem clover | 27±2$^{e/AB}$ | 30±2$^{d/A}$ | 22±2$^{d/BC}$ | 15±1$^{d/C}$ | 24±2$^{e}$ |
| Hairy vetch | 102±4$^{b/A}$ | 90±4$^{b/B}$ | 67±3$^{b/C}$ | 37±1$^{b/D}$ | 74±7$^{b}$ |
| Average of crops | 73±9$^{A}$ | 72±8$^{A}$ | 56±6$^{B}$ | 38±4$^{C}$ | |
| **Spring 2019** | Crop: $F_{2,33}$=450, p<0.001; Date: $F_{3,33}$=152, p<0.001; Crop*Date: $F_{6,33}$=24, p<0.001 | | | | |
| Winter rye | 59±2$^{c/A}$ | 60±3$^{c/A}$ | 62±1$^{b/A}$ | 45±1$^{c/B}$ | 57±2$^{c}$ |
| Winter turnip rape | 81±2$^{b/A}$ | 81±4$^{b/A}$ | 61±1$^{b/B}$ | 57±2$^{b/B}$ | 70±3$^{b}$ |
| Hairy vetch | 112±1$^{a/A}$ | 106±3$^{a/B}$ | 95±2$^{a/C}$ | 65±1$^{a/D}$ | 95±5$^{a}$ |
| Average of crops | 84±7$^{A}$ | 82±6$^{A}$ | 73±5$^{B}$ | 56±2$^{C}$ | |

Mean values without common lowercase letters (a,b,c,d) within sowing dates (in columns) and mean values without common uppercase letters (A,B,C,D) within cover crops (in rows) are statistically significantly different ($p < 0.05$, Fisher LSD test).

How to cite this article: Toom M, Tamm S, Talgre L, Tamm I, Tamm Ü et al. The Effect of Sowing Date on Biomass and Nitrogen Accumulation of Five Winter Cover Crop Species. Agri Res & Tech: Open Access J. 2021; 25 (3): 556308. DOI: 10.19080/ARTOAJ.2021.25.556308

ANOVA results showed that the variation in accumulated N depended significantly on the interaction between cover crop species and sowing date in both trial years, measured in autumn as well as in spring (Table 4 & 5), meaning that there were differences in the degree of reduction in N of different cover crop species depending on the sowing date. According to the autumn measurements, the accumulated N of winter rye was least influenced by the sowing date, varying between 28-22 kg ha$^{-1}$ in the 1st trial year and between 36-28 kg ha$^{-1}$ in the 2nd trial year. In the 1st trial year the accumulated N of berseem clover decreased the most (42-9 kg ha$^{-1}$), whereas in the 2nd trial year, biomass of hairy vetch decreased the most (102-37 kg ha$^{-1}$) between the first and the last sowing dates. Out of the five tested cover crop species forage radish accumulated significantly highest amount of N in all sowing dates in both trial years, reducing from 103 to 43 kg ha$^{-1}$ in the 1st and from 126 to 71 kg ha$^{-1}$ in the 2nd trial year.

According to the spring measurements, overall N decrease was less influenced by the delayed sowing compared to autumn (Table 4 and 5). Among the three overwintering cover crop species winter rye was the most stable, with the lowest overall N decrease due to delayed sowing date. Hairy vetch accumulated significantly the highest amount of N across all sowing dates, despite the highest overall decrease in N when comparing the 1st and the last sowing date. As an exception to the general tendency, the amount of N accumulated by hairy vetch and winter turnip rape increased significantly in the 2nd sowing date compared to the 1st sowing date in the first trial year.

## Discussion

### Cover crop species differ in biomass and N accumulation

Our results from a two-year field experiment showed that there were significant differences in biomass and N accumulated by different species of winter cover crops measured in autumn and in the following spring as an average across all sowing dates. Out of the five tested cover crop species forage radish produced the highest and berseem clover the lowest average biomass and N in autumn. Due to the large taproot, it is able to scavenge N from deeper soil layers. After winterkill and biomass decomposition in early spring, N can be released back into the upper soil layer [13]. Our results show that forage radish is a suitable winter cover crop species also in Nordic climate conditions, due to ability to produce high biomass and accumulate N. In the current study, berseem clover produced lower amount of biomass and N compared to other species. This has been confirmed in our previous study, where we also found that berseem clover is not suitable for winter cover crop when sown in autumn [23], probably because of sensitivity to cooler temperatures [4]. Additionally, when coupled with drought conditions during crop establishment as in our second trial year, berseem clover yields in extremely low biomass and N accumulation. However, when sown in spring berseem clover can accumulate high biomass and N also in Northern climate [24].

Among the five tested winter cover crop species, berseem clover was killed in autumn by the first frosts whereas forage radish was more tolerant to cold temperatures and decomposed by the end of April. Hairy vetch, winter turnip rape and winter rye overwintered in both trial years and therefore these three species were available for measurements in the following spring. Among the overwintering species hairy vetch accumulated the highest amount of biomass and N in spring. Hairy vetch is characterized as a legume with cold tolerance, fast growth and high N fixation capacity and reported to be a suitable cover crop in northern climatic conditions [6,25]. Impact of sowing date on biomass and N accumulation depend on cover crop species We found that biomass and N accumulation of cover crops in general decreased due to delayed sowing. Due to insufficient precipitation during cover crop establishment in the scond trial year, cover crops sown on Aug 3 and Aug 8 emerged at the same time and accumulated similar amount of biomass and N. The influence of sowing date on tested species was different. In particular, winter rye was least affected, whereas berseem clover and hairy vetch were most affected by the delayed sowing dates. Forage radish produced the highest amount of biomass and accumulated N in case of all sowing dates, although it was considerably affected by delayed sowing. According to autumn measurements the biomass of winter rye decreased up to 28%, while the biomass of berseem clover and hairy vetch decreased up to 82 and 69%, respectively. In addition, the accumulated N of winter rye decreased only up to 22%, whereas the accumulated N of berseem clover and hairy vetch decreased up to 79 and 64%, respectively.

Therefore, it can be concluded, that although winter rye had relatively low biomass and N in the current study, which can be attributed to the low tillering ability of cultivar Sangaste [26], winter rye can be suitable cover crop in case of delayed sowing. For instance, studies from Ontario, Canada have found no decrease in biomass and N of winter rye even when sowning has been delayed for one month [18,19]. It is evident from our results that berseem clover is particularly sentitive to delayed sowing – in the first trial year, already 5-day delay reduced its biomass and accumulated N by 53 and 48%, respectively. Therefore, this crop can be used as a winter cover crop only in the case of sowing early in the autumn, as it can not tolerate low temperatures [4]. Earlier studies in Estonia have shown that legumes field pea and faba bean can produce higher biomass in Northern climate [21,22] and therefore could be considered as more suitable winter killed legume cover crops than berseem clover. The susceptibility of legume cover crop species to delayed sowing date has also been reported previously. For example, in Central Europe, legume cover crops biomass sown in mid-August was 95% higher compared to mid-September and low temperatures in mid-October did not allow legume growth at all [27].

