Eesti Maaülikool
Estonian University of Life Sciences

BIOMASS PRODUCTION OF DIFFERENT GREEN MANURE CROPS AND THEIR EFFECT ON THE SUCCEEDING CROPS YIELD

ERINEVATE HALJASVÄETISKULTUURIDE BIOPRODUKTSIOON JA MÕJU JÄRGNEVATE KULTUURIDE SAAGILE

LIINA TALGRE

A Thesis
for applying for the degree of Doctor of Philosophy in
Plant Production

Väitekiri
Filosoofiadoktori kraadi taotlemiseks taimekasvatuse erialal

Tartu 2013

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LIST OF ORIGINAL PUBLICATIONS

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

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

III Talgre, L., Lauringson, E., Roostalu, H., Astover, A., Makke, A. 2009. Phytomass formation and carbon amount returned to soil depending on green manure crop. *Agronomy Research*, 7 (special issue 1), 517–521.

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

V Talgre, L., Lauringson, E., Makke, A., Lauk, R. 2011. Biomass production and nitrogen binding of catch crop. *Žemdirbystė=Agriculture*, Vol. 98 (3), 251–258.

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ABBREVIATIONS

C	carbon
C_{tot}	total carbon
Ca	calcium
C:N	carbon nitrogen ratio
CC	catch crop
C_{org}	organic carbon
CP	crude protein
DM	dry matter
GM	green manure
K	potassium
K_m	mineralized potassium
K_{tot}	total potassium
$LSD_{0.05}$	least significant differences
MFE	mineral fertilizer equivalent
N	nitrogen
NH_4^+	ammonium
NH_4-N	ammonium-N
N_m	mineralized nitrogen
N_{min}	mineral fertilizers nitrogen
NO_3^-	nitrate ion
NO_3-N	nitrate-N
N_{org}	nitrogen in organic matter
N_{tot}	total nitrogen
OM	organic matter
P	phosphorus
P_m	mineralized phosphorus
P_{tot}	total phosphorus
SD	standard deviation
SE	standard error
SOC	soil organic carbon
SOM	soil organic matter
S_{tot}	total sulphur
VW	volume weight
WGC	wet gluten content

1. INTRODUCTION

Attention is increasingly paid to environmental issues and organic farming as well as to the efficient use of natural resources (Park and Seaton, 1996; Struik and Bonciarelli, 1997; Bade and Kruseman, 1998; Granstedt, 2000). Conventional farming aims to maximally simplify agroecosystems, i.e. maximally intensifying and specializing production, whereas organic farming is guided by the ecological principle, i.e., the more complicated and diverse the agroecosystem the more stable it is (Luik et al., 2008). The interest in organic farming is stimulated not only by the concern for stable and well-balanced development of the economy (especially in the light of costly energy resources) but also by increased consumer awareness of food safety (Cesevičienė et al., 2009). Increasing soil fertility and maintaining it at an optimal level is one of the key factors for sustainable agriculture.

The use of synthetic N fertilizers has eliminated a major elemental constraint with respect to enriching the soil stock of organic C and N originally managed by organic manure amendments and leguminous cultures (Hirel et al., 2011). Scientists have focused in their studies on nitrogen, a factor limiting the crop to a greater extent; however, it is also important to optimise the application of phosphorus and potassium and to keep their inputs as low as possible (Lampkin, 1990; Fowler et al*.,* 1993). It is known that on the global scale P is a crop-limiting element on 30–40% of arable land (Kirkby and Roemheld, 2006). The overall balance of P and K in Estonia's agricultural soil is negative. The depletion of soil stock P and K may become a limiting factor in organic farming with a high proportion of grasslands (Astover, 2007).

It is estimated that by 2050 the earth's population is expected to increase to 10 billion and agricultural production should be increased by 2 times to feed it (Anonymus, 2010). Fertilizer application and grain sown area will have to be increased accordingly. Farming of grain as a monoculture requires higher use of herbicides (Hauggaard–Nielsen et al., 2001), fungicides (Jensen et al., 2005) and fertilizers. In today's agricultural production, opportunities need to be found to influence crops without using mineral fertilizers. The high price of fertilizers, the low sale price of crops and the concern for maintaining and improving crop fertility force us to consider growing leguminous herbs to a far greater extent than just a few decades ago.

Fertilization determines crop yield, the level of agricultural production, the balance of plant nutrients as well as the impact on the environment, as plants consume nutrients added to from the soil only partially (Roostalu, 2008). Better knowledge of plant development, biomass formation over time and herbal production formation as well as the factors influencing these processes, would help us manage the agroecosystem in such a way as to gain more produce with less negative environmental and social impact and smaller investments (Altieri, 1995).

It appears from an analysis of the use of mineral fertilizers in Europe for particular crops that soil nutrients are removed with the harvest to a greater extent than they are introduced with mineral fertilizers; hence, the nutrient balance is negative (Roostalu et al., 2000; Astover, 2007). At the same time, studies conducted in Finland (Uusitalo et al., 2007; Hakala, 2009) have shown that the N and P balances in Finland are still heavily positive and the nutrient leaching risks continue to be high. In Estonia, the soil balance of key plant nutrients and humus is negative due to inadequate fertilizer use. Considerable degradation of the arable land has taken place, which will significantly reduce the sustainability and competitiveness of agriculture (Roostalu et al., 2000; Astover and Roostalu, 2002; Astover et al., 2006). The low soil humus content is a crop yield limiting factor, particularly in south Estonia (Järvan et al., 1996). In Estonia, cereal crop yield is significantly lower than that in west European countries (EU report, 2011).

In parallel with conventional farming, transition to organic farming is increasingly taking place and organic food is valued. In organic farming, the aim is to develop production in an integrated manner, in harmony with nature, with no use of synthetic mineral fertilizers, pesticides and genetically modified organisms. Under this ecological mode of production, the pursuit is to maximise efficient use of the resources within the agroecosystem and to bring little in from outside (Kirchmann and Ryan, 2004). In Estonia, organic crop farming is concentrated in regions with relatively low soil fertility (Hiiu and Saare counties and the western and southeastern regions of Estonia) whereas in the fertile soils of central Estonia it is little employed (Luik et al., 2008). In organic farming, the cultivation of leguminous green manure (GM) crops is the main means of enriching the soil with nutrients. Leguminous GM crops bind atmospheric nitrogen and their deep-reaching roots bring plant nutrients (P, K, Ca) up into the ploughed layer (Teit, 1990), making them available to succeeding crops (Witter and Johansson, 2001). Unlike other organic fertilizers, leguminous GM crops with their strong roots break up deeper soil layers, improving soil structure and enabling the roots of succeeding crops to reach deeper down. In addition, leguminous green fertilizers stimulate soil microbiological activity, which determines soil quality and ensures soil aggregate stability (Brussard et al., 2004; Tejada et al., 2008).

As soil fertility in Estonia is predominantly low and the nutrient balance negative, GM has an important role in raising soil fertility and ensuring large and stable yields in both conventional and organic farming. The key is growing them in soils of low humus content and inadequate microbiological activity.

In recent years, many countries have started to investigate possibilities of reducing soil plant nutrient loss in the plant-free period. It is known that soil organic matter mineralization also occurs outside the crop growth period (Powlson, 1993; Vos and Van der Putten, 2001). Nutrient leaching is influenced by various factors. Several studies have suggested that green crop ploughing time and ploughed herbage influence soil nitrogen leaching. Based on studies conducted in Scandinavian countries, ploughing or other kinds of soil preparation in spring as opposed to autumn have reduced the risk of nitrogen leaching from the soil (Davies et al*.,* 1996; Stenberg et al., 1999; Lahti and Kuikman, 2003).

Considering the above, the Department of Field Crop and Grassland Husbandry of the Estonian University of Life Sciences has conducted a number of studies focused on growing various GM crops in Nordic conditions. Species theoretically cultivatable as GM by employing different agricultural techniques were selected as objects of this study. Part of the study deals with biologically bound nitrogen. Previously, few studies have been performed on such a number of GM species under similar circumstances and at the same time.

2. REVIEW OF LITERATURE

2.1. Soil organic matter

Soil organic matter (SOM) content is generally regarded as one of the main indicators of soil fertility (Carter, 2002; Schjønning et al., 2004). Soil fertility is especially affected by SOM, which depends on biomass input to compensate rapid mineralization, leaching and erosion (Roose and Barthes, 2001). SOM helps to improve the humus status of soil, thus also improving soil structure and physical as well as hydrophysical properties (Goyal et al., 1999). Carbon from plants enters the soil organic carbon (SOC) pool in the form of either aboveground biomass, litter or root material (Farrar et al., 2003; Bardgett et al., 2005). The accumulation of OM in the soil results from the activity of the soil biota: plants ensure the supply of organic matter while soil fauna and microorganisms decompose it. Decomposition drives nutrient return from plant residues to soil, which directly determines the availability of nutrients for plant uptake. SOC pools are the balance between C input via primary productivity, and output via decomposition processes (Olson, 1963; Amundson, 2001). SOM content can be increased by increasing the amount of OM taken into the soil and/or reducing the decomposition rate of the OM taken into the soil. Abundant supply of OM into the soil has a favourable effect on soil biota and soil biological activity (Eriksen-Hamel et al., 2009).

Soil humus content in Estonia is generally low, making it one of the primary crop yield limiting factors. In particular, this is a problem in south Estonia, where 40–60% of the total of arable land has a humus content of less than 2% (Järvan et al., 1996).

In the 1990s, 2–2.5 Mg ha^{-1} of dry matter (DM) was introduced into soil by means of organic fertilizers; considering also plant residue remaining in soil (4–5 Mg ha^{-1}), we may conclude based on long-term field trials that the agricultural soil humus content at that period stayed at the same level or increased annually by an average of 0.03% (Piho, 1973, 1978; Kõlli, 1986). In the ten years following the regaining of independence, production was at the expense of soil resources whereas following Estonia's accession to the European Union land use has become somewhat more extensive (Roostalu, 2008) and the use of fertilizers and manure has remained at the same level, maintaining a negative balance of plant nutrients (Astover et al., 2006), particularly in organic farming, where grasslands are significant (Astover, 2007).

In cultivated lands, the primary OM input is plant residues (roots, shoots); in addition, soil fertility is improved by adding manure to the soil. Another opportunity is to use different crops in rotations as so-called green manures (GM). In grain farming, the primary plant residue is straw. Some scientists have found that straw input has little or no effect on SOM (Campbell et al., 1991; Soon, 1998); on the other hand, results from straw ploughing show SOC increase by 5–50% (Thomsen et al., 1993; Smith et al 1997); however, this is lower than in crop rotations where manure or GM is used (Schjønning et al., 2007). Results from long-term experiments (Persson and Kirchmann, 1994) indicate that SOM declines where spring cereals are grown continuously and the application of organic manure ceases. Long-term experiments (over 30 years) show increases in SOC concentrations by 15 to 120% (Jarecki and Lal, 2003) depending on crop or rotation, bare fallow, N fertilization, manure application, duration of experiments, and other site-specific conditions (Mazzoncini et al., 2011).

2.2. Green manure crops

In either conventional or organic farming where manure is not available, one way to improve soil is to grow green manure plants. A GM is grown specifically for the purpose of improving SOM and for its 'fertilizer value' after incorporation before the following arable crop (Parsons, 1984).

The organic matter introduced into soil with GM improves soil humus status and increases SOC and total N contents. Organic C and total N contents are good soil fertility and productivity indicators, influencing soil physical, hydrophysical, chemical and biological properties (Reeves, 1997). Nitrogen is the key element in obtaining a high yield of good quality. It is involved in all of the plant's metabolic processes, its rate of uptake and partition being largely determined by supply and demand during the various stages of plant growth (Delogua et al., 1998). Application of harvested plant residues directly to a field, as GM, is commonly used in the cultivation of vegetables and crop production systems that do not involve animals, and can provide substantial amounts of plant-available N (Wivstad, 1999). Also, nutrients released from plant residues increase the yield of succeeding crops. Green manure crops are most effective in organic farming where the main issues are the application of nutrients into soil and growing grains with high-quality properties. In contrast to rapid-action mineral fertilizers, GM release nutrients over a longer period, granting a steady supply of N for succeeding crops (Jansson and Persson, 1982; Freyer, 2002) and reducing vegetative growth of succeeding crops and the risk of cereal lodging (Brown et al., 2007). Beneficial effects of the preceding crop on water use efficiency and reduction in crop diseases can in some cases account for up to 50% of the yield response of the succeeding crop (Harper et al., 1995). Green manure crops contribute to weed control, thereby reducing herbicide use (Ross et al., 2001; Linares et al., 2008); in addition, they reduce allelopathic impact in grain-rich rotations (Conklin et al., 2002; Altieri et al., 2008). Ghosh et al. (2007) found that some legumes seem to reduce the nitrate concentration in the soil profile. In addition, green manures enhance the efficiency of mineral fertilizers (Drinkwater et al., 1998) and may also offer habitat or resources for beneficial organisms (Altieri, 2002).

2.2.1. Legumes

The most commonly used GM is legumes, which fix atmospheric nitrogen. Legumes are very valuable as GM crops, due to their symbiotic N_2 fixation and their relatively low cell wall contents and C:N ratios, resulting in rapid release of N. Forage legumes are widespread, and have the potential to give high yields over a range of climatic conditions. Symbiotic N fixation by legumes is an important source of N to agriculture, particularly under organic farming conditions (Mäder et al., 2002). Obtaining N from legumes is potentially more sustainable than from mineral fertilizers (Crews and Peoples, 2004). Adding a legume into the biota improves soil nutrient cycling, which enhances the retention of new and residing C and N in soil (De Deyn et al., 2011). Legume-derived N is qualitatively important for building up SOM and storing more C (Drinkwater et al., 1998; Fornara et al., 2008). Apart from N, legumes also fix soil Ca, P, K, S and B (Frame et al., 1998; Smiley et al., 1991; Marschner, 1995; Kuusela, 2006). Legumes can absorb nutrients from lower soil layers with their well-developed and deep root systems and return the nutrients to upper soil layers with their biomass. Deep-rooted legumes can capture leached nitrate and other nutrients and return them to the active rooting zone of the companion crop (Teit 1990; Campbell et al., 1994). In addition to the N benefits, legume crops have many other positive effects on subsequent crops, such as decreased plant diseases (Harper et al., 1995), decreased weed density (Conklin et al., 2002; Halling et al., 2001; Dordas and Lithourgidis, 2011), improved soil structure (Goyal et al., 1999) and exudation of beneficial compounds, such as auxins, gibberellins and cytokinins (Van Loon, 2007).

The amount of N bound (symbiotically fixed) by legumes depends on the plant species and genotype (Unkovich and Pate, 2000), its N-fixation capacity, the amount of biomass formed, the *Rhizobia*-plant symbiosis and the efficiency of the symbiosis (Liu et al., 2011) as well as on environmental factors (Giller and Cadisch, 1995; Halling et al., 2004). N fixation by leguminous crops is at its maximum during blossoming and starts to decrease in the seed-development period (Leinonen, 2000). Soil properties also influence the growth of legumes and may be decisive for the proportion of N derived from the atmosphere. This decreases with increasing amounts of N available from SOM and from any organic or mineral fertilizer (Riesinger and Herzon, 2010). Høgh-Jensen (2003) reported that P and K deficits affect the physiological processes of leguminous plants (white clover) but do not limit the proportion of N derived from the atmosphere.

When growing legumes as the main crop, N leaching may occur. To prevent this, legumes are widely grown with graminaceous plants (Samson, 1991; Halling, 2002; Palmborg et al., 2005). Growing graminaceous and leguminous plants together increases herbage yield (Halling et al., 2001). The associated crop uses the N fixed by the legume for its growth. Nitrogen transfer from the legume to the associated crop increases the cropping system's yield and N use efficiency (Fujita et al., 1992). Heichel and Henjum (1991) found that a good soil structure also supports root growth, which is necessary for the grasses or cereals as associated crops to accumulate N from neighbouring legumes (Giller and Wilson, 1991). Simultaneously, legume biomass formation in the combination decelerates (Dordas and Lithourgidis, 2011), resulting in lower amounts of biologically bound nitrogen (Jørgensen et al., 1999).

The main contribution of legumes in supplying N to succeeding crops appears to be the maintenance or increase of soil organic N, which is decomposed at relatively slow rates in following years (Giller and Cadisch, 1995, Jørgensen et al., 1999, Sanchez, 2004). A higher proportion of applied N is usually recovered by plants from fertilizer rather than from legume residues in the first cropping cycle. In northern European conditions, 24–30% of the N contained in low C:N ratio crop residues is mineralized during one cropping period (Gunnarsson and Marstorp, 2002). Cereals grown after legumes usually take up about 15–20% of legume N (Crews and Peoples, 2005).

2.2.2. Green manure crops studied

The most widely used forage legumes in temperate and northern areas are the perennials, red clover and white clover (Huss-Danell and Chaia, 2005; Riesinger and Herzon, 2010), but there is also potential for increased use of lucerne, bird's foot trefoil and galega. Red clover and white melilot are the most popular green manure crops in Estonia, but use has also been made of annual and perennial lupin. White melilot was researched and grown in Estonia in the 1950s and 60s (Haller, 1953; Reintam, 1958; Kõrgas, 1971). Subsequently, extensive use of mineral N fertilizers and its declining importance as a forage crop resulted in reduced interest in white melilot. Recent decades have seen renewed interest in the crop. White melilot is a valued green manure crop that can also be grown on drier (Haller, 1953; Beinareet et al., 1997; Müller et al., 2003) and low-fertility thin-layer soils (Smith and Valenzuela, 2002). Bird's foot trefoil is suitable for soils too poor for red clover or lucerne, and may be productive under nutrient stress (Halling et al., 2001). In Estonia, lucerne (*Medicago sativa* L.) and hybrid lucerne (*Medicago varia* Martyn) are grown as fodder (Tamm, 2006) but their impact as green manure has not been previously studied. Graminaceous plants, such as westerwold ryegrass, which is recommended as an undersowing for cereals, can also be grown as green manure.

2.3. Catch crops

Catch crops (CC) are used more and more intensively to increase N recycling by reducing leaching (Crew and People, 2004). The term "catch crop" is used for a crop whose main purpose is to prevent nutrient leaching, because CC accumulate soil mineral N after the harvest of the main crop and thus reduce the amount of soil mineral N endangered by leaching (Rogasik et al., 1992; Karlsson-Strese et al., 1996; Knott, 1996; Richards et al., 1996; Thomsen and Christensen, 1999; Vos and van der

Putten, 2001). Appropriate CC are those that bind free soil nutrients and form a large biomass during a short growth period and are suitable for rotation botanically (similar species must not be grown too often for risk of disease and pest spread), i.e., crops grown less or not at all as main crops in the rotation. CC are usually sown late in summer, immediately after harvesting the main crop, and usually after cereals, but it's becoming more common to sow them on early vegetable and legume (bean, pea) fields as well. The risk of N leaching from soil arises when nitrates not consumed by plants remain in the soil in autumn, so it is very important to fix nutrients in the crop-free period. The CC should certainly not lead to increased fertilizer N need (Thorup-Kristensen and Dresbøll, 2010; Piotrowska and Wilczewski, 2012). Legumes as CC supply more N through fixation, thus reducing the requirement for green fallow, which is an economically unfavourable component of the crop rotation (Müller et al., 2006). Jylhä et al. (2004) argue that, in connection with future climate changes, the risk of nutrient leaching may increase as temperature rises and precipitation in winter increases, which are ideal conditions for SOM decomposition and for mineralization and leaching of nutrients.

In regions where the growing period is longer and the sum of effective temperatures is greater than in Estonian conditions, a CC may absorb up to 200 kg N ha^{-1} of residual N and thus reduce N available for leaching and denitrification (van Dam, 2006). The use of CC has been shown to reduce water runoff and with that, the amount of eroded soil and pesticides (Rüttimann, 2001; Hakala et al., 2009). Also, cruciferous CC have the ability to efficiently deplete soil sulphate levels and thus reduce sulphate leaching potential (Eriksen and Thorup-Kristensen, 2002).

The N uptake by the CC may depend on plant species, sowing date (determined by the harvest time of the previous crop), amount of available soil N and weather conditions (Van Dam, 2006). It is generally assumed that legume CC are not as effective as non-legumes in depleting soil N and thus in their ability to reduce N leaching (Thorup-Kristensen, 1994, 2001; Thorup-Kristensen et al., 2003).

2.3.1. Major catch crops studied

In Europe, the most commonly used CC are non–legumes like westerwold ryegrass (*Lolium multiflorum* Lam.), white mustard (*Sinapis alba* L.), fodder radish (*Raphanus sativus oleiformis*) and Phacelia (*Phacelia* *tanacetifolia* Benth.). These CC are able to bind loose N in the soil (Thorup- Kristensen, 1994; Brant et al*.*, 2009).

Legume CC (pea (*Pisum sativum* L.) and Faba bean (*Vicia faba* L.) produce more biomass and take up much more N than non-legumes and should be grown where little inorganic N is left in the soil (Thorup- Kristensen et al., 2003). Faba bean has a higher N uptake than field pea at low temperatures (Power and Zachariassen, 1993).

2.4. Factors influencing green manure impact on succeeding crop

2.4.1. Green manure amount and the related N

Soil fertility and structure can be maintained and improved only in those agroecosystems that return adequate amounts of plant litter to the soil. The quantity of OM that is added to soil in an agroecosystem depends on the following factors: the plant species, the pedoclimatic conditions and the field management (fertilization, agrotechnology, land use) (Bolinder et al., 1997; Kumar and Goh, 2002; Pietola and Alakukku, 2005). The more OM and carbon is applied to soil, the more humus is formed. Under favourable growth conditions the bioproduction of green manure crops in DM may exceed 10 Mg ha^{-1}, which, through the humification process, provides 2–3 Mg ha^{-1} of soil humus given the humification coefficient of the OM is 0.1–0.3, depending on its composition (Piho, 1973). Nitrogen fixation by leguminous crops can be 200–300 kg N ha^{-1} per year (Kärblane, 1991; Viil and Võsa, 2005; Tonitto et al., 2006). According to some researchers, up to 370 kg N ha^{-1} can be imported this way (Carlsson and Huss-Danell, 2003), depending on the green manure crop. According to Becker et al. (1995), even in a short growth period of 45–60 days, green manure legumes can fix 80–100 kg N ha^{-1} the bulk of which (about 80%) is derived from biological N_2 fixation.

2.4.2. Organic matter decomposition and the factors influencing it

Once plant material has been incorporated into soil, decomposition starts immediately. The decomposition of plant residue is one of the most crucial processes in the biogeochemical cycle of ecosystems. The organic residue decomposition is a complex process determined by three main interacting groups of factors: chemical (composition of the residue), physical (climate and environment surrounding the litter), and biotic (microorganisms) (Swift et al., 1979; Andersen and Jensen, 2001; Magid et al., 2001; Berg and Laskowski, 2006; Havstad et al., 2010) After incorporation into the soil, microbial processes lead to mineralization of the catch crop N, which can subsequently be utilized by succeeding crops and increase yields (Thorup-Kristensen et al., 2003). Less researched are the capacity of catch crops to fix P, K, Ca and S, and the availability of the nutrients fixed by them to succeeding main crops.

2.4.2.1. Quality of organic matter

In many studies, residue N concentration or C:N ratio has been shown to be of critical importance in OM decay (Gunnarsson and Marstorp, 2002; Kumar and Goh, 2003; Gunnarsson et al., 2008; Fornara et al., 2009). Numerous studies of net N mineralization from decomposing legume material have been conducted on whole-plant materials of different species (Marstorp and Kirchmann, 1991; Haynes, 1997). Phosphorus and potassium release from shoot OM decomposition has been studied by Canadian scientists (Soon and Ashrad, 2002; Lupwayi et al., 2006a; Lupwayi et al., 2006b; Lupwayi et al., 2007). Information on the contribution of individual plant parts and different stages of maturity is available for red clover and yellow melilot (Wivstad, 1997; Wivstad, 1999).

Nitrogen in plant tissues is mainly bound in proteins, and returns to the pool of plant-available soil N during the microbial degradation of plant residues incorporated into the soil (Carlsson, 2005). Nitrogen is either immobilised by microorganisms during the decomposition of OM or mineralised into soil as ammoniacal N. The rate of N degradation depends to a high degree on the C:N ratio and N concentration of the plant residues (Breland, 1996; Velthof et al., 2002; Crews and Peoples, 2004; Tejada and Gonzalez, 2006). The lower the ratio of OM C:N and the higher its N content, the more N is released into soil in GM mineralization (Baggs et al., 2000a; Kumar and Goh, 2002; Chaves et al., 2004). The critical C:N ratio falls into the range of 15 to 33 (Frankenberger and Abdelmagid, 1985). The critical C:N ratio may vary depending on the time-scale (Breland, 1996) and composition (leaf/stem/root ratio) of the biomass (Bloemhof and Berendse, 1995; Crews and Peoples, 2005).

Plant residue incorporated into soil that contains little N and thus has a high C:N ratio may rather have a negative effect on the succeeding crop yield, for the decomposition of such material immobilises N (Cheshire et al., 1999; Henriksen and Breland 1999b). Growing plants and the microbes participating in OM decomposition process compete for soil nutrients (particularly N) afterwards (Kuzyakov et al., 2000). The plant residue N is not sufficient for microbes to perform the decomposition process, thus the microbes need to acquire the deficient N from elsewhere, e.g., from soil organic matter. Hence, next spring the N immobilisation related to cereal straw and root decomposition must be compensated by additional fertilization in excess of the conventional fertilizer quota prescribed for the particular crop. Cereal fertilization with mineral N can increase the concentration of N in crop residue, thereby increasing the rate at which it is decomposed by soil microorganisms (Conde et al., 2005, Coulter et al., 2009). Experiments have shown that the remaining straw may account for 50–60% of the applied DM after 1 year of decomposition (Cheshire et al., 1999) and 20% of the applied carbon after 4 years.

2.4.2.2. Environmental factors

Temperature, in combination with moisture content, is the most important environmental factor affecting microbial growth and activity in soils (Paul and Clark, 1996; Dalias et al., 2001; Pietikäinen et al., 2005) and therefore temperature and moisture influence decomposition processes (Meentemeyer, 1978). Also contact between plant residues and soil affects decomposition (Douglas et al., 1980; Lupwayi et al, 2004). An increase in soil temperature (Domisch et al., 2006) and moisture (Donnelly et al., 1990) generally results in greater rates of microbial activity, and thus increased rates of plant residue mass loss (Andersen and Jensen, 2001). Microbial activity is increase up to a temperature of about 30°C (Dalais et al., 2002; Rey et al., 2005), faster under aerobic conditions than under anaerobic conditions. An optimal temperature for microbial activity is reached between 35 and 45°C, and the optimal moisture content for OM decay is 50-60% (McKinley and Vestal, 1985; Chen et al., 2000). The research of Flanagan and Veum (1974) showed that OM decomposition can be limited by low air temperature as well as low moisture content, and that increasing only one of these factors does not compensate fully for the influence of the other limiting factor.

Thus, the dynamics of GM decomposition can be enhanced by proper timing of incorporation (Francis et al., 1995; Lahti and Kuikman, 2003).

It is important for GM ploughing to occur in late autumn, when low temperatures delay mineralization, or in spring. Poutala and Kuikman (1998) found that N mineralization is absent at temperatures below 0ºC; however, it can be caused by temperature fluctuation. In case of earlier ploughing, that is, under conditions that are more favourable for decomposition, rapid mineralization of plant parts more prone to decomposition (leaves) begins, as a result of which the released nutrients may be flushed from the ploughed layer with descending water before the next year's growing period. Also, warmer winters are expected to stimulate the mineralization of SOM in agricultural soils, followed by a release of nutrients, mainly N (Olesen et al., 2004). Lahti and Kuikman (2003) found that N mineralization of GM during freezing was avoided only by green manure incorporation at the onset of the freezing period. At the same time, it has been demonstrated that slow OM decomposition occurs even in frozen soil (Heaney and Nyborg, 1988; Henriksen and Breland, 1999a).

3. Hypotheses and aims of the study

In an agroecosystem, the amount of organic matter that gets stored in the soil depends on plant species, pedoclimatic conditions and applied agrotechnology. As green manure crops and green manure undersows haven't been comparatively studied in Estonia, the current research is focused on comparing different green manure crops and their cultivation in Estonia – both when pure sown or when undersown with cereals.

Hypotheses

- When organic matter from green manure reaches the soil, its mineralization rate and its effect on succeeding crops is influenced by the way it was sown (pure or undersown), the amount of biomass, its chemical composition and weather conditions.
- The decomposition rate of organic matter and its release of nutrients to the soil varies with plant species; it also differs between roots and above-ground biomass.
- It is possible to influence succeeding crop yields by different ploughing times of green manures; the duration of the effect of the ploughed biomass depends on the plant species.
- The biomass formation and nutrient binding capacities of catch crops depend on the plant species, the climatic conditions and the length of the growing period.

The objectives of the present study were as follows:

1. To determine the amount of the aboveground biomass and root system of various green manure crops, as well as their decomposition rate and amount of nutrients (N, P, K) introduced to soil.
2. To investigate the duration of the effect of, and the efficiency of, biologically bound nitrogen based on the yield and yield quality of succeeding crops.
3. To investigate the decomposition rate of organic matter at different C:N ratios.
4. To determine catch crop biomass amount, nutrient binding capacity and effect on soil plant available nitrogen content and succeeding crop yield, and to identify catch crops most suitable for Estonian conditions.

The objectives of the trials include examining the capacity of green manure crops to form biomass **(I; II; III, IV, V)**; analyzing the amount of nitrogen and carbon returned to soil **(I; II; III, IV, V);** the extent to which green manure crops fix nutrients (**I, II, V**); and determining the effect of these factors on yield **(I; II; III, IV, V)** and the yield quality of the succeeding crop **(IV)**; the efficiency and permanence of biologically fixed nitrogen **(II)**.

4. MATERIALS AND METHODS

4.1. Experimental site and design

The trials were carried out at the Department of Field Crop Husbandry of the Estonian University of Life Sciences (EMU), Institute of Agricultural and Environmental Sciences (58°23´N, 26°44´E). The soil type of the experimental area was sandy loam *Stagnic Luvisol* in the WRB 1998 classification. The mean characteristics of the humus horizon were as follows: organic C (C_{org}) 1.1–1.2%, total N (N_{tot}) 0.10–0.12%, plant available phosphorus (P) 110–120 mg kg^{-1}, potassium (K), pH_{KCl} 5.9, soil bulk density 1.45–1.50 Mg m^{-3}. The thickness of the ploughing layer was approximately 27–29 cm.

Randomised complete block design in 4 replications was used (Hills and Little, 1972). The size of each test plot was 30 m^2 (3x10 m).

The research was based on four trials: two GM field trials, one catch crop field trial and one OM decomposition trial.

Experiment 1: Green manure trial conducted in 2004-2007. The field experiment was established in spring 2004 using the following variants of GM crops and fertilization:

Variant A: legume pure sowings - red clover (*Trifolium pratense) cv.* 'Jõgeva 205', lucerne *(Medicago sativa) cv.* 'Daisy', hybrid lucerne *(Medicago media) cv.* 'Karlu', bird's-foot trefoil *(Lotus corniculatus) cv.* 'Norcen';

Variant B: spring barley (*Hordeum vulgare* L.) with undersowings of red clover, lucerne, hybrid lucerne, bird's-foot trefoil, pea, westerwold ryegrass *(Lolium multiflorum westerwoldicum) cv.* 'Talvike';

Variant C: spring barley with dairy manure (60 Mg ha^{-1}) applied before ploughing 2004;

Variant D: spring barley with mineral fertilizer. The fertilizer treatments were 0 (N_0), 50 (N_{50}) and 100 (N_{100}) kg N ha^{-1} (every year with cereal sowing). Ammonium nitrate (AN 27) was used for fertilization.

The 2004 cover crop was spring barley *cv.* 'Arve'. The succeeding crops were oats (*Avena sativa* L.) *cv.* 'Jaak' in 2005, spring barley (*Hordeum distichon* L.) *cv.* 'Inari' in 2006 and oats *cv.* 'Jaak' in 2007.

The seed rate of germinating grains of cereals was 500 seeds m^{-1} every year. Green manure pure crops were sown at the following seeding rates: red clover 15 kg ha^{-1}, lucerne 13 kg ha^{-1}, hybrid lucerne 20 kg ha^{-1}, bird's-foot trefoil 12 kg ha^{-1}, westerwold ryegrass 20 kg ha^{-1}, white melilot 30 kg ha^{-1}. The seeding rates for undersowings were reduced by half. The barley grain crop was harvested and removed from the field.

The biomass of the legume pure sowings was ploughed into the soil in two variants – autumn and spring. Autumn ploughing alone was carried out with the other variants. The ploughing depth was 22–24 cm.

Experiment 2: Green manure trial conducted in 2006-2009 using the following variants:

The main part of the trial was established in 2007 with the following variants:

Variant A: legume pure sowings - red clover, lucerne, hybrid lucerne, bird's-foot trefoil, white melilot *(Melilotus albus* Med*) cv.* 'Kuusiku 1;

Variant B: spring barley with undersowings of red clover, lucerne, hybrid lucerne, bird's-foot trefoil, white melilot;

Variant C: spring barley with mineral fertilizer. The fertilizer treatments were 0 (N_0) 50 (N_{50}) and 100 (N_{100}) kg N ha^{-1} (every year with cereal sowing).

The 2007 cover crop was spring barley *cv.* 'Arve'.

The succeeding crops were spring wheat (*Triticum aestivum* L.) *cv.* 'Vinjett' in 2008 and spring barley *cv.* 'Inari' in 2009.

The biomass of legume pure sowings was ploughed into the soil in two variants –autumn and spring. Autumn ploughing alone was carried out with the other variants. The ploughing depth was 22–24 cm.

As a separate variant in this trial, the formation of GM crop biomass during two growing periods was investigated (the green mass was ploughed into soil in autumn the next year). This part of the trial was established in 2006, together with variants B and C, where the GM was ploughed into soil in autumn the next year.

The succeeding crop, winter wheat 'Ramiro', was sown in early September 2007.

Experiment 3: The catch crop trial conducted in 2008–2010.

Barley 'Inari' was used as the preceding crop. The field was prepared and the CC were sown immediately after the barley was harvested: on 25 August in 2008, 14 August in 2009 and 2 August in 2010. Before sowing, the soil was prepared with a spade rotary harrow.

The CC were sown at the following seed rates: winter oil turnip rape (*Brassica rapa* L. var. *Silvestris*) cv. 'Largo' and winter oilseed rape (*Brassica napus* var. *oleifera* L.) 8 kg ha^{-1}, fodder radish (*Raphanus sativus oleiformis*) cv. 'Adios' 22 kg ha^{-1}, white mustard (*Sinapis alba* L.) cv. 'Condor' 18 kg ha^{-1}, pea cv. 'Clarissa' 180 kg ha^{-1} (80 seeds m^{-2}), Faba bean (*Vicia faba* L.) cv. 'Jõgeva' 280 kg ha^{-1} (40 seeds m^{-2}), Westerwold ryegrass cv. 'Talvike' 25 kg ha^{-1}, rye (*Secale cereale* L.) cv. 'Jõgeva' 210 kg ha^{-1} and Phacelia (*Phacelia tanacetifolia* Benth.) cv. 'Stala' 11 kg ha^{-1}. The CC were ploughed into the soil in the 2nd and 3rd decades of October. The ploughing depth was 22–24 cm.

The succeeding crop was spring wheat cv. 'Mooni' in 2009 and 2010.

Experiment 4: Decomposition trial conducted in 2007–2010.

The decomposition of the OM introduced into the soil and the release of plant nutrients was studied in 2007–2009 (Trial 1) and 2008–2010 (Trial 2) in the same trial area. The dynamics and rate of legume aboveground biomass and root decomposition was investigated in the course of two years.

The plant species used in the 2007–2009 study were: red clover, lucerne, bird's-foot trefoil, white melilot. Those used in 2008–2010 were red clover and white melilot.

The roots and shoots were collected before GM ploughing (end of October), the roots were sampled by removing soil from roots by washing. The roots and shoots were separated and cut into 5-cm pieces. Fresh plant residues (25 g) were placed in 20 cm×20 cm nylon bags with a 1-mm mesh. The bags were placed within the ploughing depth (20–22 cm) with 0.3 m spacing between them. The bags were buried at the end of October, before ploughing. At the beginning of the experiment subsamples were collected for total C (C_{tot}), total N (N_{tot}), total P (P_{tot}), total K (K_{tot}) measurements (Table 1).

At 6, 12 and 24 months of decomposition, 4 bags (representing 4 replicas) for each species were selected to monitor DM and nutrient losses.

The plant materials remaining in the nylon bags at each sampling time were separated from soil and organic debris by hand and oven dried at 65^{o}C to constant weight. The oven-dried samples were weighed separately to determine DM losses.

The weight loss (%) for each period was calculated using the following formula:

$$\text{Weight loss} = 100 * (M_0 - M_t)/M_0$$

where

M_0 is the initial plant material DM mass (g) in the nylon bag;

M_t is the plant material DM mass (g) in the bag at a time t, when the bags were removed from field.

The samples were ground to pass through a 0.5-mm sieve for chemical analysis.

Table 1. Dry matter (DM) (g kg^{-1}) and C_{tot}, N_{tot}, P_{tot}, K_{tot} contents (mg kg^{-1}) and C:N ratio of legumes shoots and roots set for decomposition.

Green manure crop		DM	C_{tot}	N_{tot}	P_{tot}	K_{tot}	C:N
		2007					
Red clover	Shoots	291.2a	447c	24.7e	2.4b	22.0e	18.1d
	Roots	342.7b	429b	27.1f	3.9d	12.3c	15.8c
White melilot	Shoots	321.1b	465d	19.1c	2.4b	13.8c	24.3f
	Roots	372.9b	430b	31.1f	3.9d	11.9b	13.8b
Bird's-foot trefoil	Shoots	315.7a	462d	20.4d	2.3b	20.6e	22.6e
	Roots	402.1b	402a	26.7f	3.0c	11.2b	15.1c
Lucerne	Shoots	433.7b	457c	21.2d	2.0b	17.8d	21.6e
	Roots	459.8c	441c	25.7f	4.0	9.4a	17.1c
		2008					
Red clover	Shoots	251.2a	415b	21.1d	2.8c	26.1f	19.7d
	Roots	258.4a	399a	19.3c	2.5b	13.2c	20.7d
White melilot	Shoots	371.2b	428b	19.3c	2.9c	24.2f	22.1e
	Roots	215.6a	395a	24.1d	2.4b	13.4c	16.4c

Within each column, the mean values with different letters are significantly different ($p<0.05$).

The amount of mineralized N, P, K ($N_{m,}$ P_m, K_m) (% of initial amount) over the time of sampling (t) was calculated using the following formula:

$$N_m = 100 * (N_i - N_t)/N_i$$

where

N_i is the initial amount (mg) of N in the decomposing material;
N_t is the amount (mg) of N in the decomposing material at the point of time t.

4.2. Measurements, analyzes and calculations

4.2.1. Green manure biomass (plant samples)

Aboveground samples for determining biomass were gathered from an area 0.25 m^2 in size. The root mass was taken from a depth up to 60 cm (frame 10×25 cm).

The aboveground biomass of pure sowings, the root mass of leguminous crops and the entire biomass of CC were measured before autumn ploughing. In variants with undersowings, the aboveground biomass of GM crops was measured twice: first, immediately before harvesting (straw and leguminous biomass separately); second, the aftermath mass before autumn ploughing. Weeds were separated from the biomass gathered, and their biomass was also determined. Herbage weight was corrected to dry-matter (DM) weight.

4.2.2. Soil and plant analyses

Soil analyses were carried out at the laboratories of the Department of Soil Science and Agrochemistry of the EMU. Air-dried soil samples were passed through a 2-mm sieve. Various methods were used to determine the following soil characteristics: pH_{KCl}; organic carbon by the Tjurin method (Soil Survey Laboratory Staff, 1996); plant available P and K by the Mehlich-3 method (Handbook on…, 1992); total soil N content by the Kjeldahl method (Benton and Jones, 2001).

Soil samples to measure nitrate-N (NO_3-N) and ammonium-N (NH_4-N) content were taken during the catch crop growing period and in the spring before tillage at the depth of 20 cm. NO_3-N and NH_4-N were determined in 2 M KCl soil extracts by “FIAstar 5000”.

Plant analyses were conducted at the laboratories of both the Department of Soil Science and Agrochemistry of the EMU and the Estonian Agricultural Research Centre. Acid digestion by sulphuric acid solution was used to determine the total P, K contents in plant material. The Dumas Combustion method was used to determine the content of total carbon (C_{tot}) in the plant biomass **(I, II)**. The N_{tot}, C_{tot} and total sulphur (S_{tot}) (only in Experiment 3) contents of oven-dried samples (separately in underground and aboveground biomass) were determined by the Dumas Combustion method on a varioMAX CNS elemental analyser ("Elementar", Germany).

In Experiment 1, the C_{tot} content of GM was not determined and the relationship between the C:N ratio (y) and the N_{tot} content (x, %) of the OM was reflected in the following regression equation: $y=42.977x^{-1.0035}$; $R^2=0.99$; $p<0.001$ (Figure 1).

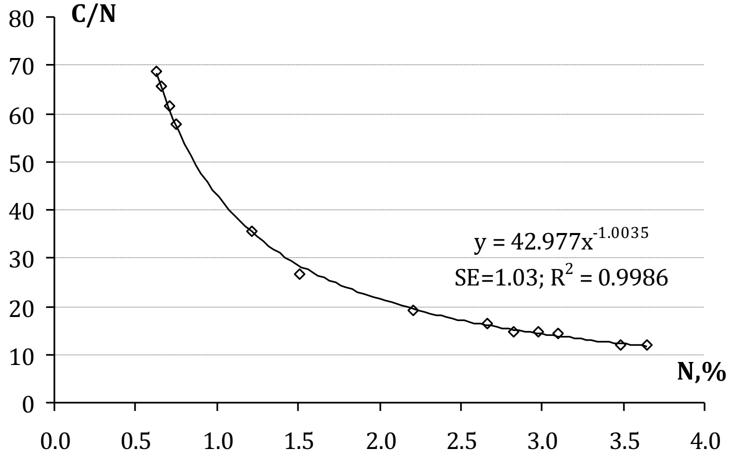

Figure 1. The relationship between the C:N ratio and the N_{tot} content of the organic matter (OM).

4.2.3. Grain yield and yield quality indicators

Grain yield was determined by weighing after harvesting and drying the grains. The yield data and grain quality parameters were adjusted to 14% moisture content. 1000 kernels were counted manually and then weighed. The volume weight (VW) was determined by ISO 7971-3:2009.

The wheat quality analyses were conducted at the Estonian Agricultural Research Centre laboratories. The crude protein (CP) concentration (%) in feeds was determined using the Kjeldahl procedure (NIT-method). The wet gluten content (WGC, %) and the gluten index (GI, %) were determined by ISO 21415-2:2006, volume weight, g/l (VW) by ISO 7971-2.

4.2.4. The weather in the trial years

The experimental area belongs to the south Estonian upland agroclimatic region, where the average annual sum of active air temperatures is 1750–1800°C and the total precipitation is 550–650 mm. The period of active plant growth (the average air temperature permanently above 10 °C) ranges usually from 115 to 135 days (Tarand, 2003). The winter period (the mean temperature continuously below 0 °C) lasts for 115 days on average.

During the experimental period, rainfall and air temperature were recorded daily at a meteorological station located within the experimental area using the Metos Model MCR300 weather station (Pessl Instruments GmbH, Weiz, Austria).

The amount of precipitation during the growing period (May to September) compared to the average varied throughout the trial; it was greater than the average in 2004 and close to it in 2005. The growing period of 2006 had a high temperature regime and a low precipitation level. The first half of the growing period (until 31 July) was very dry, with only half the average precipitation of Estonia. In 2007, the average temperature was higher than in the previous years while the average precipitation was lower. The drought reached its peak in August. The average temperature of the 2008 growing period was lower than in many previous years. In 2009, the growing period was longer than usual but with moderate temperatures. The period started with dry weather but its second half was rainy **(I, II, III, IV)**.

The sum of effective temperatures (over 5 °C) and the average precipitation (mm) were used to describe the growth period of the catch crops **(Table 1 in V)**.

4.2.5. Differential efficiency, the amount of agronomically effective nitrogen, the mineral fertilizer equivalent

Research data from the experiments (1, 2 and earlier results) representing various soil types (Kõrgas, 1971; Piho and Ojaveer, 1975; Viil and Võsa, 2005) were used to calculate N differential efficiency and the amount of agronomically effective N.

In analysing the joint database developed, the efficiency of mineral N fertilizers (N_{min}) was estimated using the simple quadratic equation:

$$Y=a_0+a_1x-a_2x^2, \tag{1}$$

where Y - yield, Mg ha^{-1}

x - amount of nitrogen fertilizer, N kg ha^{-1};

a_0 – yield, without mineral fertilizer rates (intercept);

a_1 and a_2 – regression coefficients.

A derivation

$$Y' = a_1 - 2a_2x \tag{2}$$

of the quadratic equation shows the differential efficiency of mineral fertilizer (kg N kg^{-1}) and was used to optimize N fertilization. The agronomically effective amount of mineral nitrogen fertilizer (kg ha^{-1}), which ensures a maximum grain yield, was calculated as follows (Astover et al., 2006):

$$x_{agr} = \frac{a_1}{2a_2} \tag{3}$$

To estimate the utilization of N in the leguminous plants (N_{org}) compared to mineral fertilizer, the mineral fertilizer equivalent (MFE) according to Kai et al. (2008) was used. The yield of the succeeding crop was fitted to the following formula, which was calculated by rearranging Equation 2:

$$x_{eq}=(Y_{leg}-a_0)/a_1$$

where x_{eq} - fertilizer-N equivalent of leguminous plants (N_{org}), N kg ha^{-1};

Y_{leg} - yield of succeeding crop after growth of leguminous plants, Mg ha^{-1}.

MFE is the amount of mineral fertilizer N (kg N ha^{-1}) that provides the same yield as that of the leguminous plant biomass nitrogen ploughed into the soil.

4.3. Data processing

The software STATISTICA 7.0 (Statsoft Inc, 2005) was used for statistical data analysis. Factorial analysis of variance (ANOVA) was used to evaluate the impact of the experimental variants on the grain yield. The significance of the differences between the grain yields of the variants was calculated using the Fischer (LSD) test. The Fischer test was used for testing significance differences between biomass treatments. Correlation analysis was conducted to quantify relationships between residue chemical composition and N, P, K mineralization. The levels of significance $p<0.05$ and $p<0.01$ were used.

5. RESULTS

5.1. Green manure crops

5.1.1. Green manure biomass formation

Red clover total biomass formation in different years was 6.3–8.9 Mg ha^{-1}. Of this, root mass was 3.3–3.8 Mg ha^{-1}, or 42.2–44.5% of the total mass. Lucerne and hybrid lycerne total biomass was 6.80–8.40 and 6.61–9.43 Mg ha^{-1} respectively; in their pure sowings root mass made up 49.6–52.4% of the total biomass. The total biomass of bird's foot trefoil pure sowings was the lowest compared to that of the other legumes, 4.64–5.24 Mg ha^{-1}, the difference significant ($p<0.05$), while the root mass was not significantly different ($p<0.05$). Weed invasion was greatest in the bird's foot trefoil pure sowing variant, where the biomass of the weeds was up to 1.41 Mg ha^{-1} (Figure 2).