As measured in autumn, forage radish produced the highest biomass and N across all sowing dates, despite considerable

**How to cite this article:** Toom M, Tamm S, Talgre L, Tamm I, Tamm Ü et al. The Effect of Sowing Date on Biomass and Nitrogen Accumulation of Five Winter Cover Crop Species. Agri Res & Tech: Open Access J. 2021; 25 (3): 556308. DOI: 10.19080/ARTOAJ.2021.25.556308

decrease (up to 70 and 58%, respectively). A previous study conducted in the USA, Missouri evaluated the effect of delayed sowing on radish biomass and concluded that radish produced 820–1670 kg ha$^{-1}$ more biomass at the first sowing date compared with delayed sowing [28]. Forage radish will be winterkilled and decomposes during early spring releasing N back into the upper soil layer, which can then be available for the following cash crops [13]. This was the case in our previous study, where forage radish increased significantly the yield of subsequent spring barley [29]. Therefore, forage radish can be recommended as one of the most favorable winter cover crops.

Overwintering cover crop biomass and N accumulation in the spring is influenced by the sowing date and the weather conditions during the growing period [8,16,18,30,]. Among the three overwintering species the biomass and accumulated N of winter rye decreased the least due to delayed sowing dates (up to 21 and 26%, respectively), while hairy vetch decreased the most (up to 39 and 42%, respectively). Despite considerable decrease, hairy vetch accumulated the highest amount of N across all sowing dates as measured in spring. Later termination could partially compensate for cover crop growth in case of delayed sowing [6,8]. On the other hand, delaying the termination date may decrease residue N concentration, increase C:N ratios, and result in higher residue hemicellulose and lignin concentration [20]. Previously, Teasdale et al. [6] observed that delayed sowing by 2 to 3 weeks reduced hairy vetch biomass by 43% when harvested vegetative and by 20% when harvested at the flowering stage. However, Lawson et al. [16] reported average winter cover crop biomass decrease by 50%, and N accumulation by 40% with delayed sowing and found similar reductions in biomass and N accumulation when terminated in late March compared with late April.

## Conclusion

Results from a two-year field trial showed that the tested five winter cover crop species (winter turnip rape, forage radish, winter rye, berseem clover and hairy vetch) differed in biomass and accumulated N as measured in autumn and in the following spring. Forage radish produced the highest and berseem clover the lowest average biomass and accumulated N in autumn. Furthermore, we found that biomass and accumulated N of cover crops decreased due to delayed sowing, but there were exceptions due to specific weather conditions such as drought. The influence of sowing date on tested species was different. Notably, the biomass and accumulated N of forage radish remained the highest at all sowing dates as measured in autumn, despite considerable decrease by delayed sowing. Winter rye was least affected by delayed sowing, whereas berseem clover and hairy vetch were most affected. Despite considerable decrease, hairy vetch accumulated the highest amount of N across all sowing dates as measured in spring.

Therefore, we conclude that earlier sowing of winter cover crops will result in higher biomass and accumulated N both in autumn and in the following spring. Among the tested winterkilled species forage radish turned out to be the most favourable cover crop in terms of biomass and accumulated N. Due to low biomass production berseem clover is not suitable for a cover crop in northern climate conditions when sown in autumn. When sown early over-wintering cover crops such as hairy vetch and winter turnip rape can result in high biomass and accumulated N in the following spring, particularly in case of leguminous hairy vetch.

## Acknowledgement

The research was supported by Estonian Ministry of Rural Affairs' project Varieties suitable for organic cultivation in Estonia (10.1-2/430 p.4; PA1-RUP-026) and by Designing of an agrotechnical system including evaluation of suitable catch crop species, their seed mixtures and their cultivation methods" (T170143PKTM). IH was supported by the Estonian Research Council grant PUT1170.

## References

1. Thapa R, Mirsky SB, Tully KL (2018) Cover Crops Reduce Nitrate Leaching in Agroecosystems: A Global Meta-Analysis. Journal of Environmental Quality 47(6): 1400–1411.
2. De Notaris C, Rasmussen J, Sørensen P, Olesen JE (2018) Nitrogen leaching: A crop rotation perspective on the effect of N surplus, field management and use of catch crops. Agriculture, Ecosystems and Environment 255: 1–11.
3. Lawley YE, Weil RR, Teasdale JR (2011) Forage radish cover crop suppresses winter annual weeds in fall and before corn planting. Agronomy Journal 103(1): 137–144.
4. Clark A (2007) Managing Cover Crop Profitably. In: Clark A, editor. National SARE outreach handbook series book 9. 3rd edn. Beltsville (MD). Sustainable Agriculture Network: 248.
5. Hashemi M, Farsad A, Sadeghpour A, Weis SA, Herbert SJ (2013) Cover-crop seeding-date influence on fall nitrogen recovery. Journal of Plant Nutrition and Soil Science 176(1): 69–75.
6. Teasdale JR, Devine TE, Mosjidis JA, Bellinder RR, Beste CE (2004) Growth and development of hairy vetch cultivars in the northeastern United States as influenced by planting and harvesting date. Agronomy Journal 96(5): 1266–1271.
7. Wilke BJ, Snapp SS (2008) Winter cover crops for local ecosystems: linking plant traits and ecosystem function. Journal of the Science of Food and Agriculture 88(4): 551–557.
8. Mirsky SB, Ackroyd VJ, Cordeau S, Curran WS, Hashemi M, et al., (2017) Hairy vetch biomass across the eastern united states: Effects of latitude, seeding rate and date, and termination timing. Agronomy Journal 109(4): 1510–1519.
9. Lu YC, Watkins KB, Teasdale JR, Abdul-Baki AA (2000) Cover crops in sustainable food production. Food Reviews International 16(2): 121–157.
10. Appelgate SR, Lenssen AW, Wiedenhoeft MH, Kaspar TC (2017) Cover crop options and mixes for upper midwest corn–soybean systems. Agronomy Journal 109(3): 968–984.

**How to cite this article:** Toom M, Tamm S, Talgre L, Tamm I, Tamm Ü et al. The Effect of Sowing Date on Biomass and Nitrogen Accumulation of Five Winter Cover Crop Species. Agri Res & Tech: Open Access J. 2021; 25 (3): 556308. DOI: 10.19080/ARTOAJ.2021.25.556308