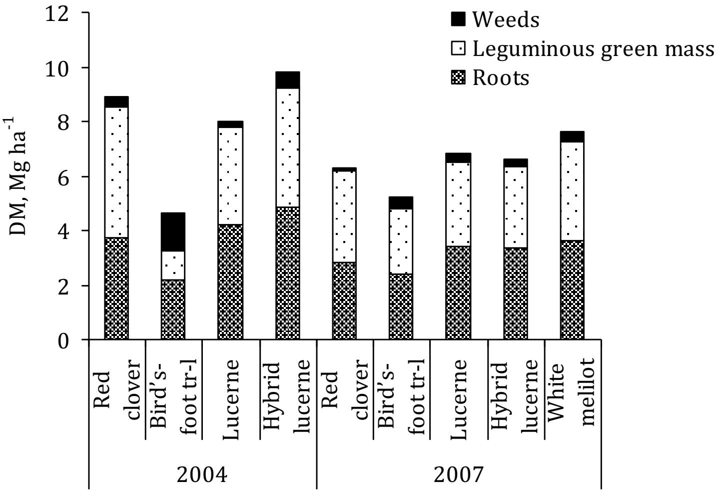

Figure 2. Quantities of dry matter (DM) of pure sowings (Mg ha^{-1}) applied into soil in 2004 and 2007.

In barley pure sowings the biomass ploughed into soil (straw + roots + weeds) was 4.1–6.6 Mg of DM per hectare, depending on the year and the N fertilizer quota, of which the root mass constituted 17.7–38.1% (Figure 2).

In undersowings, the biomass quantities and the amounts of C and N returned to the soil depended on the aftermath formation, the growth period and the competitiveness. In barley undersowings, where the biomass of the GM crops was also introduced into soil apart from straw, DM total amounts varied between 6.40–9.35 Mg ha^{-1}, the root mass comprising 18.6–33.3%, being largest in the case of barley and red clover undersowings. In hybrid lucerne undersowings the biomass ranged between 6.40–8.13 Mg ha^{-1} (Figure B). The biomass was smallest in the undersowing schemes of barley and bird's foot trefoil and barley and westerwold ryegrass (Figure 3).

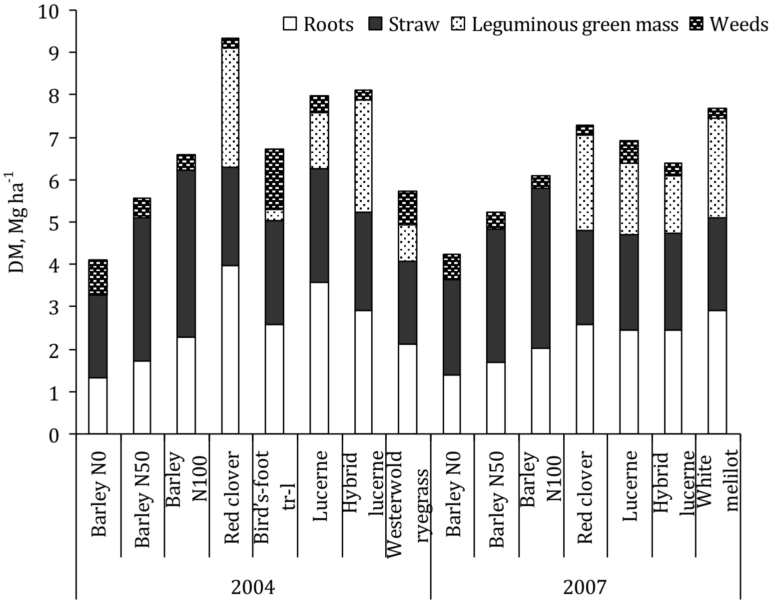

Figure 3. Quantities of DM of barley and undersowings (Mg ha^{-1}) applied into soil in 2004 and 2007.

Where the biomass of the green manure crops was ploughed into soil in autumn the next year, the biomass varied from 10.3 Mg ha^{-1} with bird's-foot trefoil to 13.9 Mg ha^{-1} with white melilot and red clover. The root mass of the leguminous crops was 3.07–4.26 Mg ha^{-1}, constituting 37–54% of the total biomass (Figure 4). The proportion was smaller for the aboveground phytomass of weeds.

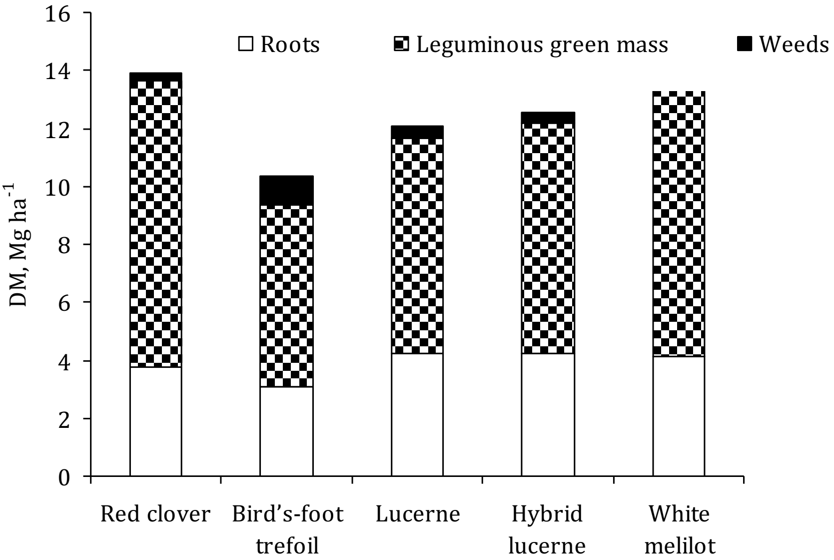

Figure 4. Quantities of DM of second growth year pure sowings (Mg ha^{-1}) applied into soil in 2007.

5.1.2. Returning N and C to soil with green manure

The straw, weeds and roots that were applied to the unfertilized barley field produced only 1.07–1.78 Mg C ha^{-1} and 41.7–60 kg N ha^{-1}. Approximately half of this was made up of N from the aboveground parts of weeds. Barley fertilization with treatments N_{50} and N_{100} resulted in significantly greater amounts of C and N being introduced into the soil than under unfertilized barley ($p<0.05$) **(Figure 2 in I; Figure 1. 2 in III)**. Barley straw N content varied between 0.63-0.74%, depending on the fertilization rates (Table 2).

Tabel 2. Estimated means (Experiment 1 and 2) and standard errors contents (%) of N_{tot}, P_{tot}, K_{tot} and C_{tot} in green manure crops and barley.

Variants	Plant part	N_{tot}	P_{tot}	K_{tot}	C_{tot}
Barley N_0	Grain	1.60±0.03	0.37±0.005	0.61±0.02	42.9±0.7
	Straw	0.63±0.04	0.16±0.003	1.35±0.04	43.0±0.5
	Roots	0.85±0.04	0.13±0.003	0.58±0.03	41.8±0.4
Barley N_{50}	Grain	1.63±0.02	0.41±0.01	0.73±0.07	42.9±0.6
	Straw	0.66±0.07	0.13±0.002	1.48±0.05	43.0±0.8
	Roots	0.89±0.05	0.18±0.01	0.50±0.03	41.8±0.3
Barley N_{100}	Grain	1.76±0.06	0.39±0.008	0.75±0.01	42.9±0.3
	Straw	0.74±0.04	0.21±0.004	2.05±0.05	43.0±0.4
	Roots	1.10±0.05	0.20±0.02	0.60±0.04	41.7±0.5
Westerwold ryegrass	Shoots	1.51±0.07	0.14±0.003	2.55±0.04	43.5±0.3
	Roots	0.85±0.04	0.11±0.003	0.58±0.001	42.9±0.4
Red clover	Shoots	2.75±0.07	0.28±0.08	2.35±0.01	42.8±0.3
	Roots	2.54±0.02	0.25±0.004	1.23±0.06	42.8±0.3
Bird's-foot trefoil	Shoots	2.49±0.06	0.39±0.009	2.36±0.02	42.8±0.3
	Roots	2.11±0.04	0.35±0.01	1.17±0.06	42.8±0.3
Lucerne	Shoots	2.65±0.06	0.22±0.004	2.20±0.03	42.8±0.3
	Roots	2.50±0.03	0.30±0.007	1.00±0.009	42.8±0.3
Hybrid lucerne	Shoots	2.55±0.05	0.28±0.004	1.85±0.03	42.8±0.3
	Roots	2.22±0.04	0.30±0.002	1.01±0.006	42.8±0.3
White melilot	Shoots	2.39±0.07	0.24±0.004	1.38±0.02	42.8±0.3
	Roots	3.06±0.06	0.32±0.005	1.24±0.04	42.8±0.3

The C and N inputs from pure sowings of legumes were 3.37–4.14 Mg ha^{-1} and 219.7–236.8 kg ha^{-1}, respectively, and the N content of the OM was 2.42–2.73%. N content was highest in white melilot roots (Table 2), differing significantly ($p<0.05$) from all the legumes represented in the trial. Red clover biomass supplemented the soil with 172.8–219.7 kg ha^{-1} of N and 2.67–3.76 Mg ha^{-1} of C. Of the pure sowings, the highest amount of C and N was returned into soil with hybrid lucerne in 2004 (Figure 5).

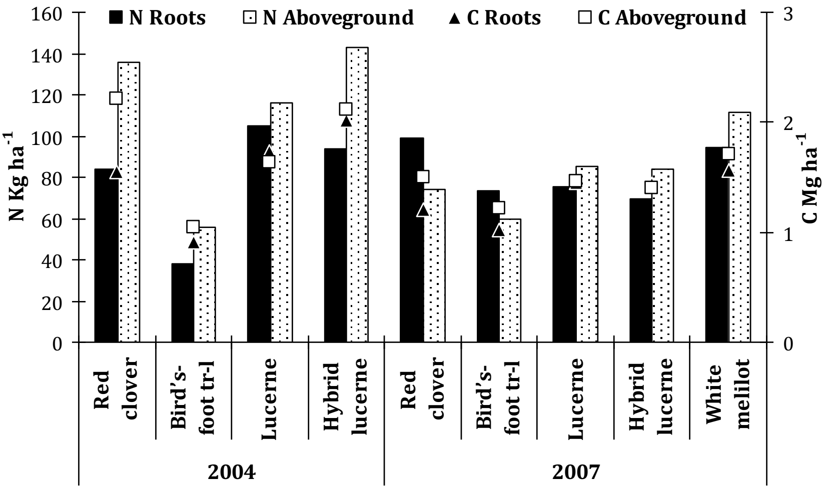

Figure 5. Quantities of organic matter nitrogen (N) (kg ha^{-1}) and carbon (C) (Mg ha^{-1}) at the application into soil of the biomass of pure sowings in 2004 and 2007.

Considerably less N, 93.1–133.1 kg ha^{-1}, and marginally less C, 1.96–2.86 Mg ha^{-1}, were added to the soil with the biomass of mixed and pure sowing of bird's foot trefoil than with that of the other leguminous crops (Figure 4, 5).

With barley undersowings, where GM biomass was used as an addition to barley straw and roots, 93.1–176.8 kg N ha^{-1} was returned to soil. In different undersowing variants, barley grain removed 43–55 kg N ha^{-1}. In barley undersowings with red clover, lucerne and hybrid lucerne, 3.45–3.96 Mg C ha^{-1} and 139.9–184.9 kg N ha^{-1} were applied into soil; the average N content of the biomass was 1.76–2.02%. In barley undersowings with white melilot, the biomass added 3.21 Mg C ha^{-1} and 205 kg N ha^{-1} into the soil (Figure 6). In barley undersowings with westerwold ryegrass, the OM introduced only 2.06 Mg C and 62 kg N (**Figure 3 in I**) into the soil.

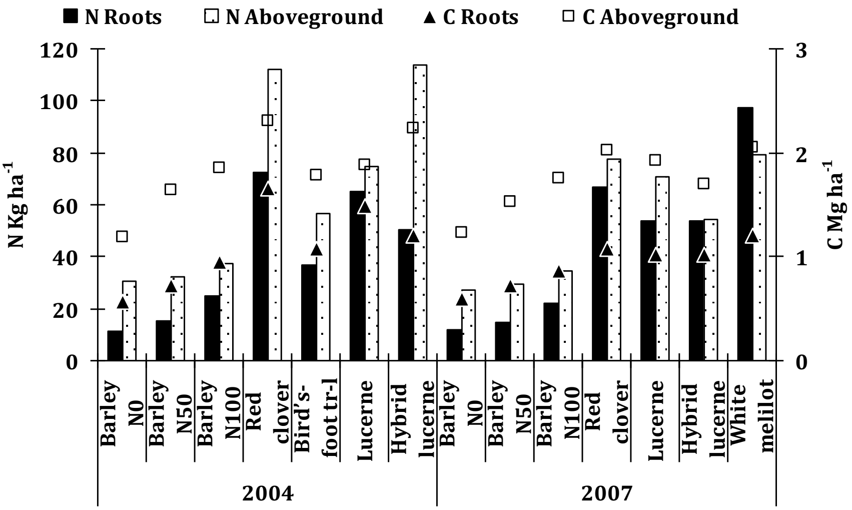

Figure 6. Quantities of organic matter nitrogen (N) (kg ha^{-1}) and carbon (C) (Mg ha^{-1}) at the application into soil of the biomass of barley and undersowings in 2004 and 2007.

Where the biomass of the GM crops was ploughed into the soil in autumn the next year, the legume biomass returned into the soil 198 (bird's foot trefoil) to 274 (white melilot) N kg ha^{-1}. C amounts fell within the range of 4.4–5.9 Mg ha^{-1}. The greatest amount of C was returned into the soil with the white melilot biomass **(IV. Figure 1).** The average N content was 2.06% in the roots and 1.90% in the aboveground mass.

5.1.2.1. C:N ratio of green manure crops

The C:N ratio of the OM incorporated into the soil varied widely. The barley straw had a C:N ratio of 42–70, depending on the quantities of N fertilizer. With barley undersowings, where leguminous GM biomass was used as an addition to barley straw and roots, the C:N ratio was 24–31 (**Figure 3 in I; Table 2 in II; Figure 2 in III).** In the case of barley-ryegrass undersowing, however, the average N content of the biomass introduced into the soil was low, 0.98%, and thus the C:N ratio was high, 43,5 **(Figure 3 in I)**.

In the aboveground biomass of leguminous crops the C:N ratio was 14–19 while in the roots it was 14–24, depending on the N content of the legume biomass. Considering the total amount of biomass that was added to soil, legume GM crops had a C:N ratio that was up to three times lower than that of cereals. The legume C:N ratio was higher in the roots than in the aboveground biomass.

5.1.3. Returning P and K to soil with green manure

Depending on biomass size, pure sowings of GM crops fixed up to 144 kg K ha^{-1} and up to 24 kg P ha^{-1} (**Table 2 in II**). The content of K in roots was lower than in the aboveground biomass. On average in the trials, the K content in roots was 1.14% and in aboveground mass 2.14%. The P content in roots fluctuated extensively, from 0.25% in red clover to 0.35% in bird's foot trefoil. The average P content in the aboveground biomass was 0.3% (Table 1 in the "Methods" section).

With the biomass from undersowings, 16–20 kg P and 98–153 kg K ha^{-1} was returned into the soil. Of the undersowings, the greatest amount of P and K was returned into the soil with red clover and the smallest with bird's foot trefoil, 20 and 16 kg P and 153 and 98 kg K ha^{-1}, respectively. The return of barley with ryegrass undersowing was 9 kg P and 81 kg K ha^{-1}.

Where the biomass of the GM crop was ploughed into the soil in autumn the next year, legumes returned up to 31 kg P (white melilot) and 230 kg K ha^{-1} (red clover). The P content was the highest in red clover roots and in white melilot aboveground biomass. The K content was the highest in the bird's foot trefoil aboveground biomass.

Depending on the amount of fertilizer, barley grains removed 7–13 kg P and 15–31 kg K ha^{-1}. Increased N rates lead to increased yields and nutrient quantities removed.

In different undersowing variants, barley grain removed 7–11 kg P and 16–21 kg K ha^{-1}.

5.1.4. Green manure effect on the yield and quality of succeeding crops

The effect of additional N in the soil was measured by weighing successive grain yields. The effect of GM crops on succeeding cereal crops is based on the amount of N in the biomass.

In Experiment 1, the succeeding crop was barley, whose yield on unfertilized soil was 2.95 Mg ha^{-1}. Under the mineral nitrogen fertilizer rates N$_{100}$, the additional yield was 1.49 Mg ha^{-1} (Table 3). The effects of all GM grops were significant ($p<0.01$). After barley undersowings with red clover and hybrid lucerne, the additional yield was 1.16–1.39 Mg ha^{-1}. When barley straw and ryegrass biomass were introduced into soil, the next year's barley yield decreased significantly compared to the N$_0$ variant. Under autumn ploughing of GM, the additional barley yield was 0.92–1.82 Mg ha^{-1}. After red clover and hybrid lucerne, barley yield exceeded that under the N$_{100}$ fertilizer rates. Spring ploughing of GM compared to autumn ploughing had a significant effect on barley yield, which was greater by 0.2–0.6 Mg ha^{-1} than under autumn GM ploughing.

In the second year, after GM ploughing, barley was grown as the succeding crop. The effect of the biomass of the red clover and hybrid lucerne undersowings on barley yield was significant but approximately half that in the first year. The effect of the biomass of the remaining undersowings on the succeeding crop in the second year was not significant. The effect of legume pure sowings on succeeding crops was significant in all the variants. Under biomass incorporation into soil in spring the barley yield was reliably greater than under GM ploughing in autumn. (**Table 1 in II**; Table 3).

Table 3. Grain yield of succeeding crops depending on nitrogen fertilizer quota and green manure application in Experiment 1.

Variants in 2004	Oats yield in 2005 Mg ha^{-1}	Barley yield in 2006 Mg ha^{-1}	Oats yield in 2007 Mg ha^{-1}
Barley N_0 (control variant)	2.95	2.10	1.97
Barley N_{50}	4.04^{a}**	3.19^{a}**	3.20^{a}**
Barley N_{100}	4.44^{b}**	3.89^{b}**	3.48^{b}**
Barley + westerwold ryegrass	2.30*	1.98	1.96
Barley + red clover	4.34**	2.79**	2.19*
Barley + bird's-foot trefoil	3.02	2.27	2.07
Barley + lucerne	3.32	2.45	2.30*
Barley + hybrid lucerne	4.11**	2.65**	2.20*
Autumn ploughing			
Red clover	4.77**	3.20**	2.27*
Bird's-foot trefoil	3.87**	2.65**	2.08*
Lucerne	4.00**	3.17**	2.46*
Hybrid lucerne	4.58**	3.46**	2.33*
Spring ploughing			
Red clover	5.08**	3.41**	2.34*
Bird's-foot trefoil	4.44**	3.19**	2.12
Lucerne	4.53**	3.42**	2.48*
Hybrid lucerne	4.78**	3.67**	2.39*

*, ** – significant at level $p<0.05$ and $p<0.01$ respectively;
[a] mineral nitrogen 50 kg ha^{-1}; [b] mineral nitrogen 100 kg ha^{-1}.

Green manure had a significant effect also in the third year for both undersowed and pure sowed trial variants of red clover, lucerne and hybrid lucerne, but the additional yield did not exceed 0.5 Mg ha^{-1}. The timing of green manure incorporation into soil did not significantly impact barley grain yield.

In Experiment 2, the first succeeding crop was spring wheat. Autumn-ploughed GM reliably increased wheat yield under both undersowings and pure sowings of legume crops. Under legume pure sowing biomass ploughing, wheat yield exceeded that under N_{100} fertilizer quota. The effect of the biomass of red clover and white melilot undersowings exceeded that of the N_{50} fertilizer quota. The timing of green mass ploughing did not have a significant effect on the succeeding wheat crop yield in this experiment. In the second year the after-effect of GM on barley yield was significant for all undersown and pure sown leguminous crops. (Table 4).

Table 4. Spring wheat and barley grain yield (Mg ha^{-1}) depending on fertilization and preceding crop in Experiment 2.

Variants in 2007	Spring wheat in 2008	Barley yield in 2009
Barley N_0 (control variant)	2.84	1.95
Barley N_{50}	3.85*	3.44*
Barley N_{100}	4.14*	4.09**
Barley + red clover	3.87*	2.48*
Barley + lucerne	3.79*	2.71*
Barley + hybrid lucerne	3.72*	2.80*
Barley + white melilot	4.00**	2.63*
Red clover	4.48**	3.02*
Bird's-foot trefoil	4.18**	2.85*
Lucerne	4.38**	3.18*
Hybrid lucerne	4.30**	3.28*
White melilot	4.87**	3.22*

*, ** – significant at level $p<0.05$ and $p<0.01$ respectively.

Where GM crop biomass was ploughed into soil in autumn the next year, winter wheat was grown as the succeeding crop. The highest winter wheat yields were attained in treatments with lucerne and red clover as preceding crops. Compared to the N_0 treatment, the additional yield under GM reached 3.26 Mg ha^{-1} (**Table 1 in IV**).

The spring drought and the extraordinarily wet August of 2008 impacted the yield quality of both winter and spring wheat. GM ploughing had a favourable impact on protein content in both spring and winter wheat but the protein content was lower than that expected of high-quality baking wheat **(Table 1 in IV)**. Leguminous green manure pure sowings increased the volume weight and 1000 seed weight of spring and winter wheat. The effect of GM undersowings was not statistically significant. Following the ploughing of pure sowings the volume weight of all the spring wheat variants exceeded those of the N_{100} variant but there were no differences between the green manures (Table 5). In the second post-green manure year barley volume weight and 1000 seed mass exceeded the corresponding figures for the N_0 variant in all the variants.

Table 5. Green manure effect on succeeding crop volume weight (g l^{-1}) and 1000 seed mass (g) in Experiment 2 in 2008–2009.

Preceding crop 2007	Spring wheat (2008)		Barley (2009)	
	Volume weight	1000 seed mass	Volume weight	1000 seed mass
Cereal pure sowing				
Barley N_0 (control variant)	712	32.1	588	37.1
Barley N_{50}	717	33.3*	609*	38.3*
Barley N_{100}	712	33.3*	631*	42.7*
Undersowing				
Barley + red clover	713	32.6	605*	38.4*
Barley + Lucerne	716	32.6	600*	39.6*
Barley + hybrid lucerne	714	32.8	605*	39.1*
Barley + white melilot	718*	33.0	601*	37.6
Legume pure sowing				
Autumn ploughing				
Red clover	747*	36.6*	646*	44.5*
Bird’s-foot trefoil	755*	38.3*	646*	43.2*
Lucerne	753*	37.8*	654*	44.6*
Hybrid Lucerne	753*	37.6*	652*	44.8*
White melilot	756*	37.5*	650*	43.8*
Spring ploughing				
Red clover	752*	38.0*	x	x
Bird’s-foot trefoil	749*	38.6*	x	x
Lucerne	755*	38.2*	x	x
Hybrid Lucerne	754*	38.3*	x	x
White melilot	753*	37.6*	x	x
$LSD_{0.05}$	5.3	1.09	2.0	0.95

x – not determined, * – significant at level $p<0.05$.

Where the GM crop biomass was ploughed into soil in autumn the next year the highest winter wheat yields were attained in treatments with lucerne and red clover as preceding crops. Compared to the N_0 treatment, the additional yield reached 3.26 Mg ha^{-1} with GM. After bird’s foot trefoil, the yield was equal to that under the treatment with 100 kg of mineral N. Both GM and mineral fertilizers enhanced the quality of winter wheat yield, but the results did not vary between different GM **(Table 1 in IV).**

5.1.5. Ploughed green manure nitrogen efficiency

The grain yields of three succeeding cereal crops were increased by increasing the N yield of the first experimental year. In the first year, after organic matter was added to the soil, the relationship between cereal yield (y, Mg ha^{-1}) and biomass nitrogen amount (x, kg N ha^{-1}) was linear ($R^2=0.66$; $p<0.001$) **(Figure 1 in II**). The average efficiency of 1 kg of N was 8.6 kg of grains. Similarly, in the next year, the amount of cereal grain yield and the amount of nitrogen in biomass were in a linear relationship ($R^2=0.70$; $p<0.001$). The average efficiency to 1 kg of N was 6.8 kg of grains. In the third year, the relationship between cereal yield and biomass N content, although much weaker than in the two previous years, continued to be linear ($R^2=0.77$; $p<0.001$). The average efficiency to 1 kg of N was 2.0 kg of grains **(Figure 1 in II**).

A comparison of the efficiency of the ploughed GM N and the ammonium nitrate N for succeeding crop yield under equal N amounts reveals that under small N quotas the differential efficiency of the mineral fertilizer N is somewhat higher than that of the N introduced into soil with OM. At higher N amounts, the differential efficiency of the OM nitrogen grows higher than that of the mineral fertilizer N. As an average of the trials, the agronomically effective amount of N, which provided the biggest yield on 0.1% N soil, was 106 kg ha^{-1} for mineral fertilizer N and 220 kg ha^{-1} for N from organic content (Figure 7).

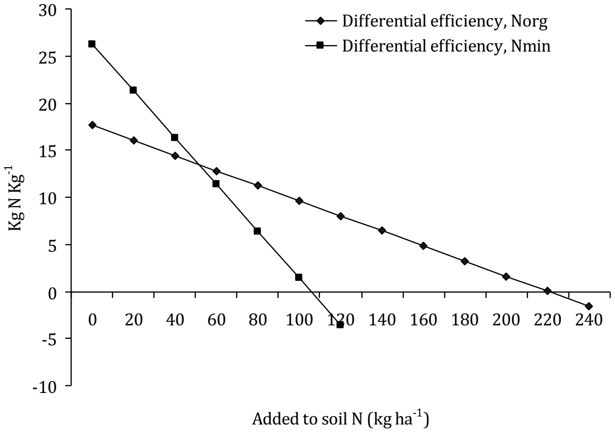

Figure 7. Nitrogen's differential efficiency and agronomically efficient nitrogen amount in 0.1% N soil (n=58, $p<0.001$).

Growing leguminous GM crops in a rotation enables reduction of the amount of mineral N required for growing succeeding crops. Fertilizer-N equivalent (MFE) of leguminous plants (replaced) N is equal to the amount of N required for cereal fertilization to attain a yield equal to that attained with GM crops (Table 6). The amount of N replaced depends on the amount of biomass ploughed. By growing red clover, hybrid lucerne and white melilot as pure sowings or by ploughing their biomass into the soil in the second year we can replace 100 kg N. The after-effect of these crops enables replacement of an average of 50 kg N $^{-1}$.

Table 6. Cereal yields (Mg ha^{-1}) and the effect of green manure crop growing on nitrogen.

	1st year aftereffect					
Preceding crop	Yield	MFE N kg ha^{-1}	Yield	MFE N kg ha^{-1}	Yield	MFE N kg ha^{-1}
	Oat 2005		Spring wheat 2008		Winter wheat 2008*	
Barley + red clover	4.34	85.5	3.87	45	5.95	100
Barley + white melilot	x	x	4.03	54	5.95	100
Barley + hybrid lucerne	4.11	70	3.72	37	6.0	100
Barley + lucerne	3.32	17	3.79	46	6.2	100
Barley+ bird's-foot trefoil	3.02	0	x	x	5.7	94
Red clover	4.77	100	4.48	88	xx	xx
White melilot	x	x	4.87	100	xx	xx
Bird's-foot trefoil	3.87	54	4.18	64	xx	xx
Hybrid lucerne	4.58	100	4.29	72	xx	xx
Lucerne	4.00	63	4.38	78	xx	xx
	2nd year aftereffect					
	Barley 2006		Barley 2009		Barley 2009	
Barley + red clover	2.79	35	2.48	15	2.49	43
Barley + white melilot	x	x	2.63	20	2.15	25
Barley + hybrid lucerne	2.65	27	2.80	26	2.4	38
Barley + lucerne	2.45	16	2.71	22	2.3	33
Barley+ bird's-foot trefoil	2.27	6	x	x	2.0	17
Red clover	3.20	58	3.02	34	xx	xx
White melilot	x	x	3.22	43	xx	xx
Bird's-foot trefoil	2.65	27	2.85	28	xx	xx
Hybrid lucerne	3.46	72	3.28	46	xx	xx
Lucerne	3.17	56	3.17	40	xx	xx

*– prior to winter wheat, 2nd-year legume was ploughed into soil
x – not grown, xx – winter crop grown only after undersowings, which were leguminous ploughed into soil in autumn the second year.

5.2. Catch crop biomass formation and nutrient uptake

From year to year, there were great fluctuations in the quantity of catch crop biomass produced, which depended on the sum of effective temperatures during the growing season (r=0.63). The smallest DM yield was 0.6 Mg ha^{-1} from winter oilseed rape, the largest 3.6 Mg ha^{-1} from fodder radish. The average catch crop N uptake was 40 kg ha^{-1}, ranging from only 8 kg ha^{-1} (westerwold ryegrass) to 100 kg ha^{-1} (pea, bean). The best nutrient binders were peas and beans. In better growth years these crops bound 50–100 kg ha^{-1} N, 7–10 kg ha^{-1} P, 40–60 kg K ha^{-1}. Of *Brassicaceae*, white mustard and fodder radish produced the highest biomass and used up to 77 kg ha^{-1} N, 9 kg ha^{-1} P and 82 kg ha^{-1} K (2010 fodder radish) in the biological cycle of OM. The biomass of westerwold ryegrass was significantly smaller and thus the related P and K amounts were small accordingly. Although the biomasses of the winter turnip rape and *Phacelia* were equal, the latter bound 1.6 times less N than the former. The C:N ratio stayed below 30 for all the catch crops, except for westerwold ryegrass (**Figures 1. 2. 3. 4. 5. 6 in V)**. The greatest amount of S was bound by pea, 7.8 kg S ha^{-1}. Although the biomass of bean was relatively large, the amount of S bound by it remained on a par with *Brassicaceae* catch crops. The westerwold ryegrass biomass returned into the soil a mere 1.5 kg S ha^{-1} (**Figure 4 in V).**

In 2009, beans had the greatest effect on the following spring wheat yield compared to the N_0 control field; the spring wheat yield was bigger by 590 kg ha^{-1}. Although beans contributed more N to the soil, the following wheat yield was not significantly different from the wheat yield after growing *Brassicaceae* catch crops. The results for 2010 showed that under spring ploughing spring wheat yield was, as an average of the variants, smaller by 0.2–0.3 Mg ha^{-1} than under autumn ploughing, but the difference between the variants was not statistically significant **(Figure 7 in V)**.

The levels of soil nitrogen in nitrates and ammonium were relatively consistent for all the catch crops; growing catch crops did not decrease soil NO_3-N and NH_4-N content compared to the treatment without catch crops **(Table 2 in V).**

5.3. Decomposition of green manure

After 6 months, aboveground residues had lost 40–50% of their initial DM weight in Trial 1 in 2007/2008 compared to 34–42% in Trial 2 in

2008/2009. Roots had lost 20–46% of the initial DM in 2007/2008 compared to 5–27% in 2008/2009. After 12 months aboveground residue had lost 61–74% and roots had lost 47–62% of their initial DM weight in both trials. After 24 months 70–83% of aboveground residue and up to 75% of roots had decomposed, depending on the plant species (Figure 8, 9).

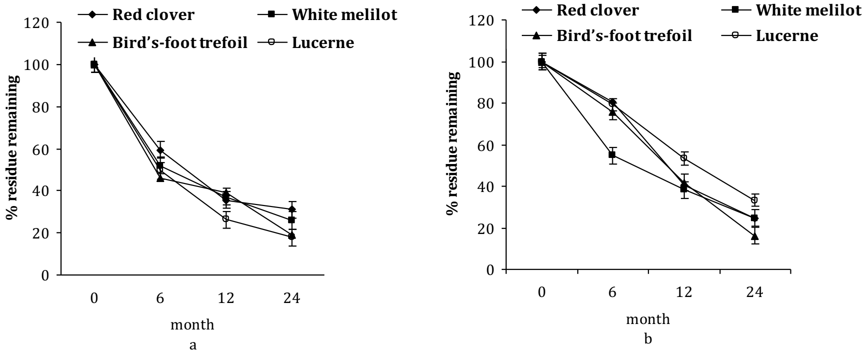

Figure 8. Residue remaining during decomposition (a – aboveground biomass, b – roots) in 2007–2009. Vertical bars denote standard deviation (SD).

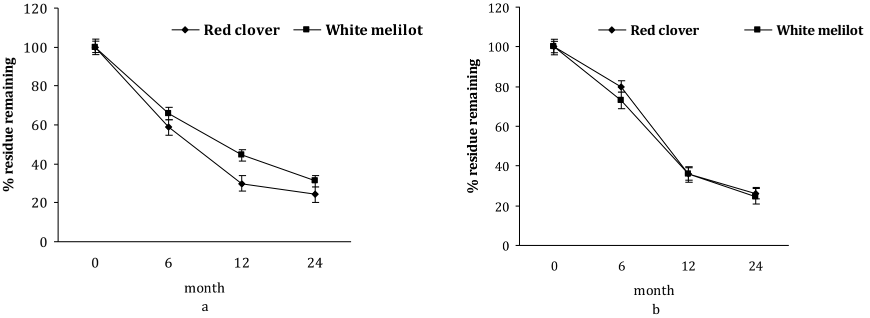

Figure 9. Residue remaining during decomposition (a – aboveground biomass, b – roots) in 2008–2010. Vertical bars denote SD.

5.3.1. Nutrient release

N release was faster from aboveground (shoots) mass. After 6 months, aboveground residue had retained from 55–59% (Trial 1, 2007–2009) to 75% (Trial 2, 2008–2010) of the initial N and the roots from 83 % to 92%, respectively (Figure 10, 11). Over the six-month decomposition period, there were no significantly differences in N release from the aboveground biomass of the legumes. Decomposition was slower in Trial 2 (Figure 11). After 12 months, 58–77% of the initial N in aboveground shoots and 32–61% in roots had been released, depending on the plant species and the year. Reliably slower was the release of N from bird's foot trefoil's aboveground biomass and from lucerne's roots. Twenty-four months from the beginning of decomposition 20% of the initial N content was retained in shoots and 27% in roots but there were no longer any differences between the species. In Trial 2, where decomposition was slower, significantly more N remained in red clover residue compared with white melilot. The amounts of N retained in the residue of white melilot roots and shoots did not differ from each other at the end of the trial.

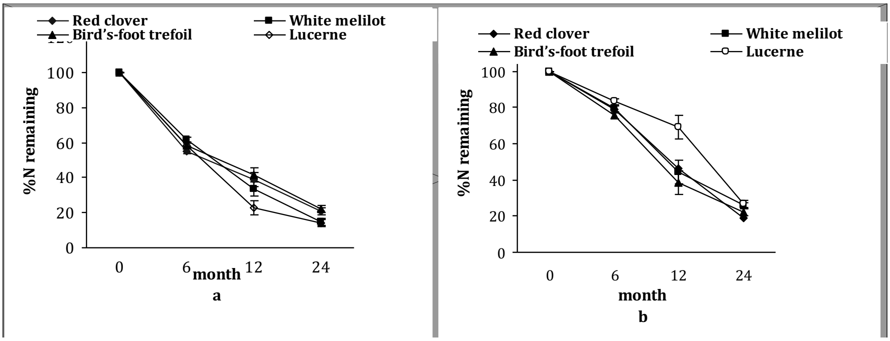

Figure 10. Biomass N remaining during decomposition (a – aboveground biomass, b – roots) in 2007–2009. Vertical bars denote SD.

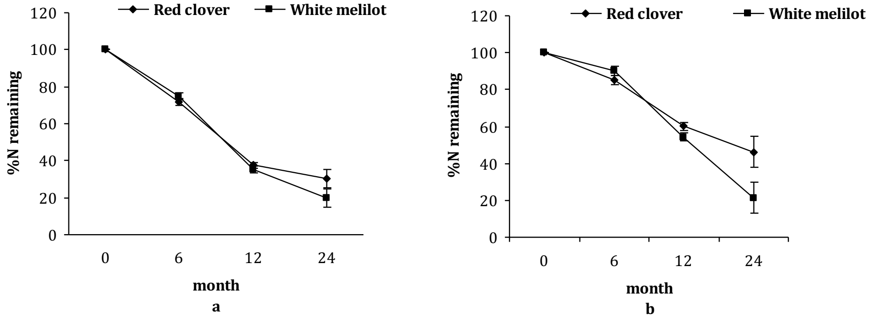

Figure 11. Biomass N remaining during decomposition (a – aboveground biomass, b – roots) in 2008–2010. Vertical bars denote SD.

The total C release from root residue after 6 months was lower was retained in the shoots of the decomposing material (residue) after a 6-month decomposition period, and 80% in the roots. Over that time, C was released reliably faster from the roots of bird's foot trefoil than from those of other legumes. There were no significantly differences between legumes in C release from the aboveground mass (Figure 12). Over 12 months, up to 79% of the initial carbon in aboveground mass and up to 30% in roots was released, depending on the plant species and the year.

Over 24 months, 72–88% of the C content was released from the aboveground mass (Figure 12, 13). After 24 months, the C concentrations were still higher in lucerne and red clover roots. The C:N ratio was significantly negatively correlated with N mineralization (*r*=-0.49).

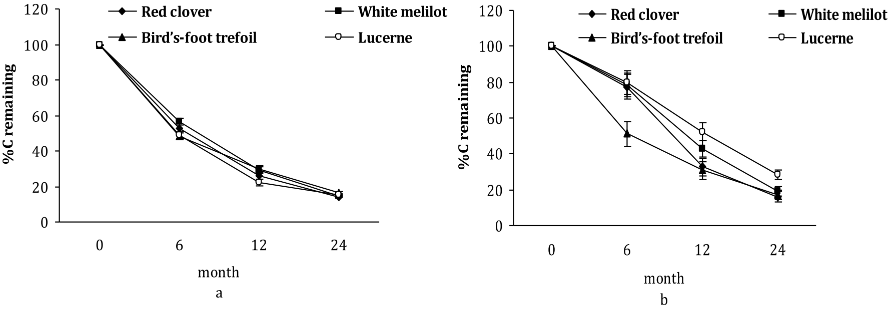

Figure 12. Biomass C remaining during decomposition (a – aboveground biomass, b – roots) in 2007–2009. Vertical bars denote SD.

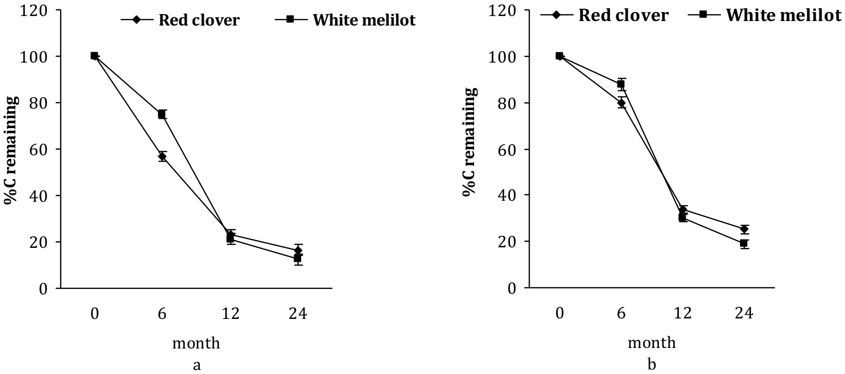

Figure 13. Biomass C remaining during decomposition (a – aboveground biomass, b – roots) in 2008–2010. Vertical bars denote SD.

In aboveground mass mineralization, 19–55% of the P therein was retained after six months, depending on the crop. P was released reliably faster from the aboveground biomass of bird's foot trefoil, lucerne and white melilot (Experiment 1). After 6 months, 20, 25 and 19% of the initial P was retained in the aboveground biomass of these crops, respectively. In Experiment 1, the roots of all the crops decomposed evenly over the first six months; subsequently, however, P release from white melilot roots ceased to be continued after 12 months of decomposition (Table 7). In Experiment 2, this cessation did not appear.

In 12 months, up to 82% of the initial P was released from the aboveground biomass and up to 79% from the roots. In 24 months, up to 89% of the P was released, depending on the crop. P release was reliably faster from white melilot aboveground mass. In Experiment 2, where decomposition was slower, the roots of red clover had retained significantly more P than those of white melilot.

The P content in the biomass and the P release were negatively correlated (*r*=-0.85 in roots and *r*=-0.40 in aboveground mass).

Both of the experiments conducted indicated that K release in 6 months is faster from the aboveground mass of legumes than from the roots (Table 8). In 6 months the greatest amount of K was released from the aboveground biomass of lucerne and bird's foot trefoil, less from the roots of white melilot.

Table 7. P remaining (%) in biomass in 2007–2009 and 2008–2010.

Green manure set for decomposition	Year	Shoots			Roots		
		Month					
		6	12	24	6	12	24
Red clover	2007–2009	44c	18a	17bc	50ab	21a	6a
White melilot		19a	19b	11a	45a	41d	7a
Bird's-foot trefoil		20a	19b	15b	43a	22a	8a
Lucerne		25a	20c	17bc	49a	27b	15c
Red clover	2008–2010	55d	23d	16b	86c	43d	19d
White melilot		28b	23d	11a	92c	36c	12b

Different letters indicate significant influence ($p<0.05$) of remaining P in biomass.

After 24 months, 93–97 % of K was released, depending on the crop. In 24 months, only 3% of the initial K remained in white melilot roots.

Our trials showed that K release is negatively correlated with K concentration (*r*=-0.80).

Table 8. K remaining (%) in biomass in 2007–2009 and in 2008–2010.

Green manure set for decomposition		Shoots			Roots		
		Month					
		6	12	24	6	12	24
Red clover	2007-2009	18c	6a	7c	61b	18a	8c
White melilot		17bc	14c	7c	79c	32c	6b
Bird's-foot trefoil		11a	9b	7c	48a	16a	10c
Lucerne		11a	6a	5b	72c	24b	16d
Red clover	2008-2010	15b	6a	3a	79c	16a	7b
White melilot		15b	10b	4a	95d	26b	3a

Different letters indicate significant influence ($p<0.05$) of remaining K in biomass.

6. DISCUSSION

6.1. Organic matter production (Paper I, II, III)

One of the most important factors influencing soil fertility is humus, the OM contained in soil. Soil fertility is closely linked to SOM (Roose and Barthes, 2001) and depends to a large extent on the use of organic fertilizers, both in organic as well as in conventional cultivation; GM crops have an important role in crop rotation (Lauringson et al., 2000). OM production (biomass amount) and its quality depend on the crop grown. On average, pure barley sowings produced 4.18–6.34 Mg ha^{-1} of ploughable (straw, stubble, roots) DM, determined by the amount of added N. Of the legumes studied by us, red clover, hybrid lucerne and white melilot produced the greatest biomass. Growth period, aftermath formation and competitiveness all had an influence on the biomass production of the undersowings. Particularly sensitive were lucernes and white melilot: belated cover crop harvest reduced the aftermath mass of these undersowings. When undersowings were used as green manure, growing red clover yielded the most stable biomass. Biomass C:N ratio of the undersowings decreased compared to cereal straw. This concurs with Dordas and Lithourgidis (2011) and with Jørgensen et al., (1999). Field experiments showed that a high biomass C:N ratio has a negative effect on N availability (Trinsoutrot et al., 2000; Nygaard Sorensen and Thorup-Kristensen, 2011). Thus, the benefit of combining low-quality crop residue with N fertilizer (legumes) in reducing N mineralization and N losses indicates that this soil fertility management strategy could be adopted in environments of higher soil N losses (Gentile et al., 2009).

Studies have shown that, in the case of 4.6 Mg ha^{-1} barley grain yield with the straw being left in the field after harvest, the estimated annual C input to the soil is 2.79 Mg ha^{-1}. If the straw is removed from the field the estimated annual C input would be reduced by 26% (Bolinder et al., 1997). On average in our trials, depending on the mineral nitrogen fertilizer quota, the annual C inputs constituted 1.79–2.81 Mg ha^{-1} with straw and 0.91–1.11 Mg ha^{-1} without straw. Considering the fact that in Estonian circumstances 20% of the carbon that is applied into soil is transformed into humus, and that 1–2% of the soil humus or C stores (45.3 Mg C ha^{-1}) are mineralised per year (Piho, 1973; Piho, 1978; Kõlli, 1986), it is also evident that, with the application of straw into soil, the humus balance remains negative if the barley yield is low. On a cereals farm, where only stubble and plant roots are ploughed into the soil after harvesting, the humus decrease is 2 to 3 times greater than the increase of humus from fresh OM (Roostalu, 2008).

The bioproduction, nitrogen uptake and C:N ratio of GM crops vary greatly depending on the plant species, soil and field management (Wivstad et al., 1996). The bioproduction of GM crops may, in favourable conditions, exceed 10 Mg ha^{-1}, of which 2–3 Mg ha^{-1} of humus is formed as a result of the humification process (Piho, 1973). In the case of barley undersowings with red clover, white melilot, lucerne and hybrid lucerne, the estimated annual C and N inputs to the soil were 3.08–3.56 Mg C ha^{-1} and 139.9–184.9 kg N ha^{-1}, respectively. In the present experiment, pure sowings of these crops resulted in applications of 3.37–4.14 Mg C ha^{-1} and 220–237 kg N ha^{-1} into the soil. Consequently, biomass from legume GM crops can add a huge amount of N and C to the soil, which improves soil humus characteristics. Cassman et al. (1996) also reported an increase in organic C content of soil after growing a legume in the cropping system. The lowest amount of biomass was from bird’s-foot trefoil where bird’s-foot trefoil remained in the lower growth layer and its annual C input to the soil was 2.2 Mg ha^{-1} on average. Thus, the present study showed that white melilot and lucerne can also be successfully used as GM, in addition to the most popular GM crops in northern Europe, red clover and white clover. But red clover is more stable and resistant to unfavourable conditions than other legumes. White melilot and lucerne are more sensitive to climatic and agrotechnical factors (Wivstad, 1989; Halling et al., 2001). Compared to other legumes, bird’s-foot trefoil had a lesser effect and is thus not suitable as a GM crop.

The trials have shown that red clover is more stable and resistant to unfavourable conditions than other legumes.

6.2. Nutrient binding of green manures as main crop (Paper I, II, IV)

The amount of N bound by legumes depends on the plant species, biomass quantity, symbiosis between *Rhizobia* and environmental factors (Giller and Cadisch, 1995), as well as on the agrotechnology applied and on the soil properties (Wivstad, 1989; Wivstad et al., 1996). In our study, pure sowings of red clover, hybrid lucerne and white melilot added 219.7–236.8 kg N ha^{-1} to soil on average. This shows that large amounts of N and C are introduced into soil with leguminous GM crop biomass, resulting in improved soil humus content and higher soil organic N, which decomposes at a relatively slow rate in the following years. Crews and Peoples (2005) found that cereals after legumes usually take up about 20% of legume N. The N introduced into soil with leguminous GM crops in our trials significantly impacted grain yield quality in succeeding cereals as well as the chemical composition of the OM returned to soil. For instance, in Experiment 1, the C:N ratio of the OM (straw + roots) of the barley returned to soil on unfertilized soil was 56 but that of the barley grown after a legume green manure crop was 32–40. Consequently, the biomass of legume-succeeding cereals, when introduced into the soil, decomposes faster and thus soil N fixing by microorganisms reduces.

Legumes, when grown as an undersown crop, had less biomass and bound less N, but the total herbage yield increased. This is corroborated by trials conducted by Halling et al., 2001. GM pure sowings of high nitrogen content should be ploughed into soil in spring, which decreases N leaching potential and environmental pollution.