11. Marcillo GS, Carlson S, Filbert M, Kaspar T, Plastina A, et al., (2019) Maize system impacts of cover crop management decisions: A simulation analysis of rye biomass response to planting populations in Iowa, U.S.A. Agricultural Systems 176: 102651.
12. Tuulos, A, Yli-Halla M, Stoddard F, Mäkelä P (2014) Winter turnip rape as a soil N scavenging catch crop in a cool humid climate. Agronomy for Sustainable Development 35: 359–366.
13. Wang F, Weil RR, Han L, Zhang M, Sun Z, et al., (2019) Subsequent nitrogen utilisation and soil water distribution as affected by forage radish cover crop and nitrogen fertiliser in a corn silage production system. Acta Agriculturae Scandinavica Section B: Soil and Plant Science 69(1): 52–61.
14. Antosh E, Idowu J, Schutte B, Lehnhoff E (2020) Winter cover crops effects on soil properties and sweet corn yield in semi-arid irrigated systems. Agronomy Journal 112(1): 92–106.
15. Finney DM, White CM, Kaye JP (2016) Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. Agronomy Journal 108(1): 39–52.
16. Lawson A, Cogger C, Bary A, Fortuna, AM (2015) Influence of seeding ratio, planting date, and termination date on rye-hairy vetch cover crop mixture performance under organic management. PLoS ONE 10: 1–19.
17. Akbari P, Herbert S, Hashemi M, Barker A, Zandvakili, et al., (2020) Winter annual rye seeding date influence on nitrogen recovery and ammonia volatilization from late fall surface-applied manure. Agronomy 10: 1–12.
18. Van Eerd LL (2018) Nitrogen dynamics and yields of fresh bean and sweet corn with different cover crops and planting dates. Nutrient Cycling in Agroecosystems 111: 33–46.
19. Zhou Y, Roosendaal L, Van Eerd LL (2019) Increased nitrogen retention by cover crops: implications of planting date on soil and plant nitrogen dynamics. Renewable Agriculture and Food Systems, 1–10.
20. Alonso-Ayuso M, Gabriel JL, Quemada M (2014) The kill date as a management tool for cover cropping success. PLoS ONE, 9(10).
21. Talgre L, Lauringson E, Makke A, Lauk R (2011) Biomass production and nutrient binding of catch crops. Zemdirbyste 98: 251–258.
22. Toom M, Talgre L, Pechter P, Narits L, Tamm S, et al., (2019) The effect of sowing date on cover crop biomass and nitrogen accumulation. Agronomy Research 17(4): 1779–1787.
23. Toom M, Talgre L, Mäe A, Tamm S, Narits L, et al., (2019) Selecting winter cover crop species for northern climatic conditions. Biological Agriculture and Horticulture 35(4): 263–274.
24. Tamm I, Tamm Ü, Ingver A, Koppel R, Tupits I, et al., (2016) Different leguminous pre-crops increased yield of succeeding cereals in two consecutive years. Acta Agriculturae Scandinavica Section B: Soil and Plant Science 66(7): 593–601.
25. Brandsæter LO, Heggen H, Riley H, Stubhaug E, Henriksen TM (2008) Winter survival, biomass accumulation and N mineralization of winter annual and biennial legumes sown at various times of year in Northern Temperate Regions. European Journal of Agronomy 28(3): 437–448.
26. Tupits I (2009) The effect of sowing and seeding rate on grain yield of winter rye. Crop varieties, characteristics and recommendations for cultivation (in Estonian): 30–35.
27. Gselman A, Kramberger B (2008) Benefits of winter legume cover crops require early sowing. Australian Journal of Agricultural Research 59: 1156–1163.
28. Sandler L, Nelson KA, Dudenhoeffer CJ (2015) Radish Planting Date and Nitrogen Rate for Cover Crop Production and the Impact on Corn Yields in Upstate Missouri. Journal of Agricultural Science, 7: 1–13
29. Toom M, Tamm S, Talgre L, Tamm I, Tamm Ü, et al., (2019) The effect of cover crops on the yield of spring barley in Estonia. Agriculture 9: 172
30. Akbari P, Herbert SJ, Hashemi M, Barker AV, Zandvakili OR (2019) Role of Cover Crops and Planting Dates for Improved Weed Suppression and Nitrogen Recovery in No till Systems. Communications in Soil Science and Plant Analysis 50(14): 1722–1731.

**How to cite this article:** Toom M, Tamm S, Talgre L, Tamm I, Tamm Ü et al. The Effect of Sowing Date on Biomass and Nitrogen Accumulation of Five Winter Cover Crop Species. Agri Res & Tech: Open Access J. 2021; 25 (3): 556308. DOI: 10.19080/ARTOAJ.2021.25.556308

# III

**Toom, M.**, Tamm, S., Talgre, L., Tamm, I., Tamm, Ü., Narits, L., Hiiesalu, I., Mäe, A., Lauringson, E. 2019. The effect of cover crops on the yield of spring barley in Estonia. Agriculture 9, 172.

agriculture

MDPI

Article

# The Effect of Cover Crops on the Yield of Spring Barley in Estonia

**Merili Toom [1,2,*], Sirje Tamm [1,*], Liina Talgre [2], Ilmar Tamm [1], Ülle Tamm [1], Lea Narits [1], Inga Hiiesalu [3], Andres Mäe [1] and Enn Lauringson [2]**

[1] Estonian Crop Research Institute, J. Aamisepa 1, 48309 Jõgeva, Estonia
[2] Institute of Agricultural and Environmental Sciences, Estonian University of Life Sciences, Fr. R. Kreutzwaldi 1, EE51014 Tartu, Estonia
[3] Institute of Ecology and Earth Sciences, University of Tartu, Lai 40, 51005 Tartu, Estonia
* Correspondence: merili.toom@etki.ee (M.T.); sirje.tamm@etki.ee (S.T.); Tel.: +372-7766921 (M.T. & S.T.)

Received: 31 May 2019; Accepted: 1 August 2019; Published: 3 August 2019

**Abstract:** Using cover crops in fallow periods of crop production is an important management tool for reducing nitrate leaching and therefore improving nitrogen availability for subsequent crops. We estimated the short-term effect of five cover crop species on the yield of successive spring barley (*Hordeum vulgare* L.) for two years in Estonia. The cover crop species used in the study were winter rye (*Secale cereale* L.), winter turnip rape (*Brassica rapa* spp. *oleifera* L.), forage radish (*Raphanus sativus* L. var. *longipinnatus*), hairy vetch (*Vicia villosa* Roth), and berseem clover (*Trifolium alexandrinum* L.). The results indicated that out of the five tested cover crops, forage radish and hairy vetch increased the yield of subsequent spring barley, whereas the other cover crops had no effect on barley yield. All cover crop species had low C:N ratios (11–17), suggesting that nitrogen (N) was available for barley early in the spring.

**Keywords:** cover crop; nitrogen accumulation; spring barley yield

## 1. Introduction

Using cover crops in fallow periods of crop production is an important management tool for reducing nitrate leaching and providing green manure service by improving the nitrogen (N) nutrition of subsequent crops [1–3]. Many studies have researched the effect of cover crops on subsequent crop yields, but the results are very variable depending on factors such as cover crop species, biomass production and quality, environmental factors, and management practices [1].

The main influence of cover crops on subsequent crop yield is through their effect on N availability in the soil. Leguminous cover crops bind N from the atmosphere and thereby provide additional nitrogen [4,5]. This causes faster mineralization of soil-incorporated leguminous residues thanks to the higher N concentration and lower C:N ratio of legumes' biomass. In contrast, a large C:N ratio can result in reduced N mobilization and lower N availability for the succeeding crop [6]. However, non-leguminous cover crops can scavenge for significant amounts of residual soil nitrate [7]. Mixtures of leguminous and non-leguminous cover crop species have been shown to be more effective in both providing nitrate supply and being employed as green manure [8–11]. Many authors have concluded that significant increases in main crop yields occur after the long-term use of cover crops in crop rotations, due to increases in both soil fertility and stores of organic matter [3,12,13]. However, the negative influence of cover crops on subsequent crops is mainly associated with the reduction of soil water storage, especially in water-limited regions [13–16]. As the effect of cover crops on subsequent crop yield has been reported to be very variable, and often depends on local climatic and soil conditions, more studies are needed from various regions. The biomass and nutrient accumulation of common winter cover crops have been recently tested in Estonia [17]. There have been some trials with winter-killed cover crops in which the effect on the following summer wheat yield was studied [18]. The aim of this experiment was to evaluate the effect of various cover crop species on the yield of subsequent spring barley, in order to find potentially beneficial cover crops that are suitable for the agro-climatic conditions prevailing in northern Europe.

## 2. Materials and Methods

We conducted a field experiment at the Estonian Crop Research Institute (58°44′59.41′′ N, 26°24′54.02′′ E) during the period of 2016–2018. The experiment was run in two sequential trials. The first trial evaluated cover crop performance (i.e., biomass and accumulation of nitrogen, phosphorus, potassium, calcium, and magnesium) in northern climatic conditions, data of which are published in Toom et al. [17]. The second and current trial evaluated the effect of cover crops on the yield of the following cash crop spring barley. However, in order to better interpret the current results, some cover crop data (biomass and nitrogen accumulation) from the first trial are referred to in the current study.