As the trial area average soil humus layer contained 430 kg of plant-available P and 1050 kg of similarly usable K – and 80% of all the nutrients are taken from humus layer, we can conclude that, in a single year, barley used up to 2–4% of P and 4–7% of K in the humus layer. In Estonia in recent years, more K and P has been removed from than added to soil. In 1996–2000, 44 kg of K per hectare of arable land was removed, while mineral and organic fertilizers returned only 19.5 kg (Kärblane et al., 2002), putting the P balance at -6.5 ha^{-1} (Astover et al., 2006). In animal-based and mixed systems, good manure management is therefore essential. Thus, both in organic and conventional cereal farming, where animal manure is not used, GM are the only means of retaining and improving soil fertility. On the other hand, nutrient uptakes of main crops decreased where ryegrass was cultivated as GM (**I**); this is also confirmed by the results of the Eichler-Löbermann et al. (2009) trial.

Forms of P and K fixed by plants – and accessible to successive plants - are also gradually released (Daroub et al*.,* 2001). As P and K are relatively stable in soil, their leaching losses are almost non-existent, and most of these elements are removed with the crop. We found that barley grains removed 40–87 kg N, 7–13 kg P and 15–31 kg K ha^{-1}, which is in line with Salo et al. (2007), who reported that 65 to 80 kg N ha^{-1} is removed from the field every year, and Kirchmann et al. (2008), who reported that around 10 kg P and 15 kg K ha^{-1} is removed from the field every year in organic farming. This rate of P and K use is usual, considering the amount of nutrients in soil and the amount of fertilizer needs. According to studies in Scandinavia, barley bound 155, 23.5 and 109 kg ha^{-1} of N, P and K, respectively (Hakala, 2009). In a study conducted in Sweden, Arvidsson (1999) found that, of the fixed nutrients, 75% of N, 84% of P and 26% of K were removed with the crop. Thus, more N and less K is removed from the field there than under our circumstances. This may be due to climatic conditions, which changed across growing seasons. The amount of nutrients removed with the crop also depends on the size of the harvest.

It is important to plough in GM biomass because using aboveground organics as fodder removes a huge amount of already fixed and plant-accessible nutrients. Our tests showed that K content in roots was lower than in aboveground biomass. Mengel (1982) found that root K content normally constitutes less than 10% of the total plant K and maintained that K uptake in the aboveground parts normally reaches its maximum at flowering (Askegaard et al., 2003). Depending on biomass size, pure and undersown GM crops fixed up to 153 kg K ha^{-1} and up to 20 kg P ha^{-1}. Considering that an average of 80% of the roots are situated in the ploughed layer (Freyer, 2002), it may be assumed that approximately 80% of the fixed P and K are from the humus layer and the rest from deeper soil layers. It has been shown that with careful management of manure, effective use of legumes and permitted inputs for P and K, farms can be managed sustainably. This is in agreement with the findings of Goulding et al. (2009).

According to research data from Estonia (Astover et al., 2012), adding balanced and optimal amounts of P and K to soil does not result in leaching: leaching of P is less than 0.5% and of K in sandy soils less than 10% and in clay soils less than 1%. Since leaching is almost non-existent, the P and K released from legumes can be used by succeeding crops. According to Lupwayi et al. (2007) the P released from leguminous GM residues meets up to 62% of succeeding wheat P requirements and 52–100% of K requirements (Lupwayi et al., 2006b).

6.3. The efficiency and permanence of biologically fixed nitrogen (Paper I, II)

Research has shown that the effect of soil GM on yield depends on the amount of N in the biomass, its release rate, the C:N ratio in OM (Kumar and Goh 2002; Schomberg et al., 2006), soil N content and climate. As the soil of the experimental field was relatively low in humus content and the amount of N in the humus layer was only 0.10–0.12% in general, N from GM crops incorporated into soil was very effective.

In Experiment 1, barley yield in leguminous GM crop undersowings in the trial establishment year was higher by 377–639 kg ha^{-1} than in unfertilized soil. This tendency did not appear in subsequent trials. Likewise, there are reports in the literature that competition may reduce mixed crop yields compared to cereal pure sowings (Caballero et al., 1995). Gleissman (2000) found that interspecies competition is more apparent where growth factors (nutrients, soil water, solar radiation) are insufficient for satisfying the needs of both crops. The total stock of N in the experimental area soils is 0.1–0.12%. This is insufficient for growing crops, for, according to Kuldkepp (1988), only ca. 1–3% of the total stock of soil N is plant-available.

First year's after-effects have been studied by several researchers (Hanly and Gregg, 2004; Tonitto et al., 2006), and beneficial effects on succeeding crops have been noticed. Our experiments confirm these results **(I, II**). From legume undersowings, the first year's additional yield was up to 1.39 Mg of grains ha^{-1}. No significant additional yield ($p>0.05$) was attained after bird's foot trefoil undersowing. The reason was that bird's foot trefoil's development is slow in the initial stages and its biomass and the fixed nitrogen amount are small in competition with the cereal. The succeeding crop yield in the first year after pure red clover and hybrid lucerne sowings was even higher than under 100 kg N ha^{-1} of mineral fertilizer. Consequently, by growing these GM crops we can replace 100 kg of mineral N ha^{-1} in the first year. In contrast, Harris and Hesterman (1990) found that lucerne residues did not provide significant amounts of N to a barley crop sown after lucerne. They thought that, due to the higher C:N ratio in roots, decomposition is slower in these parts and N becomes available later in roots. Our trials confirm that roots decompose slowly, nitrogen is released later and the effect is longer lasting; the aboveground mass, however, decomposes faster and ensures additional yield for the succeeding crop. Likewise, Puget and Drinkwater

(2001) found in their research that above-ground mass releases N faster than roots and is a source of N for succeeding crops, whereas root litter is probably largely responsible for the short-term soil structural improvements associated with the use of GM.

However, there is little information regarding the response of second- and third-year succeeding crops. Andersen and Olsen (1993) have not found any second year after-effect of GM on barley yield. In our study in the second year, the positive after-effect of GM was found. Compared to the first year, the second year's biomass effect of red clover, lucerne, hybrid lucerne and melilot undersowings was significant but approximately twice smaller. The second year's after-effect of leguminous crop pure sowings on barley yield, however, was 2–3 times greater than that of the straw and GM of red clover and hybrid lucerne undersowings ploughed into soil. The reason may be that straw N content is low, the C:N ratio of the undersowings biomass ploughed into soil is higher and thus the biomass decomposition and nutrient release are slower. According to Viil and Võsa (2005), 16–18% of red clover after-effect is manifested in the second year; the corresponding figure for white melilot is up to 28%. In our study, GM from pure red clover, lucerne and hybrid lucerne all had a significant effect even in the third year, but the effect of N in their organic matter on yield increase was lower than in the first and second years (**I, II**). Considering all our experiments carried out in 2004–2010 (Lauringson et al., 2011), we conclude that, in the first year, the average efficiency of 1 kg of N was 11.8 kg of grains. As the GM from legumes has an effect on almost all of the important chemical and physical characteristics of the soil, the effect does not last only a year, but continues to have a positive influence for a number of years. In the second year, the response to 1 kg of N was 4.2 kg of grains, and, in the third year, 1 kg of N was 2.0 kg of grains.

The yield results of the present study showed that N is released slowly from GM and that even high N amounts did not cause crop lodging and yield loss. Mineral fertilizers work quickly, and in a soil with a high N content of N_{60} may cause crop flattening in 1–2 years out of ten (Roostalu et al., 2003). Our trials showed that the agronomically effective amount of N providing the greatest yield on a 0.1% N soil was 106 kg ha^{-1} for mineral fertilizers and 220 kg ha^{-1} for N from organic content. Tonitto et al. (2006) confirmed that in temperate regions, legume-fertilized systems had 10% lower yields compared to N-fertilizer systems unless N accumulation in cover-crop residues exceeded 110 kg N ha^{-1}.

Based on many studies, GM crops should be ploughed in late autumn or early spring, resulting in reduced N leaching and increased effect on succeeding crop yield (Gustafson, 1987; Wivstad et al., 1996; Lahti and Kuikman, 2003; Viil and Võsa, 2005). Our research results confirm that under spring ploughing of GM crops its effect on succeeding cereal crop yields is greater by 0.2–0.6 Mg ha^{-1} than under GM autumn ploughing **(I)**; however, the positive effect of spring ploughing did not occur every year. This may be due to the fact that the ploughed biomass was smaller in the second experiment and the weather was not favourable for its decomposition. To reduce N losses under GM autumn ploughing, CC need to be grown, which bind nitrogen released in OM decomposition (Gladwin and Beckwith, 1992; Stenberg et al., 1999; Olesen et al., 2007). According to Aronsson et al. (2007), N use efficiency needs to be increased by better synchronisation of N mineralization from GM and N uptake by the crop.

Previous trials on various soils (Kõrgas, 1971; Piho and Ojaveer 1975; Viil and Võsa, 1995) and the present trials show that N efficiency and the additional yield obtained therefrom depends on soil N content. The higher the soil N content the less efficient the effect of adding GM nitrogen to the soil (Figure 14).

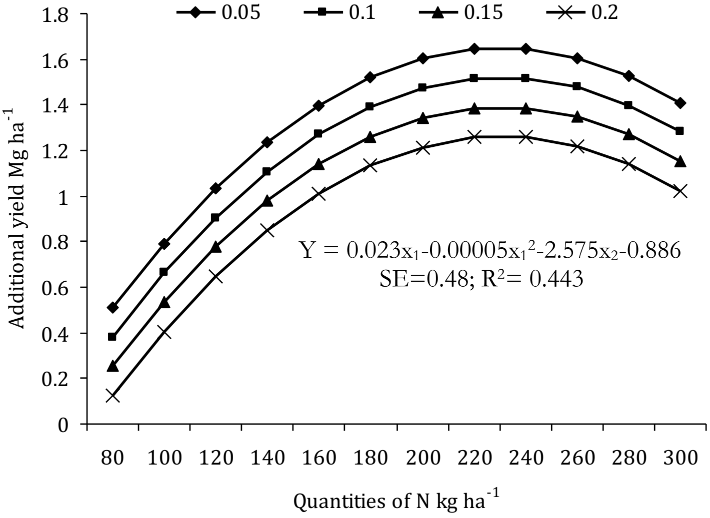

Figure 14. Cereal additional yield (Y) from organic matter nitrogen (x_1) ploughed into soil, depending on soil nitrogen content (x_2) (n=42, p<.0001).

Consequently, GM growing is of paramount importance on soils with low humus content and inadequate microbiological activity.

6.4. N effect on succeeding cereal crop quality (Paper IV)

Protein content can be increased with higher N fertilizer quotas (Peterson, 1976). Protein content increased also in the present study compared to the N_0 treatment, but remained lower than the protein content for wheat (13–15%). Studies by Doltra et al. (2011) confirm that green manure crops have a positive effect on grain yield and protein content in organic systems, but there is still a considerable yield difference between those from organic and conventional systems. Olesen et al. (2007) found that the slower mineralization of the organic matter in the incorporated GM probably increased late season N uptake, thereby primarily affecting grain protein content. This shows that the use of the more slowly decomposing source of N in OM can be used to ensure adequate protein levels in organic farming (Olesen et al., 2009).

Protein content is positively correlated with wet gluten content (Frederiksson et al., 1998), which is strongly influenced by the growing conditions (Grausgruber et al., 2000). Likewise, our trials showed that the wet gluten index increased in step with increased protein content. One of the commonest criteria for wheat quality is volume weight (VW). In Estonia, VW must be at least 750 g L^{-1} (Ingver, 2007) for the producers to be able to sell their grain yields to food processing companies. VW is influenced by many factors, including fungal infection, insect damage, kernel shape and density, agronomic practice and the climatic and weather conditions (Gaines et al., 1997). It is generally assumed that kernel size and bulk density are inversely correlated, but, in our trial, this did not hold. In the trial, increased kernel size was accompanied with increased VW. Likewise, Koppel (2011) found that this assumption did not hold for all wheat varieties, depending on the year. In our earlier studies, there was no regular correlation between kernel size and VW (Talgre et al., 2008; 2009). In the trial, the VW remained low. This may have been because the average temperature of the 2008 growing period was lower than in many previous years. In addition, the high precipitation in August on average had an influence on the yield and quality of wheat. Previous studies (Tipples, 1986) have shown that very low VW is normally associated with sub-optimum growing and harvest conditions. After the application of GM, the VW of all treatments was higher than that of the N_0 treatment. GM enhanced the quality of spring wheat yield, but the results did not vary between different GM crops.

There is a need to further investigate additional sources of N that could boost the productivity in organic farming, such as those leading to better recovery of N from soil (i.e. deep-rooted catch crops) or to higher availability to cereal of N from N-fixation during crop rotation.

6.5. Decomposition of plant residues

Green manures of different species and different ages have different decomposition rates (Wivstad, 1997). The above-ground mass and root decomposition rate of the plant species researched by us varied widely after 6 months, depending on the plant species and the weather. Where crop residues were added to soil, a rapid initial N mineralization was observed. After 6 months, above-ground residue lost 40–50% of its initial dry weight and roots 20–46% of their initial DM in 2007/2008. As in the winter of 2008/2009, the soil was frozen for 4 months and thus the activity of degrading microbes was minimal, 34–42% of the above-ground biomass and 5–27% of roots decomposed. Weather impact on biomass decomposition and nutrient release rates has also been observed by Soon and Ashrad (2002) and Kauer et al. (2012).

Nutrient release depends on nutrient concentration in OM and on the C-to-nutrient ratio (Nygaard Sorensen and Thorup-Kristensen, 2011). Our trials showed that K release is negatively correlated with K concentration, which is in line with Lupwayi et al. (2005). Our trial results did not confirm the suggestion by Lupwayi et al. (2007) that the percentages of residue P released were positively correlated with P concentration; rather, a clearly negative correlation occurred in our trial. Our trial results confirm that P release is negatively correlated with C:P ratio, as has also been found by Lupwayi et al. (2007).

N release depends on plant material N content and C:N ratio (Handayanto et al., 1997; Trinsoutrot et al., 2000; Stadler et al., 2006). For optimum growth of degrading microorganisms, C:N ratios of 25–30:1 are usually ideal during the initial phase (Biddlestone et al., 1994). At a ratio of C:N <20 in decomposing material, further increases in nitrogen content and the related decreases in the C:N ratio do not influence the decomposition rate of the material (Wagner and Wolf, 1999; Kauer, et al., 2012). In our study, the C:N ratio in above-ground biomass was 18–23 and in roots 14–21. This indicates that there is sufficient nitrogen for microbiological activity and that much plant-available N is released into soil during the decomposition process. A close relationship between N release from OM and their N content and C:N ratio was found for crop residues. Our trial results confirmed the previous results (Kumar and Goh, 2000; Muhammad et al., 2011), according to which the C:N ratio is significantly negatively correlated with N mineralization (r=-0.49). In general, legume shoots decomposed faster than roots, although their C:N ratio was higher than that of roots. This may be due to the fact that roots contain more hard-to-decompose compounds, such as cellulose and lignin. Fox and Piekielek (1988) reported that 70%, 20%, and 10% of lucerne root residues mineralized in the three years following lucerne. The total N, C, P and K mineralization of root residue after 6 months was lower than that of shoot residue. For the first 6 months all the crops decomposed evenly but subsequently P release from white melilot roots ceased and a degree of P immobilisation occurred. Such immobilisation has also been observed in previous trials (Schomberg and Steiner, 1999; Soon and Arshad, 2002; Lupwayi et al., 2007; Rodriguez-Lizana et al., 2010). That nutrients are released from GM over a longer period of time was also corroborated in our trials: legumes had a positive effect on succeeding crop yield even in the third year after their incorporation into soil.

It has been found that legumes (*Trifolium repens*) decompose faster than graminaceous plants as they contain a higher degree of non-structural easier-to-degrade carbon compounds and decompose early in the decomposition process (Gunnarsson et al., 2008). In our trial (Lauringson et al., 2011), where the aboveground biomass decomposition of straw and straw-clover mix was studied, the C:N ratio in the straw-clover mix decreased significantly as there was sufficient N in the decomposable source material for microbiological activity. The N content of straw was low; thus its decomposition rate was slow, and N immobilisation by bacteria was likely in the decomposition process. Hence, growing legumes as undersowings improves the C:N ratio in OM, which creates better conditions for OM decomposition in soil.

6.6. The effect of catch crops (Paper V)

Over the years, there were great fluctuations in the quantity of CC biomass produced, which depended on the sum of effective temperatures during the growing season (r=0.63). Especially significant positive correlations were detected between fodder radish biomass and the sum of effective temperatures (r=0.88). This is supported by Arlauskiene and Maiksteniene (2008), Brant et al. (2011), Marcinkevičienė and

Bogužas (2011). The total biomass of CC varied in test years from 0.57 Mg ha^{-1} winter oilseed rape to 3.55 Mg ha^{-1} from fodder radish. In our experiment westerwold ryegrass and rye produced the least biomass and they also bound less N than *Brassicaceae* and leguminous crops. This is in accordance with Laine et al. (1994) who found the N uptake of crucifer species to be less sensitive to low temperatures than the N uptake by monocot species. The most stable biomass in the trial years was from legumes. This corresponds with the results from Askegaard and Eriksen (2007), who found that legumes form greater above-ground biomass than non-legumes in autumn. Power and Zachariassen (1993) found that Faba bean is the most appropriate leguminous catch crop for colder climate.

Many studies have shown that non-leguminous CC effectively reduce nitrogen leaching from arable land (Francis et al., 1992; Davies et al., 1996; Lord and Mitchell, 1998; Thorup-Kristensen and Nielsen, 1998). In all the soil sample measurements of our study, NO_3-N and NH_4-N content was low. According to the literature (Thorup-Kristensen and Nielsen, 1998), CC bind soil N, which should decrease mineral N content. In the present experiment, CC did not decrease soil NO_3-N and NH_4-Ncontent, compared to the control treatment (**Table 2 in V**). This may be due to the overall low soil N content.

The ability of CC to bind P and K nutrients for the main crop has been less studied. Thorup-Kristensen et al. (2003) argue that CC and GM as main crops take up soil P and K and thus convert it from inorganic to organic form. Some species may have especially high nutrient uptake capability, e.g., by forming particularly long root hairs. This is supported by Thorup-Kristensen (2001), who found that CC nutrient uptake effectiveness is highly correlated with rooting depth but not with root density. In our experiment, fodder radish roots constituted up to 39% of its total biomass; the root % of the other crops was lower. Likewise, previous studies confirm the findings by Thorup-Kristensen (2001) that fodder radish have a well-developed root system, which enables it to uptake water and nutrients from lower soil layers and to improve soil structure. Thorup-Kristensen (2001) found that Phacelia establishes quickly and its roots can reach great depths in a short time. This does not agree with the findings of our study. The establishment of Phacelia after cereals is risky, as in Nordic conditions its growth period is too short to form a large above-ground biomass and a deep-reaching root system.

Both positive (Lewan, 1994) and negative effects (Nygaard Sorensen and Thorup-Kristensen, 1993; Davies et al., 1996) of incorporated catch crops on the grain yield of the subsequent crop have been reported in the literature. Despite the fact that greater amounts of N were incorporated into soil with bean, the post-bean wheat yield of 2009 did not differ reliably from that of wheat following leguminous CC, and, in 2010, the CC did not affect grain yields significantly. One reason may be that if the CC is ploughed in, spring N may become available too late for increased yields. Allison et al. (1998) found that due to its high C:N ratio (20:1), little N would be mineralized after cover crop destruction. A consequence of high C:N ratios is that, in the short term, little or no N is released from crop residues after incorporation into the soil. If the catch crop is ploughed in late autumn, the reason may be that, in autumn soil samples, most of the N was in the form of the NH_4^+ ion, which is less susceptible to leaching. Leaching is normally associated with losses of NO_3^- only (Kärblane, et al., 1996; Baggs et al., 2000a). In winter there is no nitrification as low temperatures suppress bacterial activity. In spring, the NH_4^+ was transformed by nitrifying bacteria into NO_3^-, which leached out before commencement of crop growth (sample taken on 21 April). This may be confirmed by previous studies (Kärblane et al., (1996), where it was found that, as the NO_3^- ion is fast-moving in soil, its leaching in our climate occurs mainly in the seasons of autumn rains and spring snow melting. Baggs et al. (2000b) did not detect catch crop effect on succeeding cereal crop yield increase, and they supposed that N was not sufficiently limiting in this soil for any benefits to become apparent immediately. However, the benefits of increased sustainability as a result of increased OM concentrations may be seen in long-term organic rotations.

There is a need to further investigate the issues related to N leaching and the opportunities for growing catch crop mixes in Estonia. Further research is also needed on the capacity of CC to fix P, K, Ca and S and on the availability of the nutrients fixed by them to the succeeding main crop.

CONCLUSIONS

The formation of legume crop biomass varied with legume species, trial year weather and herbage use duration. Of the pure crop legumes studied by us, red clover, hybrid lucerne and white melilot produced the greatest biomass. When under sown, the amounts of biomass, N and C returned to the soil depended on aftermath formation. The amounts of nutrients returned to the soil were mostly influenced by biomass size and its nutrient content. Pure sown legume crops returned 89–220 kg N, 7–27 kg P, 83–177 kg K and 4.6–9.8 Mg C ha^{-1} to the soil, depending on the species and the year. Second year legumes returned up to 274 kg N and 13.9 Mg C ha^{-1}. Of the legumes used in the trials, bird's foot trefoil was not suitable as a green manure crop when under-sown, and even when pure sown its efficiency on succeeding crop yield was the lowest. Westerwold ryegrass use reduced succeeding crop yield (reason: high C:N ratio); thus it could be used as a catch crop for cereal crops on nitrogen-rich soils prone to N leaching.

Nitrogen mineralization was faster from the biomass of legumes whose C:N ratio was lower and N content higher. The biomass of bird's foot trefoil and red clover decomposed faster and their effect materialised in the succeeding crop yield. The effect of the lucernes and white melilot, which decompose more slowly, on succeeding crop yield materialised also in the second and third years.

Another major conclusion is that it is important for the N effect of green manures to be utilised by subsequent crops. Red clover, white melilot and hybrid lucerne pure sowing biomass effect was roughly equal to that of the N_{100} treatment. The effect of bird's foot trefoil was smaller than that of other leguminous green manure crops, with following cereal yield approximately equal to that after N_{50}. Cereal yield was similar after under-sowings biomass incorporation into soil.

Leguminous green manure crops annually bind into the biological cycle fairly large amounts of phosphorus and, in particular, potassium. Consequently, it is important for the green manure entire biomass to be ploughed into the soil, for, if the above-ground biomass is removed from the field, the soils may be depleted of nutrients, particularly in organic farming.

After spring ploughing of green manure, the succeeding crop yield increased more than with spring ploughing alone, but this effect was not evident in all trial years. This shows that apart from incorporated biomass biochemical composition, weather has a significant effect on the nutrient release rate from green manures. In systems where crops are already optimally supplied with N, the effect of a green manure may lead to excessive supply and thereby later to increased nutrient leaching.

Where legumes were grown as under-sowings the C:N ratio of incorporated organic matter improved, which creates better conditions for organic matter decomposition in soil and reduces microbiological soil nitrogen binding. Consequently, legume under-sowings significantly contributing to cereal straw decomposition are to be recommended in crop rotation. Under-sowings are of particular importance in low input systems where crops are more or less N limited.

Mineral fertilization and green manures enhanced winter and spring wheat yield quality but there were no differences between the green manure crops. Green manures release nitrogen over a prolonged period of time and thus their use provides a steady supply of nitrogen to plants, which is conducive to attaining higher wheat quality. Yield quality was also influenced by trial year weather conditions, which had an effect on incorporated organic matter decomposition and thereby on nitrogen fertilization efficiency.