The soil in the trial site was of Cambic Phaeozem (Loamic) soil type [19]. The soil characteristics were as follows: $pH_{KCl}$ 6.9, P 104 mg $kg^{-1}$, K 195 mg $kg^{-1}$, Ca 3700 mg $kg^{-1}$, Mg 510 mg $kg^{-1}$, $C_{org}$ 2.1%, and $N_{tot}$ 0.16%. The trial site is situated in a climate zone with a long-term average annual temperature of 5.3 °C and precipitation of 670 mm [20].

The study used the following cover crop species with seeding rates that were adjusted for Estonia: forage radish (Tillage radish® at 10 kg $ha^{-1}$), winter turnip rape (cultivar (cv.) Largo at 10 kg $ha^{-1}$), hairy vetch (cv. Villana at 50 kg $ha^{-1}$), berseem clover (cv. Akenaton at 15 kg $ha^{-1}$), and winter rye (cv. Sangaste at 180 kg $ha^{-1}$). The study also included control plots where the cover crop was omitted. In both years, the cover crops were sown on 3 August, immediately after winter wheat (*Triticum aestivum* L.) had been harvested. Each test plot was 4 × 6 m in size and arranged in a randomized complete block design that was repeated four times. At the end of October, cover crop above- and below-ground biomass samples were collected from four randomly placed squares sized 0.25 $m^2$ from each plot. The biomass of the overwintered species was measured again in spring, before the cover crops were ploughed into the soil (on 4 May 2017 and 7 May 2018). After the cover crop was incorporated into the soil, spring barley was established. The above-ground biomass was cut at the ground level for measurements. In order to measure the below-ground biomass, the soil inside the squares was excavated to a depth of 25 cm and the roots were washed on a sieve (mesh size 0.5 mm). The weight of the biomass was measured after desiccating the material at 65 °C to a constant weight. For C and N analysis, the samples were milled, and plant total C and total N concentration was analyzed by the Dumas Combustion method on a VarioMAX CNS elemental analyzer ("Elementar Analysensysteme", GmbH, Langenselbold, Germany) in the Soil Science and Agrochemistry laboratory at the Estonian University of Life Sciences.

The biomass of cover crops was ploughed into soil in spring by using a mold-board plough Kverneland to a depth of 22–24 cm. Immediately after ploughing, the spring barley cultivar Maali (at 400 seeds $m^2$) was sown without any additional fertilizers. When barley had reached its physiological maturity, it was harvested with a Hege plot combine harvester (on 30 August 2017 and 6 August 2018). The grain yield of dried and cleaned seeds was adjusted to 14% moisture level and expressed in kg $ha^{-1}$.

In order to study the effect of cover crops on the yield of spring barley, an analysis of variance (ANOVA) was carried out. The models included the effect of cover crops, the year, and the interaction between the two. The differences between individual cover crop species were calculated using the post hoc Fisher's Least Significant Difference (LSD) test. Statistical analyses were carried out using the statistical software package Agrobase Generation II SQL ("Agronomix Software", Inc., Winnipeg, Manitoba, CA, USA).

## 3. Results and Discussion

### 3.1. Weather Conditions

The average air temperature during the cover crops' main growing period from August until the end of October in 2016 and 2017 (10.5 and 10.8 °C, respectively) was similar to the 10.4 °C long-term average of these months. Compared to the long-term average precipitation (74 mm), the average amount of precipitation was higher in 2016 (84 mm) and slightly lower in 2017 (70 mm). The average temperature during the main growing period in April was lower in 2017 (2.8 °C) and higher in 2018 (6.2 °C) than the long-term average (3.8 °C). Compared to the long-term average of precipitation in April (36 mm), the average amount was considerably higher in 2017 (52 mm) and lower in 2018 (21 mm). More detailed data about the weather conditions during the growing period of cover crop species can be found in Toom et al. [17].

The air temperatures during the growing period of barley in 2017 were 0.8 °C lower than the long-term average in May. In June it was 1.1 °C lower and in July it was 1.9 °C lower. August was 0.5 °C warmer than the long-term average (Table 1). The amount of precipitation from May until the end of August (278 mm) was similar to the long-term average (285 mm). The weather in 2018 was warm and dry: The air temperatures were higher than the long-term average by 4.1 °C in May; 0.5 °C in June; 3.5 °C in July; and 2.5 °C in August. The amount of precipitation from May until the end of August (131 mm) was lower than the long-term average (285 mm).

**Table 1.** Average air temperature and precipitation per month during the experimental period and their long-term average (1922–2017).

| Month | Average Air Temperature per Month (°C) | | Long-Term Average Temperature per Month (°C) | Precipitation per Month (mm) | | Long-Term Average Precipitation per Month (mm) |
|---|---|---|---|---|---|---|
| | 2017 | 2018 | | 2017 | 2018 | |
| May | 9.6 | 14.5 | 10.4 | 8 | 17 | 50 |
| June | 13.4 | 15.0 | 14.5 | 99 | 23 | 68 |
| July | 14.9 | 20.3 | 16.8 | 73 | 15 | 78 |
| August | 15.9 | 17.9 | 15.4 | 98 | 76 | 89 |

### 3.2. Cover Crop Biomass, Nitrogen Accumulation, and C:N Ratio

According to the ANOVA results, there were significant differences between the biomass and N values of cover crop species, measured in both autumn and spring (Table 2). Post hoc analyses of Fisher's LSD test showed that among the tested leguminous and non-leguminous cover crop species, forage radish produced the highest average biomass (3178 kg $ha^{-1}$) and contained the highest amount of N (86 kg $ha^{-1}$) when measured in autumn. However, among the three cover crops that survived the winter (hairy vetch, winter turnip rape, and winter rye), hairy vetch accumulated the highest average biomass (2210 kg $ha^{-1}$) and N (73 kg $ha^{-1}$) when measured in spring (Table 3). The C:N ratio of all the cover crop species remained relatively low; it ranged on average from 12 to 17. Specifically, hairy vetch had the lowest C:N ratio. More detailed analyses on the amount of biomass and nutrients of all the tested cover crop species are found in Toom et al. [17].

**Table 2.** Analyses of variance for cover crop biomass and nitrogen accumulation depending on species, year, and the interaction between the two. *

| Characteristic | Source of Variation | df | SS | MS | F | *p* |
|---|---|---|---|---|---|---|
| Autumn | | | | | | |
| Biomass | Species | 4 | 23,837,346.850 | 5,959,336.713 | 125.18 | <0.001 |
| | Year | 1 | 2,522,550.625 | 2,522,550.625 | 52.99 | <0.001 |
| | Species × year | 4 | 2,262,263.250 | 565,565.813 | 11.88 | <0.001 |
| Nitrogen | Species | 4 | 17,698.269 | 4424.567 | 106.58 | <0.001 |
| | Year | 1 | 3301.489 | 3301.489 | 79.53 | <0.001 |
| | Species × year | 4 | 1886.884 | 471.721 | 11.36 | <0.001 |
| Spring | | | | | | |
| Biomass | Species | 2 | 1,783,399.693 | 891,699.847 | 20.64 | <0.001 |
| | Year | 1 | 5,513,483.760 | 5,513,483.760 | 127.64 | <0.001 |
| | Species × year | 2 | 55,743.960 | 27,871.980 | 0.65 | 0.5385 |
| Nitrogen | Species | 2 | 4146.318 | 2073.159 | 47.80 | <0.001 |
| | Year | 1 | 2042.415 | 2042.415 | 47.09 | <0.001 |
| | Species × year | 2 | 54.768 | 27.384 | 0.63 | 0.5454 |

Notes: df—degrees of freedom; SS—sums of squares; MS—mean squares. F—treatment mean square/error mean square. *p*—significance probability value. * Table modified from Toom et al. [17].