The effectiveness of catch crops depended on the choice of species, sowing time and main crop harvesting time, as well as on weather conditions during the autumn and winter. Catch crops also have the potential to supply significant amounts of N available to succeeding crops, which can be valuable especially in organic farming. As the trial area soils had low nitrogen content, catch crops did not decrease soil NO_3-N and NH_4-N content compared to the variant without catch crops. On soils with a high N content, growing catch crops is necessary to reduce nutrient leaching in the non-growing period. The optimal catch crops in Estonian weather conditions were fodder radish and white mustard.

Issues requiring further research:

1. To investigate whether green manure crops summer cutting during the growth period is necessary. To find the optimal number for green

manure crop cutting times during summer to ensure weed control, minimal nutrient loss through evaporation and leaching and maximal impact on succeeding winter crop yield.

2. To specify why our research results were partly different from those of previous studies (why catch crop growing did not reduce soil mineral nitrogen content). Subsequent studies should clarify what determines soil N content and its dynamics during and after succeeding crop growing and whether and how much it is dependent on soil humus content, weather and preceeding crop.

3. To investigate the P, K, Ca and S binding capacity of catch crops and the availability of nutrients bound by them to the succeeding main crop. No research has been conducted in Estonia on the possibilities of growing various catch crop mixes. In other European countries, the tendency is, conversely, toward growing various mixes to ensure better nutrient fixing and the formation of a larger biomass, thereby improving winter surface cover. Finally, catch crop impact on the succeeding crop weed invasion and yield should be studied.

Use of the research results:

One of the yield-limiting factors in our circumstances has been soil fertility reduction caused by the soil preparation regimes of preceding decades (compacted soils, poor soil structure, and water and air regimes unfavourable for plant growth). Many land users have negative humus balances in their crop rotations. We can impact humus content by agricultural engineering devices, of which the most important are a proper choice of crops in rotation and skilful fertilization with organic fertilizers. Organic matter incorporated into soil improves soil humus content, resulting in improved nutrient regime, structure, physical and hydro-physical properties as well as enhanced biota and biological activity of the soil.

Green manure crops making soil humus balance more positive and increasing organic manure amounts should be introduced into crop rotation. As manure amounts have decreased, more and more green manure fertilization should be used. In organic farming, growing green manure crops is the only way of raising soil fertility. In conventional farming, likewise, green manures have become a significant source of organic fertilization, as mineral fertilizers have become too expensive for the agricultural producer. In addition, farmers are required to grow legumes in crop rotation and keep the soil surface covered in winter.

It is known that soil organic matter mineralization also occurs in the non-growing period of arable crops; in addition, autumn soil preparation increases the risk of nitrogen leaching, particularly in more fertile soils. An autumn-grown catch crop, by consuming soil water, reduces soil water mobility and thereby nutrient leaching.

SUMMARY IN ESTONIAN

ERINEVATE HALJASVÄETISKULTUURIDE BIOPRODUKTSIOON JA MÕJU JÄRGNEVATE KULTUURIDE SAAGILE

Sissejuhatus

Väetiste kõrge hind, põllukultuuride aastati kõikuv müügihind ning mure mullaviljakuse säilitamise ja parandamise pärast sunnivad mõtlema liblikõieliste heintaimede kasvatamisele hoopis rohkem kui mõnikümmend aastat tagasi. Liblikõielised haljasväetiskultuurid sümbioosis mügarbakteritega seovad õhulämmastikku, toovad sügavamale ulatuva juurestikuga künnikihti taimedele vajalikke toitaineid (P, K, Ca) (Teit, 1990) ning muudavad need järgnevatele kultuuridele kättesaadavaks (Witter and Johansson, 2001). Erinevalt teistest orgaanilistest väetistest kobestavad haljasväetiskultuurid oma tugeva juurestikuga sügavamaid mullakihte, parandades mullastruktuuri ja soodustades järgnevate kultuuride juurte sügavamale tungimist. Lisaks eeltoodule elavdavad liblikõielised haljasväetised ka mulla mikrobioloogilist tegevust, mis määrab mulla kvaliteedi ja tagab mullaagregaatide stabiilsuse (Tejada et al., 2008). Haljasväetiskultuurid aitavad kontrolli all hoida umbrohtu, vähendades seega herbitsiidide kasutamist (Ross et al., 2001; Linares et al., 2008), peale selle vähendavad nad teraviljarohkes külvikorras allelopaatilist mõju (Conklin et al., 2002; Altieri, et al., 2008).

Mida kitsam on orgaanilise aine C:N suhe ja mida suurem on selle lämmastikusisaldus, seda enam vabaneb mulda haljasväetise mineralisatsioonil lämmastikku (Kumar and Goh, 2002; Baggs et al., 2000a, Chaves et al., 2004). On teada, et mulla orgaanilise aine mineralisatsioon toimub ka väljaspool põllukultuuride kasvuperioodi (Powlson, 1993; Vos and Van der Putten, 2001). Mitmetes uuringutes on leitud, et haljasväetise muldakünni aeg ja sisseküntav taimik mõjutavad lämmastiku väljaleostumist mullast. Skandinaaviamaades läbiviidud uuringute tulemusena on leitud, et kevadkünd vähendab lämmastiku mullast väljauhtumise riski (Davies et al., 1996, Stenberg et al., 1999, Lahti ja Kuikman, 2003). Lämmastiku mullast väljaleostumise oht tekib, kui sügisel jääb mulda taimede poolt kasutamata nitraatset lämmastikku (Lasa et al., 2001). Järelikult on väga oluline siduda toitained kultuuridest vabal perioodil, kasvatades selleks vahe- ehk püüdjaid kultuure.

Käesolev doktoritöö keskendub erinevate haljasväetiskultuuride uurimisele põhjamaistes tingimustes nii katteviljata- ja katteviljaga- kui ka vahekultuuridena kasvatamisel. Doktoritöö raames uuriti millistes kogustes kasutavad ja seovad need taimed toitaineid ning bioloogiliselt seotud lämmastiku mõju kestvust ja efektiivsust järelkultuuride saagile ja selle kvaliteedile.

Töö hüpoteesid on:

- Haljasväetiste orgaanilise aine mineralisatsiooni kestus mullas ja mõju järgnevate kultuuride saagile sõltub erinevate haljasväetiskultuuride puhas- ja allakülvidest, biomassi suurusest, selle keemilisest koostisest ning ilmastikutingimustest. Orgaanilise aine lagunemisdünaamika ja toitainete vabanemise kiirus mulda sõltub taimeliigist ning on erinev juurtes ja maapealses massis. Haljasväetiste mõju järgnevate kultuuride saagile ja selle kvaliteedile oleneb biomassi sissekünniajast. Vahekultuuride bioproduktsioon ja toitainete sidumine sõltub taimeliigist, ilmastikutingimustest ja kasvuperioodi pikkusest.

Tulenevalt püstitatud hüpoteesidest oli uurimustöö eesmärkideks:

1. Selgitada erinevate haljasväetiskultuuride bioproduktsiooni, maapealse biomassi ja juurte koguseid, keemilist koostist, erineva koostisega orgaanilise aine lagunemise kiirust mullas ja haljasväetistega mulda viidavaid toiteelementide (N, P, K) koguseid.

2. Uurida bioloogiliselt seotud lämmastiku efektiivsust ja mõju kestust järgnevate kultuuride saagikusele ja saagi kvaliteedile.

3. Uurida, kuidas laguneb erineva C:N suhtega orgaaniline aine mullas.

4. Selgitada, millised on Eesti tingimustesse kõige sobivamad vahekultuurid, kui suur on nende bioproduktsioon, millisel hulgal seovad nad toitaineid ja milline on nende mõju mulla liikuva mineraaliseerunud lämmastiku sisaldusele ja järgneva kultuuri saagile.

Metoodika

Uurimistöö tugineb neljale põldkatsele, kus uuriti erinevate haljasväetiskultuuride biomassi moodustamist, nende toitainete sidumise võimet, biomassi lagunemise kiirust ja haljasväetiste mõju järgnevate kultuuride saagile.

Põldkatsed 1 ja 2.

Katsevariandid olid järgmised:

a) liblikõielised haljasväetiskultuurid (punane ristik, harilik lutsern, hübriidlutsern, nõiahammas, valge mesikas (põldkatse 2)) katteviljata külvina;

b) liblikõielised haljasväetiskultuurid (punane ristik, harilik lutsern, hübriidlutsern, nõiahammas, valge mesikas ((põldkatse 2), itaalia raihein (põldkatse 1)) katteviljaga külvina;

c) mineraalväetisega väetatud oder (N_{50} ja N_{100} kg ha^{-1});

d) väetamata oder (kontroll).

Katteviljana külvati oder 'Arve'.

Eraldi variandina uuriti haljasväetiskultuuride biomassi moodustamist kahe vegetatsiooniperioodi jooksul (haljasmass künti mulda järgmise aasta sügisel).

Proovid teravilja biomassi määramiseks võeti enne saagi koristust ja juurte mass määrati 10 cm kaupa kuni 60 cm sügavuseni. Katteviljaga variantides määrati haljasväetiskultuuride maapealne biomass kahel korral: esimene kord üheaegselt teravilja koristamisega ja teine kord ädala mass enne sügiskündi ning samaaegselt ka juurte mass. Liblikõieliste kultuuride katteviljata külvide biomass ja juurte mass määrati enne kündi (ka kevadkünni variantides). Teravilja põhk ja haljasväetiste biomass künti 20–22 cm sügavusele. Sõltuvalt variandist künti liblikõieliste katteviljata külvide biomass mulda kahel ajal: nii sügisel kui kevadel. Katteviljaga külvide korral oli kasutusel ainult sügiskünd.

Põldkatse 3.

Vahekultuuride katsed 2008–2010 aastal rajati vahetult pärast oder 'Inari' koristamist. Enne vahekultuuride kündi hariti katseala nugaäkkega.

Vahekultuurina kasutati järgmisi kultuure: talirüps ja taliraps, õlirõigas, valge sinep, hernes, põlduba, itaalia raihein, rukis ning keerispea. Vahekultuuride maapealne biomass ja juurte mass määrati kasvuperioodi lõpus, enne kündi. Olenevalt kasvuperioodi pikkusest künti vahekultuurid 22–24 cm sügavusele mulda oktoobri II–III dekaadis.

Põldkatse 4.

Liblikõieliste maapealse biomassi ja juurte lagunemise dünaamikat ja kiirust uuriti 2007–2010. a. kahe aasta kestel järgmistel liikidel: punane ristik, harilik lutsern, nõiahammas ja valge mesikas. Eraldati liblikõieliste juured ja maapealne mass, mis tükeldati 5 cm pikkuseks ja pandi 20 x 20 cm nailonkottidesse (ava läbimõõt 1.0 mm) ja kotid asetati 20–22 cm sügavusele mulda samale katsealale. Kuue, kaheteistkümne ja kahekümne nelja kuu möödudes võeti kotid mullast välja ja toimus kottide sisu analüüsimine.

Tulemused

Haljasväetiskultuuride biomassi kogus ja selle keemiline koostis sõltus kasvatavast taimeliigist. Kui senini on Eestis enam kasvatatud haljasväetiskultuuridena punast ristikut ja valget mesikat, siis antud katsete põhjal saab väita, et perspektiivikad on ka lutsernid. Punase ristiku kogu biomass varieerus 6,3–8,9 Mg ha^{-1}, millest juurte mass moodustas 42,2–44,5%. Hariliku ja hübriidlutserni biomass oli vastavalt 6,80–8,40 ja 6,61–9,43 Mg ha^{-1}, kusjuures nende katteviljata külvides moodustas juurte mass kogu biomassist 49,6–52,4%. Võrreldes teiste liblikõieliste katteviljata külvidega oli madalaim nõiahamba kogu biomass: 4,64–5,24 Mg ha^{-1}. Katteviljaga külvidel sõltus biomassi suurus ja mulda tagastatava C ja N kogus ädala moodustumisest, kasvuajast ja taimede konkurentsivõimest.

Mulda viidud orgaanilise aine lämmastikusisaldus kui ka C:N suhe erines väga suurtes piirides. Lämmastikusisaldus oli kõige kõrgem valge mesika juurtes, erinedes usutavalt ($p<0,05$) kõigist katses olnud liblikõielistest. Punase ristiku biomassiga viidi mulda 172,8–219,7 kg N ha^{-1} ja 2,67–3,76 Mg ha^{-1} C. Puhaskülvidest tagastati mulda kõige suurem kogus süsinikku ja lämmastikku 2004. aastal hübriidlutserniga. Liblikõieliste haljasväetiste maapealse biomassi C:N suhe oli 14–19, juurtes 14–24, sõltudes liblikõieliste biomassi lämmastikusisaldusest, olles kuni kolm korda kitsam kui teraviljapõhus. Seega, liblikõieliste kasvatamisel katteviljaga paraneb C:N suhe mulda tagastuvas orgaanilises aines, mis loob paremad tingimused selle lagunemiseks mullas.

Katteviljata külvidest suurim kogus fosforit ja kaaliumi tagastati mulda punase ristikuga ja väikseim nõiahambaga, vastavalt 20 ja 16 kg P ning 153 ja 98 kg K ha^{-1}. Katteviljata liblikõieliste puhul aga olid fosfori ja kaaliumi kogused vastavalt 17–24 ja 89–144 kg ha^{-1}, sõltudes haljasväetise liigist ja biomassi suurusest. Katsed kinnitasid, et kaaliumi sisaldus juurtes oli madalam võrreldes maapealse biomassiga. Sellest lähtuvalt on oluline haljasväetiste kogu biomassi muldaviimine, sest maapealse massi koristamisel näiteks loomasöödaks viiakse ära suur kogus taimede poolt seotud toitainetest.

Kasvatades külvikorras liblikõielisi haljasväetiskultuure on võimalik oluliselt vähendada järgnevate kultuuride kasvatamiseks vajaminevat mineraalset lämmastikväetise kogust. Muldaviidud lämmastiku efektiivsust hinnati järgnevate teraviljade saagi kaudu. Esimesel aastal kujunes antud katsete põhjal haljasväetise lämmastiku efektiivsuseks 8,6 kg teri kg lämmastiku kohta ja see ei vähenenud ka suurte lämmastikunormide korral. Kuna liblikõielised haljasväetised avaldavad mõju peaaegu kõigile olulisematele mulla keemilistele ja füüsikalistele omadustele, siis ei piirdu nende mõju ühe aastaga, vaid võib kesta mitu aastat. Teisel aastal pärast haljasväetiste mulda viimist oli orgaanilise aine lämmastiku efektiivsus 6,8 kg teri N kg^{-1}. Kolmandal järelmõju aastal oli orgaanilise aine lämmastiku mõju olemas, kuid see oli ligi kolm korda madalam kui eelneval aastal.

Kevadine haljasväetise sissekünd võrreldes sügiskünniga suurendas usutavalt järgneva teravilja saaki, sügiskünni korral oli saak 2004. a rajatud katses usutavalt madalam kui kevadkünnil ja seda nii esimesel kui teisel järelmõju aastal. Kolmandal järelmõju aastal kevadkünni mõju ei avaldunud.

Kevadine põud ja erakordselt sademeterohke august halvendas 2008. aasta tali- ja suvinisu saagi kvaliteeti. Haljasväetiste sissekünd suurendas nii suvi- kui talinisu proteiinisisaldust, kuid see jäi siiski madalamaks sellest, mis peaks olema heade küpsetusomadustega nisul. Liblikõieliste haljasväetiskultuuride sissekünd suurendas suvi- ja talinisu mahumassi ja 1000 seemne massi, katteviljaga liblikõieliste mõju ei olnud statistiliselt usutav.

2007. aasta sügisel mulda viidud haljasväetiskultuuride maapealsest biomassist lagunes poole aastaga 40–50% ja juurtest kuni 46%, 2008. aastal muldaviidud biomassist lagunes 6 kuuga vastavalt 34–42% ja juurtest 20–46%. Aastaga lagunes lehtedest/vartest 61–74% ja juurtest 47–62%. Kahe aasta möödudes oli maapealsest massist lagunenud, sõltuvalt taimeliigist, 70–83% ja juurtest kuni 75%. Kiiremini lagunes nõiahamba ja punase ristiku biomass ning kõige aeglasemalt lagunesid lutserni juured ja valge mesika kogu biomass.

Vahekultuuridena kasvatatavate taimede biomass ja seotud toitainete kogused olid aastate lõikes varieeruvad, sõltudes kultuurist ja efektiivsete temperatuuride summast. Kindlasti mõjutab nende kasvu ka sademete hulk, kuid katseaastatel oli sademeid vahekultuuridele piisavalt. Ristõielistest vahekultuuridest võib efektiivsemateks pidada õlirõigast ja valget sinepit, mis moodustasid teistest katses olnud ristõielistest suurema biomassi, millega viidi mulda ka suurem kogus toitaineid. Suurimad toitainete sidujad on liblikõielised hernes ja uba. Mulda viidava biomassi C:N suhe varieerus vahemikus 13 (uba) kuni 31 (itaalia raihein).

Töös püstitatud eesmärkidest lähtuvalt saab teha järgmised järeldused:

Liblikõieliste kultuuride biomassi moodustumine sõltus liblikõielise liigist, katseaastate ilmastikust ja taimiku kasvuaja kestusest. Liblikõieliste kultuuride katteviljata külvidega viidi mulda 89–220 kg N, 7–27 kg P, 83–177 kg K ning 2,67–3,76 Mg C ha^{-1} sõltuvalt liigist ja aastast. Katteviljaga külvidel sõltus biomassi suurus ning mulda tagastatava N ja C kogus ädala moodustumisest. Katsetes olnud liblikõielistest ei sobi harilik nõiahammas haljasväetiskultuuriks katteviljaga kasvatades, kuid ka katteviljata külvi korral oli selle mõju järelkultuuride saagile kõige väiksem. Itaalia raiheina kasvatamine haljasväetiseks vähendab järgnevate kultuuride saaki (põhjuseks lai C:N suhe ja lämmastiku immobilisatsioon), kuid seda sobib kasvatada teraviljade allakülvi korral vahekultuurina kõrge lämmastikusisaldusega muldadel, kus on lämmastiku leostumise oht.

Lämmastiku vabanemine orgaanilise aine mineraliseerumisel toimus kiiremini nende liblikõieliste biomassist, mille C:N suhe oli kitsam ja lämmastiku sisaldus suurem. Kiiremini lagunes nõiahamba ja punase ristiku biomass ning nende mõju realiseerus järgneva kultuuri saagikuses. Aeglasema biomassi lagunemisega lutsernide ja valge mesika mõju järgnevate kultuuride saagile realiseerus veel ka teisel ja kolmandal järelmõju aastal.

Katteviljata külvatud punase ristiku, valge mesika ja hübriidlutserni biomassi mõju oli esimesel järelmõju aastal ligikaudu võrdne mineraalse lämmastikväetisnormiga N_{100}. Tagasihoidlikumaks, võrreldes teiste liblikõieliste haljasväetistega jäi hariliku nõiahamba mõju, mille järgselt oli teravilja saagitase võrdne ligikaudu N_{50} mineraalse lämmastikväetisnormi tasemega. Samale tasemele jäi ka katteviljaga külvatud liblikõieliste biomassi muldaviimise järgse teravilja saak.

Liblikõieliste haljasväetiskultuuridega seotakse aastas bioloogilisse ringesse küllalt suured kogused fosforit ning eriti kaaliumi. Järelikult on oluline, et haljasväetiste kogu biomass küntakse mulda, sest kui maapealne biomass eemaldatakse põllult, siis eriti maheviljeluses, kus mineraalväetisi ei kasutata, võivad mullad toitainetest vaesuda.

Võrreldes sügisese künniga suurenes haljasväetiste kevadise sissekünni järgselt järelkultuuri saak, kuid kevadkünni efekt ei ilmnenud kõikidel katseaastatel. Sellest järeldub, et lisaks muldaviidud biomassi biokeemilisele koostisele on oluline ka ilmastiku mõju haljasväetistest toitainete vabanemise kiirusele. Kui mulla lämmastiku sisaldus on kõrge ja taimed lämmastikuga varustatud, tuleb jälgida, et liblikõielistest vabanev lämmastik ei leostuks künnikihist välja.

Liblikõieliste kasvatamisel allakülvidena paranes muldaviidava orgaanilise aine C:N suhe, mis loob paremad tingimused orgaanilise aine lagunemiseks mullas ja vähendab lämmastiku sidumist mullast mikroorganismide poolt. Sellest tulenevalt on soovitav kasvatada viljavahelduses liblikõieliste allakülve, mis oluliselt aitavad kaasa teravilja põhu lagundamisele. Eriti oluline on allakülvide kasvatamine madala mullaviljakusega aladel, kus taimede lämmastikuga varustamine on limiteeritud.

Väetamine mineraalväetisega ja haljasväetiste kasutamine parandasid tali- ja suvinisu saagi kvaliteeti, kuid haljasväetiste vahel erinevused puudusid. Kasutades haljasväetisi, vabaneb neist lämmastikku pika aja jooksul ja taimede varustamine lämmastikuga on ühtlane kogu kasvuperioodi jooksul, mis aitab tagada kõrgemat nisu kvaliteeti. Katseaastate ilmastikutingimused mõjutasid mulda viidud orgaanilise aine lagunemist ja seeläbi lämmastikuga väetamise efektiivsust.

Vahekultuuride efektiivsus sõltub kasvatatavast kultuurist, kasvuperioodi pikkusest ja efektiivsete temperatuuride summast kasvuperioodil. Vahekultuurid seovad arvestataval hulgal toitaineid. Kuna katseala mullad olid madala lämmastikusisaldusega, siis meie katsetes NO_3-N and NH_4-N sisaldus mullas vahekultuuride kasvatamisel ei vähenenud. Kõrge lämmastikusisaldusega muldadel on vahekultuuride kasvatamine toitainete leostumise vähendamiseks taimekasvuperioodi välisel ajal vajalik. Kõige sobivamad vahekultuurid Eesti tingimustesse on õlirõigas ja valge sinep. Vahekultuuride valikul tuleb lähtuda sellest, et nad sobiksid külvikorda ka botaaniliselt (sarnaseid liike ei tohi haiguste ja kahjurite leviku tõttu kasvatada liiga sageli).

Edasist uurimist vajavad küsimused:

1. Uurida, kas haljasväetiskultuuride suvine niitmine on vajalik. Leida optimaalne taimiku niitmiskordade arv suve jooksul, et oleks tagatud umbrohtude kontrolli all hoidmine ja et toitainete kaod lendumise ja leostumise läbi oleksid võimalikult madalad ning mõju järgneva teravilja saagile oleks võimalikult suur.

2. Täpsustada, miks meie uurimistöö tulemused erinesid osaliselt varasematest uurimustest (miks vahekultuuride kasvatamine ei vähendanud mullas taimedele omastatava lämmastiku kogust). Edaspidistes uurimustes tuleks selgitada, millest sõltub järelkultuuride kasvatamise ajal ja nende sissekünni järgselt mulla mineraalse lämmastiku sisaldus ja selle dünaamika. Kas, ja kui palju mõjutab seda mulla huumusesisaldus, ilmastik, eelnev kultuur.

3. Uurida nii tava- kui maheviljeluses ka vahekultuuride P, K, Ca ja S sidumise võimet ja nende poolt seotud toitainete kättesaadavust järgnevale põhikultuurile. Eestis ei ole uuritud erinevate vahekultuuride segude kasvatamisvõimalusi. Euroopas on suund just erinevate segude kasvatamisele, et tagada parem toitainete sidumine ja suurem biomassi moodustumine ja seeläbi parem pinnakaetus talvel. Ja lisaks tuleks uurida seda, kuidas mõjutab vahekultuur järgneva kultuuri umbrohtumust ja saaki.