**Table 3.** Cover crop biomass, nitrogen accumulation, and C:N ratio.

| The Time of Sampling | Cover Crop | Winter Turnip Rape | Winter Rye | Hairy Vetch | Berseem Clover | Forage Radish |
|---|---|---|---|---|---|---|
| *Autumn 2016 | Biomass kg ha$^{-1}$ | 1169c | 667d | 1422b | 1415b | 2515a |
| | N kg ha$^{-1}$ | 29c | 16d | 52b | 33c | 69a |
| | C:N | 16 | 17 | 11 | 18 | 15 |
| *Autumn 2017 | Biomass kg ha$^{-1}$ | 1752b | 1188d | 1362cd | 1556bc | 3841a |
| | N kg ha$^{-1}$ | 64b | 28e | 53c | 42d | 103a |
| | C:N | 11 | 17 | 10 | 15 | 14 |
| Autumn 2016–2017 average | Biomass kg ha$^{-1}$ | 1461b | 928c | 1392b | 1486b | 3178a |
| | N kg ha$^{-1}$ | 47c | 22e | 53b | 38d | 86a |
| | C:N | 14 | 17 | 11 | 17 | 15 |
| **Spring 2017 | Biomass kg ha$^{-1}$ | 1531a | 1009b | 1731a | x | x |
| | N kg ha$^{-1}$ | 48b | 31c | 62a | x | x |
| | C:N | 13 | 14 | 11 | x | x |
| **Spring 2018 | Biomass kg ha$^{-1}$ | 2372b | 2086c | 2689a | x | x |
| | N kg ha$^{-1}$ | 62b | 51c | 84a | x | x |
| | C:N | 16 | 17 | 13 | x | x |
| Spring 2017–2018 average | Biomass kg ha$^{-1}$ | 1952b | 1548c | 2210a | x | x |
| | N kg ha$^{-1}$ | 55b | 41c | 73a | x | x |
| | C:N | 15 | 16 | 12 | x | x |

Notes: Different lowercase letters within row are significantly different ($p < 0.05$; ANOVA, Fisher's Least Significant Difference (LSD) test). * The biomass of the winter-killed species, measured at the end of October. ** The biomass of the overwintered species, measured in the following spring before incorporating the cover crops into the soil, x no data (winter-killed species).

### *3.3. Spring Barley Yield*

According to the ANOVA results, the spring barley yield was significantly affected by cover crop species and year, but not the interaction between the two (Table 4). Barley yield level was relatively low because no fertilizers were added. The average yield was higher in the first year of harvest compared to the second year (3223 and 2693 kg ha$^{-1}$, respectively). The difference was caused by heavy drought in the second harvest year. However, the effect of cover crop species on the subsequent yield of barley was similar in both years, as indicated by the lack of significant interaction between the effects of cover crop species and the year.

**Table 4.** Analyses of variance for spring barley yield depending on cover crop species, year, and the interaction between the two.

| Characteristic | Source of Variation | df | SS | MS | F | *p* |
|---|---|---|---|---|---|---|
| Spring barley yield | Cover crop | 5 | 785,047 | 157,009 | 3.52 | 0.0127 |
| | Year | 1 | 8,709,144 | 8,709,144 | 195.35 | 0.001 |
| | Cover crop × year | 5 | 222,218 | 44,444 | 1.00 | 0.4364 |

Notes: df—degrees of freedom; SS—sums of squares; MS—mean squares. F—treatment mean square/error mean square. *p*—significance probability value.

Among the tested cover crop species, forage radish and hairy vetch significantly increased the grain yield of subsequent barley by 11 and 9%, respectively (Figure 1). The level of grain yield of barley after other cover crop species (winter turnip rape, winter rye, and berseem clover) remained similar to the control.

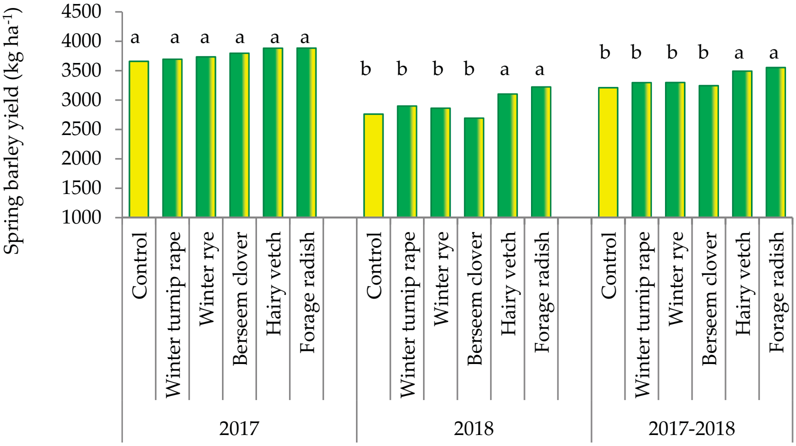


**Figure 1.** The effect of cover crops on the yield of spring barley (kg $ha^{-1}$) in 2017 and 2018, and the average of these years compared to the control (without cover crop). Within years, bars marked with different lowercase letters indicate significant differences at $p < 0.05$ according to the Fisher's LSD test.

The beneficial effect of radish cover crop is mainly associated with rapid growth during autumn and the ability to scavenge large amounts of residual N from deep soil layers with its large tap root [2,7]. This was confirmed in our experiment, where forage radish accumulated highest biomass and N in autumn, compared to other leguminous and non-leguminous species. As a result, it is likely that a major amount of N became available to the subsequent crop. With winter-killed cover crops it is recommended to sow the subsequent main crop early in spring to recapture the accumulated N. Minimizing spring leaching losses is of essential importance in soils that are coarse-textured and well-drained to excessively drained [21]. Our results on the positive effect of forage radish confirm several previous studies. For example, in Denmark, Sapkota et al. [2] evaluated the effect of different cover crop species on N leaching and barley yield. They found that fodder radish grown before barley (which was sown in the previous autumn) grew its roots deeper and depleted N from deeper soil layers. When chicory and ryegrass were used as barley undersows, they decreased N leaching, but also reduced spring barley yield. This was probably caused by competition for light, water, and nutrients.

In our study, none of the tested cover crop species reduced the yield of spring barley. Jahanzad et al. [7] found that when choosing a cover crop for potato, forage radish was a better option than rye, as it needed less N fertilizer and sustained tuber yield and mineral nutrient concentration in tubers. Using rye as a cover crop gave a higher potato yield than using no cover crop at all, but it did not release enough N for the potatoes since it was terminated in early spring when it had a limited biomass. In addition to N cycling, forage radish can contribute to the yield of succeeding crops through other mechanisms. According to Weil and Kremen [22], forage radish is effective in suppressing weeds and reducing the effects of soil compaction. They also found that using forage radish resulted in improved soybean growth and higher soybean seed yields.

In accordance with our results, previous studies have also reported the beneficial effects of hairy vetch. Campiglia et al. [23] found that in Italy, hairy vetch ensured a similar potato yield to that obtained by mineral fertilization, but rye or ryegrass monoculture either did not affect or had a negative effect on corn yield and N availability in soil. According to Sainju et al. [24], hairy vetch and crimson clover caused an increase in tomato yield.