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I

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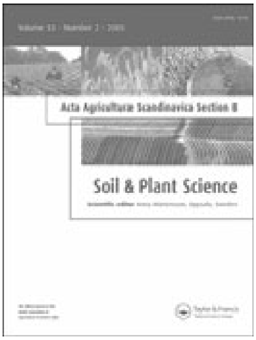

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The effects of pure and undersowing green manures on yields of succeeding spring cereals

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The effects of pure and undersowing green manures on yields of succeeding spring cereals

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Abstract

A field experiment was conducted in 2004–2006 to investigate the effect of green manure treatments on the yield of oats and spring barley. In the experiment, different green manure crops with undersowing and pure sowing were compared for amounts of N, C, and organic matter driven into soil and their effect on cereal yield. The spring barley field had a total of 41.7–62.4 kg N ha^{-1} and 1.75–2.81 Mg C ha^{-1} added to the soil with straw, weed, and roots, depending on the level of fertilisation; with red clover, and both common and hybrid lucerne undersowing, with barley straw and roots, the values were 3.45–3.96 Mg C ha^{-1} and 139.9–184.9 kg N ha^{-1}. Pure sowings of these three leguminous green manure crops had total applications of 3.37–4.14 Mg C ha^{-1} and 219.7–236.8 kg N ha^{-1}. The mixed and pure sowing of bird's-foot trefoil provided considerably less nitrogen and carbon to the soil with the biomass than with the other leguminous crops. Application of biomass with a high C/N ratio reduced the yield of the succeeding spring cereals. Of the green manures, the most effective were red clover and both common and hybrid lucerne, either as undersowing or as pure sowing. Undersowings with barley significantly increased the N supply for the succeeding crop without yield loss of the main crop compared with the unfertilised variant. Compared with ploughing-in of green manure in autumn, spring ploughing gave a 0.2–0.57 Mg ha^{-1} larger grain yield.

Keywords: *Biomass, carbon, grain yield, green manure crops, nitrogen, phytoproductivity.*

Introduction

Efficient and economic utilisation of natural resources is crucial in farming systems (Granstedt, 2000). Each farming system determines the nutrient inputs and balance of soils (Kätterer et al., 2004; Montemurro et al., 2006), nutrient availability and sequestration in the soil (Schaldach & Alcamo, 2006), nutrient leaching (Hansen et al., 2000; Kutra & Aksomaitiene, 2003) as well as the general state of the environment and agro-ecosystem productivity (Waldon et al., 1998; Eltun et al., 2002).

The present global area of organically managed land exceeds 31.5 million hectares (The World of Organic Agriculture . . . , 2007). Since the beginning of the 1990s, organic farming has rapidly developed in European countries: across the EU, more than 6.4 million hectares, representing 3.5% of the utilised agricultural area (The World of Organic Agriculture . . . , 2007), are under organic management. By the end of 2005, the agricultural area occupied by organic farming in Estonia was 59 862 hectares, or 7.2% of total agricultural land.

Organic fertilisers play the central role in sustaining soil fertility and crop productivity in organic farming. In specialised crop farms where the use of animal manure is limited, green manures provide the most effective way to improve the N supply for succeeding crops (Thorup-Kristensen et al., 2003). Organic crop farming in Estonia is mainly centred on the islands of Hiiumaa and Saaremaa and on the

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west and south-eastern mainland, where soil fertility is relatively low, and is infrequently employed in the fertile soils of central Estonia. The yield level of crops throughout Estonia is lower than in other European countries (Roostalu et al., 2000), partly due to the insufficient use of fertilisers; Astover et al. (2006) determined that the low input of plant nutrients limits the actual yield level.

One limiting factor is low humus content – below 2% – especially in 40–60% of the total cultivated area of southern Estonia (Järvan et al., 1996). Currently, in Estonia's small farms, animal manure and mineral fertilisers are used considerably less than in large-scale agricultural production, resulting in a negative soil humus balance (Roostalu et al., 2000). Thus, both soil fertility and crop productivity depend largely on the use of organic fertilisers in both organic and conventional cultivation; consequently, green manure crops have an increasingly important role in crop husbandry.

Organic matter has a favourable effect on the soil biota and the biological activity of soil, improving their humus condition, which in turn improves soil structure and its physical and hydrophysical characteristics. The concentration of organic C and N are good indicators of soil quality and productivity, affecting those characteristics (Reeves, 1997). The C and N pools in the soil play an important role in nutrient cycling, plant productivity and the quality of the environment. The content and balance of soil C and N can be influenced by various management practices, such as rate of fertilisation, soil tillage, the cultivation of different field crops and crop rotation. A common practice for guaranteeing maximally high and stable yields of field crops in contemporary intensive agriculture is the use of comparatively large quantities of mineral and organic fertilisers, including green manures. However, the application of high fertiliser norms can lead to appreciable nutrient losses from the soil, which affects the quality of groundwater and contributes to the eutrophication of water bodies (Tilman et al., 2002). To obtain a balance between agronomic, economic and environmental targets, the know-how of green manure management is essential. The aim of the present study was to investigate the influence of various green manures on the yield of oats and spring barley.

Methods and materials

The trials were carried out during the 2004–2006 growing seasons at the Department of Field Crop Husbandry in the Estonian University of Life Sciences (EMU), Institute of Agricultural and Environmental Sciences (58° 23′ N, 26° 44′ E). Random block-placement in 4 replications was used (Hills & Little, 1972). The size of each test plot was 30 m^2. The soil type of the experiment area was sandy loam Stagnic Luvisol in the WRB 1998 classification. The mean characteristics of the humus horizon were as follows: C_{org} 1.1–1.2%, N_{tot} 0.10–0.12%, P 110–120 mg kg^{-1}, K 253–260 mg kg^{-1}, pH_{KCl} 5.9, soil bulk density 1.45–1.50 Mg m^{-3}. The thickness of the ploughing layer was approximately 27–29 cm. Soil analyses were carried out at the laboratories of the Department of Soil Science and Agrochemistry, EMU. Air-dried soil samples were passed through a 2 mm sieve. Various methods were used to determine the following soil characteristics: pH_{KCl}; organic carbon by the Tjurin method (Soil Survey Laboratory Staff, 1996); P and K by the Mehlich-3 method (Extracting Reagent 0.2N CH_3CO_2H; NH_4NO_3; 0.015N 0.001M EDTA) (Handbook on . . . , 1992); the Kjeldahl method was used to determine the total-N content of soil (Benton & Jones, 2001). Plant analyses were conducted at both the Department of Soil Science and Agrochemistry of EMU and the Estonian Agricultural Research Centre laboratories. Acid digestion by sulfuric acid solution (Methods of Soil . . . , 1986) was used to determine N, P, K content in plant material. The Dumas Combustion method was used to determine the content of carbon in the plant biomass.

The field experiment was established in 2004 using the following variants of green manure crops and fertilisation:

Variant A) legume pure sowings (i) red clover (*Trifolium pratense)*, (ii) lucerne *(Medicago sativa)*, (iii) hybrid lucerne *(Medicago media)*, (iv) bird's-foot trefoil (*Lotus corniculatus)*, (v) pea (*Pisum sativum*);

Variant B) spring barley (*Hordeum vulgare* L.) with undersowings of (i) red clover, (ii) lucerne, (iii) hybrid lucerne, (iv) bird's-foot trefoil, (v) pea, (vi) westerwold ryegrass *(Lolium multiflorum westerwoldicum)*;

Variant C) spring barley with dairy manure applied on 25 October 2004 (60 Mg ha^{-1});

Variant D) spring barley with mineral fertiliser rates (i) N_0 – the control variant (ii) N_{50}, (iii) N_{100} (every year with cereal sowing).

The 2004 cover crop was spring barley *cv. "Arve"*, sown on 30 April. Succeeding crops were, in 2005, oats (*Avena sativa* L.) *cv. "Jaak"* (3 May), and, in 2006, spring barley (*Hordeum distichon* L.) *cv. "Inari"* (2 May). The seed rate of germinating grains of cereals was 500 m^{-1} every year. Green manure pure crops were sown according to the following norms: red clover 15 kg ha^{-1}, lucerne 13 kg ha^{-1}, hybrid lucerne 20 kg ha^{-1}, bird's-foot trefoil 12 kg ha^{-1}, westerwold ryegrass 10 kg ha^{-1}, pea 220 kg ha^{-1}. The seeding rates for undersowings were reduced by half. In all variants, barley straw and the biomass of legumes were ploughed into the soil (20–22 cm). The biomass of legume pure sowings (variant A) was ploughed into the soil in two variants – (i) autumn (end of October) and (ii) spring (end of April) (exception: pea was ploughed into the soil only in autumn). Autumn ploughing alone was carried out with the other variants. In autumn 2005, straw of the oat crop was ploughed into the soil. Samples of aboveground biomass were taken before harvesting of the cereals and the root mass was taken from 0–60 cm in depth. In variants with undersowings (B), the aboveground biomass of green manure crops was measured twice: first, during harvesting; secondly, the aftermath mass was taken before autumn ploughing. The aboveground biomass of pure sowings and the root mass of leguminous crops were measured before ploughing.

The experimental area belongs to the south-Estonian upland agroclimatic region, where the average annual sum of active air temperatures is 1750–1800°C and total precipitation is 550–650 mm. The period of active plant growth (mean diurnal temperature continuously above 10°C) ranges usually from 115 to 135 days (Tarand, 2003). The amount of precipitation during the vegetation period (from May to September) compared with the average varied through the trial: it was greater than average in 2004, similar in 2005, but lower in 2006 (Table I).

Analysis of variance (ANOVA) was used to evaluate the impact of the experimental variants on the grain yield. The significance of differences between grain yields of the variants was calculated using the Fischer test, and the levels of significance $p < 0.05$ and $p < 0.01$ were used. The software STATISTICA 7.0 (StatSoft, Inc., 2005) was used for the statistical data analysis.

Results

The barley yield in 2004, the year the trial was established, was 0.38–0.64 Mg ha^{-1} higher in the mixed sowings with leguminous green manure crops than for the unfertilised control variant (Figure 1). The grain yield of barley was higher with undersowings of pea and bird's-foot trefoil, but the ryegrass yield did not differ from the control variant (N_0). The mineral nitrogen fertiliser norms N_{50} and N_{100} increased the barley yield by 1.78 and 2.50 Mg ha^{-1}, respectively.

The total phytomass of pure sowings of barley constituted 6.55–11.54 Mg of dry matter per hectare depending on the nitrogen fertiliser norm, of which the root mass constituted 17.7–20.4% and the grain yield 37.3–43.2%. The total phytomass of mixed sowings varied within the range 8.13–12.13 Mg ha^{-1}, the root mass comprising 18.6–33.3% and the grain yield 22.9–31.4%. The smallest total phytomass of legume pure sowings was bird's-foot trefoil at only 4.64 Mg ha^{-1}, while those of red clover, lucerne, and hybrid lucerne were 8.91, 8.40, and 9.43 Mg ha^{-1}, respectively. The root mass constituted 42.2–51.6% of the total biomass in these legume pure sowings.

The amount of organic material left in the soil was affected by the crop grown: The highest was left in the soil with pure sowing of legumes, and the lowest with pure sowing of nonfertilised barley (Figure 2). The larger total quantity of aboveground dry matter (x, kg ha^{-1}) that was formed [Equation (1)] the smaller was the proportion of the aboveground phytomass of weeds (y,%).

$$y = -0.0039x + 37.441; \; R^2 = 0.62; \; p < 0.05 \qquad (1)$$

Both the nitrogen content and the C/N ratio of the applied organic matter varied considerably. The variance in the nitrogen content of barley straw,

Table I. Weather conditions for 2004–2006 (according to the Erika weather station) and the average for 1966–1998* in Tartu (Jaagus, 1999).

	Air temperatures, °C				Precipitation, mm			
Month	2004	2005	2006	Average*	2004	2005	2006	Average*
January	−7.6	−1.7	−5.5	−7.1	6	114	5	29
February	−4.5	−7.3	−8.7	−6.6	18	0	8	23
March	−0.4	−4.9	−3.5	−2.4	36	4	13	26
April	5.6	5.0	6.2	4.2	8	22	15	33
May	12.7	10.8	11.9	11.6	34	114	34	55
June	13.4	14.4	16.2	15.1	210	54	47	66
July	16.4	19.5	18.7	16.7	113	22	16	72
August	17.0	16.5	17.1	15.6	116	92	80	79
September	11.9	12.7	13.6	10.4	99	59	35	66
October	5.7	6.7	8.1	5.7	61	38	111	52
November	−0.7	2.6	5.3	0.3	25	30	10	48
December	−0.1	−3.2	3.8	−4.2	27	17	38	40

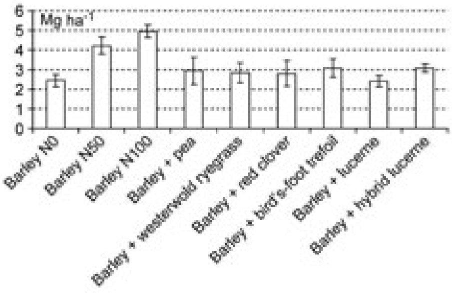

Figure 1. Grain yield of spring barley (Mg ha^{-1}) in pure and undersowings in 2004. Vertical bars denote confidence limits (CL) (CL 0.05 – level of statistical significance).

0.63–0.74%, depended on the fertiliser norm; the aboveground biomass of leguminous crops contained 2.42–3.51% of nitrogen; the roots and the aboveground phytomass of weeds contained 1 and 2.2% of nitrogen, respectively. The relationship between the C/N ratio (y) and the nitrogen content (x,%) of the organic matter was reflected in regression Equation (2).

$$y = 42.977x^{-1.0035};\ R^2 = 0.99;\ p < 0.000 \qquad (2)$$

The barley straw had a C/N ratio of 60–70; it was 12–18 in the aboveground biomass of leguminous crops. Taking into account the total quantity of organic matter applied to the soil, 41.7–236.8 kg N ha^{-1} was applied to the soil depending on the variant (Figure 3).

The straw, weeds, and roots that were applied to the unfertilised barley field produced only 41.7 kg N ha^{-1}, approximately half of which comprised nitrogen from the aboveground parts of weeds. The mean nitrogen content of the organic matter applied to soil was 1.02% and the C/N ratio was 41.9; the mean quantity of carbon applied was 1.75 Mg C ha^{-1}. The quantity of nitrogen applied to the soil was also small in the mixed sowing of barley and ryegrass – 46.3 kg N ha^{-1}; the average biomass nitrogen content was low – 0.98%; the C/N ratio was 43.5, and the quantity of carbon applied into the soil was 2.02 Mg C ha^{-1}. In barley mixed sowings with red clover, lucerne, and hybrid lucerne, 3.45–3.96 Mg C ha^{-1} and 139.9–184.9 kg N ha^{-1} were applied to soil; the average nitrogen content of biomass was 1.76–2.02%. The carbon and nitrogen inputs from pure sowings of legumes were 3.37–4.14 Mg ha^{-1} and 219.7–236.8 kg ha^{-1}, respectively, and the nitrogen content of the organic matter was 2.42–2.73%. Considerably less nitrogen, 93.1–94.1 kg ha^{-1}, and marginally less carbon, 1.96–2.86 Mg ha^{-1}, were added to the soil with the biomass of mixed and pure sowing of bird's-foot trefoil than from the other leguminous crops.

The shoot-to-root ratio (S/R) was 4–4.6 depending on the nitrogen fertiliser norm, with roots comprising 31–35% of the total returned organic matter. Depending on the mineral nitrogen fertiliser norm, the annual C inputs constituted 1.75–2.81 Mg ha^{-1} with straw and 0.91–1.11 Mg ha^{-1} without straw.

In the second year of the trial (2005), oats, the succeeding crop on unfertilised soil, gave a grain yield of 2.95 Mg ha^{-1}. However, the mineral nitrogen fertiliser norm N_{100} produced a yield increase of 51% (Table II). The effect of the biomass of the mixed sowings with red clover and hybrid lucerne was significant, giving a yield increase of 39–47%. By contrast, the oat yield in 2005 decreased by 22% (0.65 Mg ha^{-1}) as a result of the application of barley straw and ryegrass biomass into the soil, compared with the control variant. The effect of green manure pure sowings of leguminous crops was

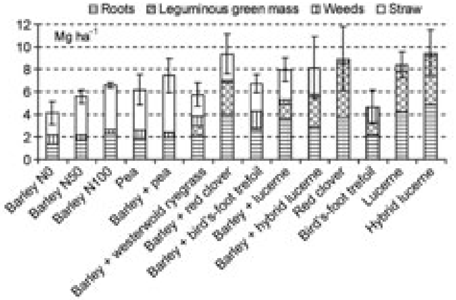

Figure 2. Quantities of dry matter (Mg ha^{-1}) applied to soil in 2004. Vertical bars denote confidence limits (CL) (CL 0.05 – level of statistical significance).

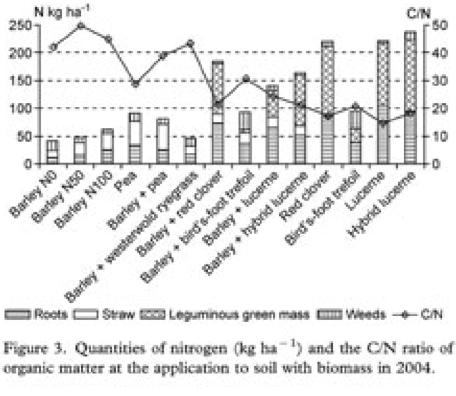

Figure 3. Quantities of nitrogen (kg ha^{-1}) and the C/N ratio of organic matter at the application to soil with biomass in 2004.

Table II. Grain yield of succeeding crops depending on nitrogen fertiliser norm and green manure application.

	Oats		Barley	
Variants in 2004	Yield in 2005, Mg ha^{-1}	Yield increase, Mg ha^{-1}	Yield in 2006, Mg ha^{-1}	Yield increase, Mg ha^{-1}
Barley N_0 (control variant)	2.95	–	2.10	–
Barley N_{50}	4.04[a]**	1.09	3.19[a]**	1.09
Barley N_{100}	4.44[b]**	1.49	3.89[b]**	1.79
Barley+manure 60 Mg ha^{-1}	3.77**	0.82	2.44	0.34
Pea	3.45*	0.50	2.38	0.28
Barley+pea	3.13	0.18	2.24	0.14
Barley+westerwold ryegrass	2.30*	−0.65	1.98	−0.12
Barley+red clover	4.34**	1.39	2.79**	0.69
Barley+bird's-foot trefoil	3.02	0.07	2.27	0.17
Barley+lucerne	3.32	0.37	2.45	0.35
Barley+hybrid lucerne	4.11**	1.16	2.65**	0.55
Autumn ploughing				
Red clover	4.77**	1.82	3.20**	1.10
Bird's-foot trefoil	3.87**	0.92	2.65**	0.55
Lucerne	4.00**	1.05	3.17**	1.07
Hybrid lucerne	4.58**	1.63	3.46**	1.36
Spring ploughing				
Red clover	5.08**	2.13	3.41**	1.31
Bird's-foot trefoil	4.44**	1.49	3.19**	1.09
Lucerne	4.53**	1.58	3.42**	1.32
Hybrid lucerne	4.78**	1.83	3.67**	1.57

*, ** Significant at level $p < 0.05$ and $p < 0.01$, respectively. [a] Mineral nitrogen 50 kg ha^{-1}. [b] Mineral nitrogen 100 kg ha^{-1}.

dependent on when the biomass was ploughed into the soil. Autumn ploughing produced an increase in the oat yield of 31–62%, red clover and hybrid lucerne having the greatest effect. The effect of green manure was even higher when applied the following spring. The spring ploughing of green manure compared with the autumn version gave a 4–15% extra yield. The effect of leguminous green crops on the yield of oats is 2–2.5-times greater than that of manure norm 60 Mg ha^{-1} applied in the autumn.

Barley was grown again in 2006, the control variant (N_0) producing a yield of 2.10 Mg ha^{-1}. Undersowings of the biomass with red clover and hybrid lucerne that had been applied to soil in autumn 2004 still had a significant effect, although it resulted in approximately half the grain yield two years later. The decrease in the cereal yield was to some extent due to nitrogen-deficient biomass, which was applied with the mixed sowing of barley and ryegrass. The rest of the mixed legume sowings had a relatively small after-effect on the barley yield. The second-year after-effect of the pure sowings of leguminous crops on the barley yield was 2–3-times greater than the effect of the straw and green manure crops ploughed into soil through the mixed sowings with red clover and hybrid lucerne. The yields of second-year succeeding crops revealed that the spring ploughing-in of the biomass gave a 0.21–0.54 Mg ha^{-1} greater cereal yield than did the autumn ploughing of green manure crops.

Discussion

The quantity of organic matter that is added to soil in an agroecosystem depends on the following factors: the plant species, pedoclimatic conditions, and the agricultural engineering applied (Bolinder et al., 1997; Pietola & Alakukku, 2005). Mean S/R ratios for annual crops were the highest for small-grain cereals and lowest for forages, but the ratio varies greatly. For example, depending on farming conditions, the S/R ratio may vary from 2–17 for barley (Bolinder et al., 2007). The S/R ratios depend on the nitrogen fertiliser norm, with roots comprising 31–35% of the total returned organic matter.

Studies have shown that in the case of 4.6 Mg ha^{-1} barley grain yield, with the straw being left in the field after harvest, the estimated annual C input to the soil is 2.79 Mg ha^{-1}. If the straw is removed from the field, then the estimated annual C input would be reduced by 26% (Bolinder et al., 1997). In our experiment, depending on the mineral nitrogen fertiliser norm, the annual C inputs constituted 1.75–2.81 Mg ha^{-1} with straw and 0.91–1.11 Mg ha^{-1} without straw. Considering the fact that under Estonian conditions 20% of the carbon that was applied to soil is transformed into humus, and that 1–2% of the soil humus or carbon stores (45.3 Mg C ha^{-1}) are mineralised per year (Piho, 1973), it is also evident that with the application of straw to soil, the humus balance remains negative if the barley yield is low. On a cereals farm, where only stubble and plant roots are ploughed into the soil after harvesting, the humus decrease is 2- to 3-times greater than the increase of humus from fresh organic matter. Thus, both in organic and conventional cereal farming, where animal manure is not used, green manures are the only means for retaining and improving soil fertility

The bioproduction, nitrogen uptake, and C/N ratio of green manure crops vary greatly depending on the plant species, soil, and agricultural engineering applied (Wivstad et al., 1996). The bioproduction of green manure crops may, under favourable conditions, exceed 10 Mg ha^{-1}, of which 2–3 Mg ha^{-1} of humus is formed as a result of the humification process (Piho, 1973). Nitrogen fixation by leguminous crops can be 200–300 kg N ha^{-1} per year (Tonitto et al., 2006). In the case of barley undersowings with red clover, lucerne, and hybrid lucerne, the estimated annual C and N inputs to the soil were 3.45–3.96 Mg C ha^{-1} and 140–185 kg N ha^{-1}, respectively. In the current experiment, pure sowings of these three crops resulted in applications of 3.37–4.14 Mg C ha^{-1} and 220–237 kg N ha^{-1} into the soil.

The decomposition of organic matter in soil is largely determined by its C/N ratio. The smaller the C/N ratio of organic matter and the greater its nitrogen content, the more nitrogen is mineralised into soil from green manure (Chaves et al., 2004). Nitrogen is either immobilised by micro-organisms during the decomposition of organic matter or it is mineralised into soil as ammoniacal nitrogen. We confirmed the finding that the application of biomass with a high C/N ratio (i.e., ryegrass) reduces the yield of the succeeding crop (Thorup-Kristensen et al., 2003). The consumption of carbon is more important for micro-organisms than is the consumption of nitrogen (McGill & Cole, 1981). Since the decomposition of organic matter and the uptake of nitrogen by micro-organisms are dependent on soil temperature (Andersen & Jensen, 2001), it is crucial from the standpoint of nitrogen loss to optimise the time of the green manure application. According to numerous studies, green manure should be ploughed into the soil in late autumn or early spring, thus decreasing the leaching of nitrogen and increasing the effect on the yield of succeeding crops (Wivstad et al., 1996). The results of the present trial attest that with spring ploughing, the efficiency of green manure is 0.2–0.6 Mg ha^{-1} greater on the yield of cereals grown as succeeding crops than with the autumn ploughing-in of green manure. Andersen and Olsen (1993) have not found any second-year after-effect and Schröder et al. (1996) found only a slightly increasing after-effect of green manures on barley yield. However, in our study there was a significant positive second-year after-effect on the barley yield with pure sowings of leguminous crops and in undersowings of red clover and hybrid lucerne as green manures.