Berseem clover in our study did not increase barley yield significantly. This is likely because it did not produce a sufficient biomass and could not provide enough N for barley, since berseem clover was killed by frosts. However, when sown in spring, berseem clover can produce sufficient biomass and increase the yield of subsequent winter cereals [25].

In order to prevent the loss of accumulated N, it is recommended to sow subsequent crops as soon as possible after incorporating the biomass of leguminous cover crops with low C:N ratios, such as hairy vetch. Sievers et al. [26] pointed out that most of the N in hairy vetch tissues is released in the first two weeks after termination. Therefore, it is susceptible to leaching out or denitrification if the following crop is not planted on time or it is not able to reach the growth stage where it could use the N from hairy vetch. In our study, barley was sown immediately after cover crop incorporation and was presumably able to use the accumulated N.

Rye has been found in some cases to make less N available to the following crop. This happens due to microbial immobilization if rye is terminated when its C:N ratio has risen above 30 [21]. In our study, winter rye produced a modest biomass and had quite a low C:N ratio (14–17), probably because it did not reach maturity before termination.

## 4. Conclusions

The results of our two-year experiment in northern Europe (Estonia) show that cover crops have either a positive effect or no effect on subsequent barley yield, depending on the cover crop species. Specifically, forage radish and hairy vetch showed the potential to increase the yield of subsequent crops, likely due to their ability to provide N for the barley. Although forage radish was winter-killed, it accumulated both a high biomass and high N levels in autumn, whereas hairy vetch was the best biomass producer and N accumulator in spring. Nevertheless, the rest of the tested cover crops did not reduce the yield of subsequent barley crops.

**Author Contributions:** Conceptualization, M.T. and E.L.; methodology, M.T., L.N., L.T., and A.M.; software, I.T., S.T; formal analysis, M.T., Ü.T., and I.H.; writing—all authors contributed to writing the manuscript.

**Funding:** The research was supported by the Estonian Ministry of Rural Affairs' project "Varieties suitable for organic cultivation in Estonia" (10.1-2/430 p.4; PA1-RUP-026). I.H. was supported by the Estonian Research Council grant PUT1170.

**Acknowledgments:** The authors would like to thank the two anonymous reviewers for helpful comments on the manuscript.

**Conflicts of Interest:** The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

## References

1. Askegaard, M.; Eriksen, J. Growth of legume and nonlegume catch crops and residual-N effects in spring barley on coarse sand. *J. Plant Nutr. Soil Sci.* **2007**, *170*, 773–780. [CrossRef]
2. Sapkota, T.B.; Askegaard, M.; Lægdsmand, M.; Olesen, J.E. Effects of catch crop type and root depth on nitrogen leaching and yield of spring barley. *Field Crop Res.* **2012**, *125*, 129–138. [CrossRef]
3. Doltra, J.; Olesen, J.E. The role of catch crops in the ecological intensification of spring cereals in organic farming under Nordic climate. *Eur. J. Agron.* **2013**, *44*, 98–108. [CrossRef]
4. Büchi, L.; Gebhard, C.A.; Liebisch, F.; Sinaj, S.; Ramseier, H.; Charles, R. Accumulation of biologically fixed nitrogen by legumes cultivated as cover crops in Switzerland. *Plant Soil* **2015**, *393*, 163–175. [CrossRef]
5. Li, X.; Petersen, S.O.; Sørensen, P.; Olesen, J.E. Effects of contrasting catch crops on nitrogen availability and nitrous oxide emissions in an organic cropping system. *Agric. Ecosyst. Environ.* **2015**, *199*, 382–393. [CrossRef]
6. Justes, E.; Beaudoin, N.; Bertuzzi, P.; Charles, R.; Constantin, J.; Dürr, C.; Hermon, C.; Joannon, A.; Le Bas, C.; Mary, B.; et al. The use of cover crops to reduce nitrate leaching: Effect on the water and nitrogen balance and other ecosystem services. In *Synopsis of the Study Report INRA*; INRA: Paris, France, 2012; 68p.
7. Jahanzad, E.; Barker, A.V.; Hashemi, M.; Sadeghpour, A.; Eaton, T.; Park, Y. Improving yield and mineral nutrient concentration of potato tubers through cover cropping. *Field Crops Res.* **2017**, *212*, 45–51. [CrossRef]
8. Sainju, U.M.; Whitehead, W.F.; Singh, B.P. Biculture legume–cereal cover crops for enhanced biomass yield and carbon and nitrogen. *Agron. J.* **2005**, *97*, 1403–1412. [CrossRef]
9. Tosti, G.; Benincasa, P.; Farneselli, M.; Pace, R.; Tei, F.; Guiducci, M.; Thorup-Kristensen, K. Green manuring effect of pure and mixed barley—Hairy vetch winter cover crops on maize and processing tomato N nutrition. *Eur. J. Agron.* **2012**, *43*, 136–146. [CrossRef]
10. Tribouillois, H.; Cohan, J.P.; Justes, E. Cover crop mixtures including legume produce ecosystem services of nitrate capture and green manuring: Assessment combining experimentation and modelling. *Plant Soil* **2016**, *401*, 347–364. [CrossRef]
11. Couëdel, A.; Alletto, L.; Tribouillois, H.; Justes, E. Cover crop crucifer-legume mixtures provide effective nitrate catch crop and nitrogen green manure ecosystem services. *Agric. Ecosyst. Environ.* **2018**, *254*, 50–59. [CrossRef]
12. Justes, E.; Mary, B.; Nicolardot, B. Quantifying and modelling C and N mineralization kinetics of catch crop residues in soil: Parameterization of the residue decomposition module of STICS model for mature and non mature residues. *Plant Soil* **2009**, *325*, 171–185. [CrossRef]
13. Blanco-Canqui, H.; Shaver, T.M.; Lindquist, J.L.; Shapiro, C.A.; Elmore, R.W.; Francis, C.A.; Hergert, G.W. Cover crops and ecosystem services: Insights from studies in temperate soils. *Agron. J.* **2015**, *107*, 2449–2474. [CrossRef]
14. Nielsen, D.C.; Lyon, D.J.; Hergert, G.W.; Higgins, R.K.; Calderon, F.J.; Vigil, M.F. Cover crop mixtured do not use water differently than single-species plantings. *Agron. J.* **2015**, *107*, 1025–1038. [CrossRef]
15. Handlířová, M.; Lukas, V.; Smutný, V. Yield and soil coverage of catch crops and their impact on the yield of spring barley. *Plant Soil Environ.* **2017**, *63*, 195–200.
16. Ćupina, B.; Vujić, S.; Krstić, D.J.; Radanović, Z.; Čabilovski, R.; Manojlović, M.; Latković, D. Winter cover crops as green manure in a temperate region: The effect on nitrogen budget and yield of silage maize. *Crop Pasture Sci.* **2017**, *68*, 1060–1069. [CrossRef]
17. Toom, M.; Talgre, L.; Mäe, A.; Narits, L.; Tamm, S.; Edesi, L.; Haljak, M.; Lauringson, E. Selecting winter cover crop species for northern climatic conditions. *Biol. Agric. Hortic.* **2019**. [CrossRef]
18. Talgre, L.; Lauringson, E.; Makke, A.; Lauk, R. Biomass production and nutrient binding of catch crops. *Žemdirb. Agric.* **2011**, *98*, 251–258.
19. [IUSS] Working Group WRB. *World Reference Base for Soil Resources 2014, Update 2015 International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*; World Soil Resources Reports No. 106; FAO: Rome, Italy, 2015.
20. Estonian Weather Service. Estonia (EE). Available online: http://www.ilmateenistus.ee/kliima/kliimanormid/sademed/?lang=en (accessed on 30 April 2019).
21. Dean, J.E.; Weil, R.R. Brassica cover crops for nitrogen retention in the mid-Atlantic coastal plain. *J. Environ. Qual.* **2009**, *38*, 520–528. [CrossRef]

22. Weil, R.; Kremen, A. Thinking across and beyond disciplines to make cover crops pay. *J. Sci. Food Agric.* **2007**, *87*, 551–557. [CrossRef]
23. Campiglia, E.; Paolini, R.; Colla, G.; Mancinelli, R. The effects of cover cropping on yield and weed control of potato in a transitional system. *Field Crop Res.* **2009**, *112*, 16–23. [CrossRef]
24. Sainju, U.M.; Singh, B.P.; Whitehead, W.F. Comparison of the effects of cover crops and nitrogen fertilization on tomato yield, root growth, and soil properties. *Sci. Hortic.* **2001**, *91*, 201–214. [CrossRef]
25. Tamm, I.; Tamm, Ü.; Ingver, A.; Koppel, R.; Tupits, I.; Bender, A.; Tamm, S.; Narits, L.; Koppel, M. Different leguminous pre-crops increased yield of succeeding cereals in two consecutive years. *Acta Agric. Scand. Sect. B* **2016**, *66*, 593–601. [CrossRef]
26. Sievers, T.; Cook, R.L. Aboveground and root decomposition of cereal rye and hairy vetch cover crops. *Soil Sci. Soc. Am. J.* **2018**, *82*, 147–155. [CrossRef]

# CURRICULUM VITAE

| | |
|---|---|
| **First name:** | Merili |
| **Last name:** | Toom |
| **Date of birth:** | 23.06.1983 |
| **Position:** | Junior researcher |
| **Employment:** | Estonian Crop Research Institute, Jõgeva Plant Breeding Department |
| **Academic degree:** | Master of Science (MSc), Estonian University of Life Sciences |

**Education:**

| | |
|---|---|
| 2011–2021 | Estonian University of Life Sciences, PhD studies in Agriculture |
| 2006–2008 | Estonian University of Life Sciences, MSc studies in production and marketing of agricultural products |
| 2003–2006 | Estonian University of Life Sciences, BSc studies in production and marketing of agricultural products |

**Professional employment:**

| | |
|---|---|
| Since 2013 | Estonian Crop Research Institute, junior researcher |
| 2009–2011 | Estonian University of Life Sciences, technician |

**Administrative activities:**

| | |
|---|---|
| Since 2011 | Member of Estonian Plant Protection Society |
| Since 2010 | Member of Estonian Academic Agricultural Society |

**Research interests:**

Sustainable agriculture, cover crops

**Participation in research projects:**

| | |
|---|---|
| 2021 | PRG1260 *Correlation of farming systems and gene expression in crops* |
| 2016−2020 | PA1-RUP-026 *Varieties suitable for organic production in Estonia* |
| 2016−2019 | 616215780031 *Effective organic production and improvement of soil fertility, producing high quality organic seed* |
| 2014−2017 | 613781 *Enhancing of legumes growing in Europe through sustainable cropping for protein supply for food and feed* |

**Professional training:**

| | |
|---|---|
| 2015 | *Terminology in Estonian language*, Estonian University of Life Sciences |
| 2014 | *Advancing of professional terminology in Estonian language*, Estonian University of Life Sciences |

**Honours and awards:**

| | |
|---|---|
| | ASTRA Doctoral School of Earth Sciences and Ecology, the European Regional Development Fund. Project *Development of a research center for plant breeding and agrotechnology*<br>– to attend a conference in 2018 and 2019 |
| | Archimedes DoRa Plus short-term mobility<br>– to visit a university abroad in 2017 |
| 2018 | AS Baltic Agro scholarship |
| 2018 | Young researcher's award, Research Centre of Organic Farming |
| 2017 | Young researcher's award, Research Centre of Organic Farming |

# ELULOOKIRJELDUS

| | |
|---|---|
| **Eesnimi:** | Merili |
| **Perekonnanimi:** | Toom |
| **Sünniaeg:** | 23.06.1983 |
| **Ametikoht:** | Nooremteadur |
| **Töökoht:** | Eesti Taimekasvatuse Instituut |
| **Teaduskraad:** | Magistrikraad põllumajandussaaduste tootmise ja turustamise erialal |

**Haridustee:**

| | |
|---|---|
| 2011–2021 | Eesti Maaülikool, doktoriõpe põllumajanduse erialal |
| 2006–2008 | Eesti Maaülikool, magistriõpe põllumajandussaaduste tootmise ja turustamise erialal |
| 2003–2006 | Eesti Maaülikool, bakalaureuseõpe põllumajandussaaduste tootmise ja turustamise erialal |

**Teenistuskäik:**

| | |
|---|---|
| Alates 2013 | Eesti Taimekasvatuse Instituut, nooremteadur |
| 2009–2011 | Eesti Maaülikool, katsetehnik |

**Teadusorganisatsiooniline tegevus:**

| | |
|---|---|
| Alates 2011 | Eesti Taimekaitse Seltsi liige |
| Alates 2010 | Akadeemilise Põllumajanduse Seltsi liige |

**Teadustöö põhisuunad:**

Keskkonnasäästlik põllumajandus, vahekultuurid

**Osalemine teadusprojektides:**

| | |
|---|---|
| 2021 | PRG1260 *Viljelusviisi ja geenide ekspressiooni seosed põllumajandustaimedes* |
| 2016−2020 | PA1-RUP-026 *Mahepõllumajanduses Eestis kasutamiseks sobivad sordid* |

| | |
|---|---|
| 2016−2019 | 616215780031 *Kvaliteetse maheseemne tootmine, efektiivne mahetootmine ja viljakas muld* |
| 2014−2017 | 613781 *Kaunviljade kasvatamise edendamine Euroopas toidu- ja söödaotstarbeliste valgukultuuride jätkusuutlikuks kasvatamiseks* |

**Enesetäiendus:**

| | |
|---|---|
| 2015 | *Terminiloomine, termin tekstis ja terminibaaside kasutamine*, Eesti Maaülikool |
| 2014 | *Eestikeelne terminikoolitus*, Eesti Maaülikool |

**Teaduspreemiad ja stipendiumid:**

| | |
|---|---|
| 2017 | Archimedes DoRa Pluss lühiajaline õpiränne ASTRA Maateaduste ja ökoloogia doktorikool. Projekt *Sordiaretuse ja agrotehnoloogia teaduskeskuse väljaarendamine* (SORDIARETUS) – osalemine konverentsil 2018 ja 2019 |
| 2018 | AS Baltic Agro stipendium |
| 2018 | Noorteadlase mahestipendium |
| 2017 | Noorteadlase mahestipendium |

# LIST OF PUBLICATIONS

## Scholarly articles indexed by Web of Science (1.1.)

**Toom, M**., Talgre, L., Mäe, A., Tamm, S., Narits, L., Edesi, L., Haljak, M. & Lauringson, E. (2019). Selecting winter cover crop species for northern climatic conditions. Biological Agriculture and Horticulture, 35(4), 263–274.

**Toom, M**., Tamm, S., Talgre, L., Tamm, I., Tamm, Ü., Narits, L., Hiiesalu, I., Mäe, A. & Lauringson, E. (2019). The effect of cover crops on the yield of spring barley in Estonia. Agriculture 9, 172–180.

**Toom, M**., Talgre, L., Pechter, P., Narits, L., Tamm, S. & Lauringson, E. (2019). The effect of sowing date on cover crop biomass and nitrogen accumulation. Agronomy Research, 17 (4), 1779−1787.

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 system. Agronomy Research, 15 (5), 1934−1943.

Kuht, J., Eremeev, V., Talgre, L., Madsen, H., **Toom, M**., Mäeorg, E. & Luik, A. (2016). Soil weed seed bank and factors influencing the number of weeds at the end of conversion period to organic production. Agronomy Research, 14 (4), 1372−1379.

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

**Toom, M**., Tamm, S., Talgre, L., Tamm, I., Tamm, Ü., Narits, L., Hiiesalu, I., Edesi, L., Talve, T., Mäe, A. & Lauringson, E. (2021). The effect of sowing date on biomass and nitrogen accumulation of five winter cover crop species. Agricultural Research and Technology, 25, 133–140.

## Articles published in local conference proceedings (3.5.)

Kuht, J., Eremeev, V., Talgre, L., Madsen, H., **Toom, M**., Loit, E. & Luik, A. (2017). Muutused mulla umbrohuseemnete sisalduses maheviljelusliku taimekasvatuse alguses. Ilme Tupits, Sirje Tamm, Ülle Tamm, Anu Toe (Toim.). Taimekasvatuse alased uuringud Eestis 2017 (53−58). AS Rebellis.

**Toom, M**., Lauringson, E., Talgre, L., Tamm, S. & Narits, L. (2017). Sügiseste ja talviste vahekultuuride biomassi moodustumine ja toitainete sidumine. Ilme Tupits, Sirje Tamm, Ülle Tamm, Anu Toe (Toim.). Taimekasvatuse alased uuringud Eestis 2017 (26−32). AS Rebellis.

Narits, L. & **Toom, M.** (2017). Sojaoa saaki ja saagi kvaliteeti mõjutavad tegurid. Ilme Tupits, Sirje Tamm, Ülle Tamm, Anu Toe (Toim.). Taimekasvatuse alased uuringud Eestis 2017 (106−111). AS Rebellis.

**Toom, M**., Lauringson, E., Talgre, L., Tamm, S. & Narits, L. (2017). Uute vahekultuuride liikide sobivus Eesti oludesse. Luule Metspalu, Anne Luik, Elen Peetsmann (Toim.). Teaduselt mahepõllumajandusele (145−148). Eesti Loodusfoto.

## Published conference abstracts (5.1. and 5.2.)

**Toom, M**., Narits, L., Tamm, S., Talgre, L. & Lauringson, E. (2019). Nitrogen fixing winter cover crops for Estonian conditions. 21st International Congress on Nitrogen Fixation, Programme & Abstracts: *21st International Congress on Nitrogen Fixation*, Wuhan, China, 10–15 October 2019.

Narits, L. & **Toom, M**. (2017). Yield formation and protein and nitrogen content of field pea (*Pisum sativum* L.) depending on inoculation. In: Nitrogen Fication for Agriculture and Environment, Proceeding of the 20th International Congress on Nitrogen Fixation. *20th International Congress on Nitrogen Fixation*, Granada, Spain, 3–7 September 2017.

**Toom, M**., Narits, L. & Tamm, S. (2017). Yield formation and protein and nitrogen content of faba bean (*Vicia faba* L.) depending on inoculation. In: Advances in grain legume breeding, cultivation and uses for a more competitive value-chain. *International Conference Advances in* *grain legume breeding, cultivation and uses for a more competitive value-chain*, Novi Sad, Serbia, 27–28 September 2017.

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 system. 8th *International Conference on Biosystems Engineering 2017*. Book of Abstracts: 8th International Conference Biosystems Engineering 2017, Tartu, Estonia, 11–13 May 2017.

**Toom, M**., Lauringson, E., Talgre, L., Tamm, S. & Narits, L. (2017). Finding new cover crops for Estonian conditions. NJF Seminar 495 – 4th organic Conference: *Organics for tomorrow's food systems*, 13 (1), NJF Report, Mikkeli, Finland, 19–21 June 2017.

**Toom, M**., Narits, L., Sooväli, P., Põllumaa, L. & Mäe, A. (2016). Finding of superior *Rhizobium* strains for field pea and faba bean in Estonian soils. In Book of Abstracts: Second International Legume Society Conference. *Legumes for a sustainable world*, Portugal, 11–14 October 2016.

Kuht, J., Eremeev, V., Talgre, L., Madsen, H.; **Toom, M**.; Mäeorg, E. & Luik, A. (2016). Soil weed seed bank and factors influencing the number and species of weeds at the end of conversion period to organic production. Book of Abstracts: 7th International Conference Biosystems Engineering 2016. 7th *International Conference Biosystems Engineering 2016,* Tartu, Estonia, 12–13 May 2016.

Narits, L., **Toom, M**. & Sooväli, P. (2015). Selection of appropriate *Rhizobium* strains for field pea and faba bean. In Book of Abstract: NCC2015. *The 32nd Nordic Cereal Congress Future Food Security*, Espoo, Finland, 7–9 September 2015.

# VIIS VIIMAST KAITSMIST

**MARIANA MAANTE-KULJUS**
VIINAPUU (*VITIS* SP) SAAGI KÜPSUSNÄITJAD
MATURITY PARAMETERS OF GRAPEVINE (*VITIS* SP) YIELD
Professor **Kadri Karp**, dotsent **Leila Mainla**, dotsent **Ele Vool**
24. mai 2021

**BURAK ÖĞLÜ**
KLIIMAMUUTUSTE JA TEISTE ÖKOLOOGILISTE TEGURITE MÕJU VALITUD KALALIIKIDE POPULATSIOONIDELE JA KALAPÜÜGILE EESTI SUURJÄRVEDES
IMPACT OF CLIMATE CHANGE AND OTHER ECOLOGICAL FACTORS ON SELECTED FISH POPULATIONS AND FISHERY IN ESTONIAN LARGE LAKES
**Tanel Kaart, Külli Kangur, Fabien André Daniel Cremona**
28. mai 2021

**TARMO PILVING**
KOOSTÖÖ EESTI MAATURISMIS
COLLABORATION IN ESTONIAN RURAL TOURISM
Vanemteadur **Ants-Hannes Viira**, professor **Tiiu Kull**, nooremprofessor **Monika Suškevičs**
11. juuni 2021

**MARIKA KOSE**
RANNANIIDUD: SÄILIMINE, TAASTAMINE JA TAASTUMINE
COASTAL MEADOWS: MAINTENANCE, RESTORATION AND RECOVERY
Vanemteadur **Karin Kauer**, vanemteadur **Kadri Tali**
11. juuni 2021

**ELINA KARRON**
ERINEVATE KASVATUSTEHNOLOOGIATE MÕJU FUSARIUM SPP. ESINEMISELE JA MÜKOTOKSIINIDE TEKKIMISELE TERAVILJADEL
INFLUENCE OF CULTIVATION TECHNOLOGIES ON PATHOGENIC FUSARIUM SPP. OCCURRENCE AND PRODUCTION OF MYCOTOXINS IN CEREALS
Dotsent **Eve Runno-Paurson**, professor **Ülo Niinemets**, emeriitdotsent **Enn Lauringson**
15. juuni 2021

ISSN 2382-7076
ISBN 978-9949-698-86-8 (trükis)
ISBN 978-9949-698-87-5 (pdf)