Green manure helps to improve the fertility of soil in organic and conventional plant production where animal manure is not used or is used in limited quantities. Undersowings with barley provide a significant increase in the N supply for the succeeding crop without any yield loss of the main crop compared with the unfertilised variant (N_0). The bioproduction of pure sowings of red clover, lucerne, and hybrid lucerne reaches 8.5–9.5 Mg ha^{-1} in dry matter; the quantity of nitrogen applied to the soil is 220–240 kg ha^{-1}. The biomass (including straw) applied to soil with the mixed sowings of barley with red clover or lucerne and hybrid lucerne has nearly the same quantity of dry matter, but its C/N ratio is considerably larger: the input to soil is 140–180 kg N ha^{-1} with organic matter. The effect of nitrogen applied to the soil with green manure on succeeding crops depends on the C/N ratio of the applied organic matter and the time of application. Green manure of high nitrogen content should be ploughed into soil in spring, thereby decreasing the leaching potential of nitrogen and environmental pollution.

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II

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Green manure as a nutrient source for succeeding crops

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ABSTRACT

The trials were carried out in the Estonian University of Life Sciences (58°23'N, 26°44'E), and studied to what extent green manure crops bind nutrients and the effect and stability of biologically fixed nitrogen (N). Our research covered more species than most of the earlier studies in the Nordic countries. Compared with biomass from unfertilized barley, legume undersowing, straws plus roots added up to 4 times more N, 2.8 times more phosphorus (P) and 2.5 times more potassium (K) returning to the soil. Red clover, hybrid lucerne and white melilot as pure sows produced the highest biomass, amounts of N, P, and K being up to 206, 24 and 144 kg/ha, respectively. The effect of additional N in soil was measured by weighing successive grain yields. In the first test year, 1 kg of N from green manure had the effect of producing 8.6 kg grain and this relation did not change even for higher N amounts. Green manure had a significant effect even in the third year after the green manure was ploughed into soil.

Keywords: biomass; biologically fixed nitrogen; phosphorus; potassium; grain yield

Crop yield, soil nutrient content, amount of agricultural production and their environmental effects are all influenced by fertilizer use. Decreased soil fertility and increased mineral fertilizer prices made legumes a popular option as organic fertilizers. Organic fertilizers have an important role in improving soil fertility. Manures are most often not sufficiently available in organic arable farming, and this necessitates the use of other sources of N for fully fertilizing high yielding cereals under organic farming in Northern Europe (Olesen et al. 2009). One option is to use green manure. Correctly managed, green manures can replace some or all of the N required for non-leguminous succeeding crops (Guldan et al. 1997). The average amounts of N accumulated by green manures can entirely substitute for mineral fertilizer N at current average application rates. It was often observed that legumes, in contrast to cereals, have a beneficial effect on grain yield of subsequent cereal crops (Olesen et al. 2007).

Soil fertility is especially affected by soil organic matter, which depends on biomass input to compensate mineralization. Higher biomass return to the soil can increase soil organic carbon and soil total N. N is the most studied nutrient, but P and K levels are also important. Askegaard and Eriksen (2008) reported that in organic farming, K deficiency may become a significant problem. Perennial legumes such as lucerne, with their deep root systems, import additional nutrients (P, K, Ca) (Teit 1990) to the soil that are accessible to succeeding crops (Witter and Johansson 2001). Some researchers consider that plant residues and green manure are not rich in K and especially P (Maiksteniene and Arlauskiene 2004), but they improve the physical characteristics and stimulate microbial activity of the soils. After decomposition, the organic P and K bound in the green manure crop may provide an easily accessible form of P and K to succeeding crops (Askegaard and Eriksen 2008, Eichler-Löbermann et al. 2009).

For maximum yield and crop quality, big amounts of fertilizers are used. However, application of high mineral fertilizer amounts can bring about considerable nutrient losses from the soil, which affects the quality of surface- and groundwater. With green manure also, large amounts of N are applied into soil, but nutrients are released from green manure at a slower rate; also, N from N-fixing bacteria becomes accessible over a long time span. These processes grant steady sources of N for succeeding crops (Freyer 2003).

Our research concentrates on determining the effects of growing various legumes as green manure crops in Nordic conditions. Crucial parts of this research are studies of biologically fixed N and its efficiency. There are not many preceding studies about these effects. Our research covered more species than most of the earlier studies in Nordic countries. The purpose of the experiment was to study (i) to what extent the green manure crops fix nutrients and (ii) the duration of release of fixed N.

METHOD AND MATERIALS

The trials were carried out during the 2004–2009 growing seasons in the Estonian University of Life Sciences (58°23'N, 26°44'E). The experiment was designed in fully randomized blocks with 4 replicates. The size of each test plot was 30 m^2. The soil type of the experiment area was sandy loam Stagnic Luvisol according to the WRB 2006 classification. The mean characteristics of the humus horizon were as follows: C_{org} 1.1–1.2%, N_{tot} 0.10–0.12%, P 110–120 mg/kg, K 253–260 mg/kg, pH_{KCl} 5.9, soil bulk density 1.45–1.50 g/cm^3. The ploughing layer was 27–29 cm. Soil organic carbon was determined by the Tjurin method, P and K by the Mehlich III method, and the total-N content by the Kjeldahl method.

Two field experiments were constructed to study the effects of green manures. The first field experiment was established in 2004 using the following variants of green manure crops and fertilization:

(A) legume pure sowings red clover (*Trifolium pratense)*, lucerne *(Medicago sativa)*, hybrid lucerne *(Medicago media)*, bird's-foot trefoil (*Lotus corniculatus)*;

(B) spring barley (*Hordeum vulgare* L.) with undersowing of red clover, lucerne, hybrid lucerne, bird's-foot trefoil;

(C) spring barley without mineral fertilizer rates N_0 – the control variant and with mineral fertilizer N_{50}, N_{100} (every year with cereal sowing).

The undersown main crop was spring barley cv. Arve. Succeeding crops were, in 2005, oats (*Avena sativa* L.) cv. Jaak, in 2006, spring barley (*Hordeum distichon* L.) cv. Inari, and, in 2007 oats cv. Jaak.

The second field experiment was established in 2007 using the same variants of green manure crops and fertilization, but white melilot (*Melilotus albus* Med) was added in variant A and B. The cover crop was spring barley cv. Arve. Succeeding crops were, in 2008, spring wheat (*Triticum aestivum* L.) cv. Vinjet, in 2009, spring barley (*Hordeum distichon* L.) cv. Inari.

The seed rate of germinating grains of cereals was 500 seeds per m^2 every year. Green manure pure crops were sown according to the following norms: red clover 15 kg/ha, lucerne 13 kg/ha, hybrid lucerne 20 kg/ha, bird's-foot trefoil 12 kg/ha, white melilot 30 kg/ha. The seeding rates for undersowing were reduced by half.

Biomass (shoots + roots + weeds) of cereals was measured before harvesting. The aboveground biomass (shoots + weeds) of undersown crops was measured at cereal harvest and before autumn ploughing. The aboveground biomass (shoots + weeds) of pure legumes were measured before ploughing. The root mass (0–60 cm in depth, frame 10 × 25 cm) of leguminous crops were measured before ploughing. Roots were sampled by washing roots from soil. Aboveground biomass was taken by cutting below the surface, allocated weeds and all plant samples were dried (80°C). In all variants, barley straw and the biomass of legumes were ploughed into the soil (20–22 cm) in the end of October.

Acid digestion by sulphuric acid solution was used to determine P and K content in plant material. Total N and C content of oven-dried samples were determined by dry combustion method on a varioMAX CNS elemental analyzer (ELEMENTAR, Hanan, Germany).

The experimental area belongs to the South-Estonian upland agroclimatic region. During the experimental period, rainfall and air temperature were recorded daily at a meteorological station located within the experimental area (Table 1).

The software STATISTICA 10 (StatSoft Inc., Tulsa, USA) was used for the statistical data analysis. The trial data were processed using descriptive statistics. The means are presented with their standard errors (± SE), $P < 0.05$. The significance of differences between grain yields of the variants was calculated using the Fischer's test, the level of significance $P < 0.05$.

RESULTS

Biomass formation and nutrient absorption. On average, pure barley sows produced 4.18–6.34 t/ha of ploughable (straws, stubble, roots) dry matter, determined by the amount of added nitrogen

Table 1. Monthly precipitation and average temperature during the experiment

Month	Air temperatures (°C)						Precipitation (mm)					
	2004	2005	2006	2007	2008	2009	2004	2005	2006	2007	2008	2009
January	-7.6	-1.7	-5.5	-2.2	-1.3	-3.4	6	114	5	59	22	10
February	-4.5	-7.3	-8.7	-10.9	0.6	-4.9	18	0	8	11	34	7
March	-0.4	-4.9	-3.5	4.0	0.4	-1.5	36	4	13	24	8	22
April	5.6	5.0	6.2	5.1	7.1	5.3	8	22	15	32	27	14
May	12.7	10.8	11.9	12.0	10.6	11.5	34	114	34	92	27	13
June	13.4	14.4	16.2	15.9	14.4	13.8	210	54	47	44	110	137
July	16.4	19.5	18.7	16.9	16.1	16.9	113	22	16	55	54	55
August	17.0	16.5	17.1	18.1	17.7	15.4	116	92	80	11	118	89
September	11.9	12.7	13.6	11.1	9.8	12.8	99	59	35	9	46	49
October	5.7	6.7	8.1	6.8	8.2	4.1	61	38	111	8	68	116
November	-0.7	2.6	5.3	-0.2	2.3	2.3	25	30	10	18	49	36
December	-0.1	-3.2	3.8	0.6	-1.1	-3.8	27	17	38	7	24	41

(Table 2). Barley roots yield was 1.36–2.15 t/ha. Barley roots and straws returned to soil 39–59 kg N, 8–14 kg P and 55–102 kg K/ha. Organic matter in soil left after barley harvest was relatively low in N content, the C/N ratio was 42–47. Barley grains removed 39–80 kg N, 7–13 kg P and 15–31 kg K/ha. As the soil humus layer contained 430 kg of plant-available P and 1050 kg of similarly usable K – and 80% of all nutrients are taken from humus layer – then we can conclude that in a single year, barley

Table 2. Average dry matter yield (t/ha) of shoots, roots and weeds of pure spring barley with three N fertilization rates, five legume species undersown in spring barley and legumes grown as pure crops in 2004 and 2007

	Quantities of dry matter (t/ha) applied into soil (mean ± SE)			
	barley straw	shoots	roots	weed
Barley N_0	2.10 ± 0.09^{c}	×	1.36 ± 0.08^{c}	0.71 ± 0.07^{b}
Barley N_{50}	3.27 ± 0.12^{b}	×	1.70 ± 0.08^{b}	0.41 ± 0.13^{c}
Barley N_{100}	3.86 ± 0.13^{a}	×	2.15 ± 0.12^{b}	0.33 ± 0.05^{c}
Undersown legumes				
Red clover	2.25 ± 0.10^{c}	2.52 ± 0.39^{b}	3.29 ± 0.43^{a}	0.25 ± 0.03^{c}
Bird's-f. tr-l*	2.46 ± 0.29^{c}	0.26 ± 0.05^{d}	2.57 ± 0.77^{a}	1.43 ± 0.20^{a}
Lucerne	2.45 ± 0.17^{c}	1.50 ± 0.19^{c}	3.05 ± 0.32^{a}	0.46 ± 0.15^{c}
Hybrid lucerne	2.29 ± 0.20^{c}	2.01 ± 0.53^{b}	2.69 ± 0.14^{a}	0.27 ± 0.08^{c}
White melilot	2.17 ± 0.05^{c}	2.36 ± 0.09^{b}	2.91 ± 0.14^{a}	0.25 ± 0.05^{c}
Legume pure sowings				
Red clover	×	4.09 ± 0.36^{a}	3.28 ± 0.57^{a}	0.24 ± 0.8^{c}
Bird's-f. tr-l*	×	1.72 ± 0.35^{c}	2.30 ± 0.28^{ab}	0.92 ± 0.24^{b}
Lucerne	×	3.36 ± 0.14^{a}	3.80 ± 0.26^{a}	0.45 ± 0.11^{c}
Hybrid lucerne	×	3.67 ± 0.37^{a}	4.11 ± 1.18^{a}	0.24 ± 0.07^{c}
White melilot	×	3.63 ± 0.36^{a}	3.64 ± 0.12^{a}	0.35 ± 0.01^{c}

Means followed by different letters in the same column are significantly different at $P < 0.05$. Bird's-f. tr-l* – Bird's-foot trefoil

Table 3. Estimated means and standard errors of N, P, and K (kg/ha) in barley grains and incorporated biomass (shoots and roots), and C/N of the biomass in two trials in 2004 and 2007

Variant	Barley grain			Biomass remained at field			
	N	P	K	N	P	K	C/N
Barley N_0	39 ± 1.27	7 ± 0.29	15 ± 0.48	40 ± 1.85	8 ± 0.30	55 ± 2.06	44
Barley N_{50}	63 ± 2.32	12 ± 0.58	25 ± 1.04	46 ± 2.35	9 ± 0.49	68 ± 2.32	47
Barley N_{100}	80 ± 2.65	13 ± 0.59	31 ± 1.13	60 ± 1.36	14 ± 1.24	102 ± 9.96	42
Undersown legumes							
Red clover	47 ± 2.59	10 ± 0.55	17 ± 1.23	165 ± 10.6	19 ± 1.59	153 ± 8.87	25
Bird's-foot tr-l	55 ± 1.77	12 ± 0.37	19 ± 0.59	93 ± 5.07	17 ± 0.84	98 ± 2.12	31
Lucerne	47 ± 2.90	10 ± 0.62	14 ± 0.97	136 ± 5.19	20 ± 1.70	114 ± 5.51	26
Hybrid lucerne	48 ± 3.20	10 ± 0.68	16 ± 1.07	139 ± 17.61	16 ± 1.85	118 ± 12.3	24
White melilot	43 ± 1.05	9 ± 0.22	14 ± 0.35	177 ± 1.59	20 ± 0.25	112 ± 2.03	27
Legume pure sowings							
Red clover	×	×	×	196 ± 1.74	20 ± 1.25	144 ± 13.09	17
Bird's-foot tr-l	×	×	×	114 ± 8.42	17 ± 1.32	89 ± 3.32	19
Lucerne	×	×	×	191 ± 13.9	19 ± 0.64	120 ± 12.02	16
Hybrid lucerne	×	×	×	195 ± 15.9	24 ± 1.22	123 ± 13.95	18
White melilot	×	×	×	206 ± 3.51	22 ± 0.39	104 ± 2.86	17

used up 2–4% of P and 4–7% of K in the humus layer. With undersown barley, where green manure biomass was used as an addition to barley straws and roots, the total amount of dry matter produced varied from 6.72–8.31 t/ha. Roots yielded 2.57–3.29 t/ha. Thus, 93–177 kg N/ha, 16–20 kg P and 98–153 kg K/ha was returned to soil. The C/N ratio of the total biomass was 24–31 (Table 3). Therefore undersown legumes improve the C/N ratio in organic matter, which creates better conditions for organic matter decomposition in soil. Growth period, aftermath formation and competitiveness all had an influence on biomass production. The lowest amount of biomass was from undersown bird's-foot trefoil, where bird's-foot trefoil remained in the lower growth layer and its aboveground biomass was only 0.26 t/ha. The biggest biomass from undersowing was from red clover – 8.32 t/ha, of which 40% were roots and 27 cereal straws (Tables 2 and 3).

Total dry matter yield (shoots and roots, including weeds) of pure legume crops were: bird's-foot trefoil 4.94 t/ha, red clover and common lucerne 7.60 t/ha, white melilot 7.61 t/ha and hybrid lucerne 8.02 t/ha. Roots yielded 2.30–4.11 t/ha, which was 45–57% of total mass. N, P, and K yields of the total

Table 4. Yield increase of succeeding crops (kg/ha) depending on green manure application compared with unfertilized cereal

Green manure	Undersown legumes			Legume pure sowings		
	1st year	2nd year	3rd year	1st year	2nd year	3rd year
Red clover	1206*	608*	219*	1725*	1086*	305*
Bird's-foot tr-l	123	238	98	1128*	724*	108
Lucerne	659*	555*	335*	1292*	1143*	494*
Hybrid lucerne	1017*	697*	234*	1540*	1345*	365*
White melilot	1106*	603*	×	1969*	1198*	×

*significant at level $P < 0.05$; × – yield was not measured. Unfertilized cereal yield in 1st year 2897; 2nd year 2025; 3rd year 1967 kg/ha biomass were 113–206 kg, 17–24 and 89–144 kg/ha. K content in roots was lower than in above-ground biomass. The C/N ratio was 16–19 (Tables 2 and 3). Considering the total amount of biomass that was added to soil, legume pure sowings have up to three times narrower C/N ratio than cereals.

Nitrogen efficiency for succeeding crops. The effect of additional N in soil was measured by weighing successive grain yields. Still in the third year, pure and undersown red clover, lucerne and hybrid lucerne had a significant effect (Table 4). Grain yields of three succeeding cereal crops was increased with increasing N yield of the first experimental year. In the first year, after organic matter was added to the soil, the relationship between cereal yield and the amount of N in biomass was linear ($P < 0.00$). The response of 1 kg of N was 8.6 kg of grains. Also in the next year, the response of 1 kg of N was 6.8 kg of grains ($P < 0.000$). The relationship between cereal yield and biomass N content stayed linear in the third year ($P < 0.000$), although the relationship was much weaker than in previous two years. The response of 1 kg of N was 2.0 kg of grains (Figure 1).

100 kg N/ha added to soil in biomass (pure and undersowing), resulted in 43, 34, and 10% increase in grain yield of the first, second and third succeeding cereal respectively, compared to the unfertilized control field.

DISCUSSION

Earlier experiments showed that the amount of biomass depends on plant species, tillage methods and environment (Kumar and Goh 2002, Talgre et al. 2009). Current study showed that also lucerne and white melilot can be successfully used for green manure, in addition to the most popular green manure crops in Northern Europe, red and white clover. Compared with other legumes, bird's-foot trefoil had a less prominent effect. Thereby it was proved that bird's-foot trefoil is not suitable as a green manure crop. Red clover, hybrid lucerne and white melilot produced the highest biomass. Undersown legumes produced less biomass and absorbed less N than pure legumes, but the total biomass, legumes and cereal together, increased compared to pure cereal crops. The C/N ratio of incorporated biomass decreased in context of undersowing, compared to pure cereal crop. This is in accordance with Dordas and Lithourgidis (2011) and with Jørgensen et al. (1999). High C/N ratio of cereal straw have a negative effect on N availability (Taylor et al. 1989, Nygaard Sorensen and Thorup-Kristensen 2011).

According Becker et al. (1995), even with a short growth period of 45–60 days, green manure legumes can fix 80–100 kg N/ha of which the major portion (about 80%) is derived from biological N_2 fixation. Therefore – biomass from legume green manure crops can add a huge amount of N and C to the soil, which improves soil humus characteristics. Legumes can absorb nutrients from lower soil layers, with their well developed and deep root systems and return the nutrients to upper soil layers with their biomass. The relocation of plant nutrients (especially P and K) is particularly useful in organic farming.

As P and K are relatively stable in soil, their leaching losses are almost nonexistent and most of these elements are removed with the crop. We found that barley grains removed 7–13 kg P and 15–31 kg K/ha, which is in accordance with Kirchmann et al. (2008) who reported that around 10 kg P and

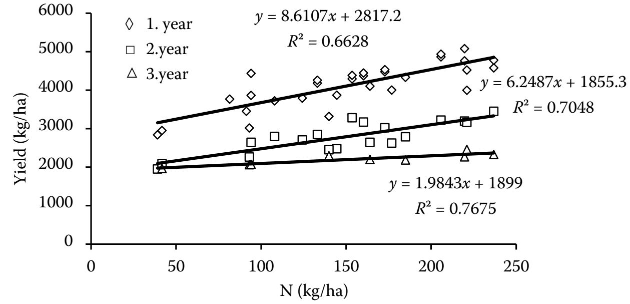

Figure 1. Correlation between cereal grain yields in three succeeding years and nitrogen input through organic matter. y – cereal yield (t/ha); x – nitrogen amount in biomass (kg N/ha); R^2 – relationship between cereal yield and the amount of nitrogen in biomass. In the 1st year $R^2 = 0.66$; $P < 0.00$; 2nd year $R^2 = 0.70$; $P < 0.000$ and 3rd year $R^2 = 0.77$; $P < 0.000$

15 kg K/ha is removed from the field every year in organic farming. This rate of phosphorus and potassium use is usual, considering the amount of nutrients in soil and the amount of fertilizer needs. Green manure biomass ploughed in can release nutrients needed by cereal crop. Our tests showed that K content in roots was lower than in the above-ground biomass. Mengel (1982) found that root K content normally constitutes less than 10% of the total plant K content. The release of nutrients depends on the nutrient concentration of the organic matter and the C-to-nutrient ratio (Nygaard Sorensen and Thorup-Kristensen 2011). Martin and Cunningham (Ha et al. 2008) found that up to 40 and 60% of P in residues is water-soluble and rapidly released after incorporation into soil. Depending on biomass size, pure and undersown green manure crops fixed up to 153 kg K/ha and up to 20 kg P/ha. It was shown that with careful management of manure and the effective use of legumes, and by using permitted inputs for P and K, organic farms can be managed sustainably.

N is the key element in obtaining a high yield with good quality. It is involved in all of the plant's metabolic processes, its rate of uptake and partition being largely determined by supply and demand during the various stages of plant growth (Delogua et al. 1998). Research showed that the yield effect of green manure in soil depends on the amount of N in biomass, its release rate, the C/N ratio in organic matter (Kumar and Goh 2002), soil N content and climate. Our experiments showed the beneficial effects on succeeding crops. The first year after effects were studied by Hanly and Gregg (2004), Tonitto et al. (2006) who confirm our results. As the soil in our experimental field was relatively low at humus content and the general amount of N in the humus layer was only 0.10–0.12%, N from green manure crops in soil was very effective. The succeeding crop yield in the first year after pure red clover and hybrid lucerne sows was even higher than when 100 kg N/ha was used as a mineral fertilizer. In contrast, Harris and Hesterman (1990) found that lucerne residues did not provide significant amounts of N to a succeeding barley crop explaining it with high C/N ratio in roots, leading to slow decomposition and later N availability. There is little information regarding the response of second – and third year succeeding crop. Andersen and Olsen (1993) did not find any second year after-effect of green manures on barley yield. In our study in the second year, the positive after-effect of green manure was found. According to Viil and Võsa (2005) 16–18% of red clover's after effect becomes apparent in the second year; it is up to 28% for white melilot. In our study, still in the third year, green manure from red clover, lucerne and hybrid lucerne all had a significant effect, but the effect of N in their organic matter on yield increase was three times lower than in the first year. Yield results of the present study showed that N is slowly released from green manure, which may decrease lodging and yield loss. Mineral fertilizers work quickly, and in a soil with high N content fertilization rate of 60 kg/ha N, may cause crop flattening in 1–2 years out of ten (Roostalu et al. 2003).

Biomass from pure green manure legume undersowing adds a considerable amount of nitrogen to the soil, but is released over long time. Because of that, green manure had a significant effect even in the third year after the green manure was ploughed into soil.

Undersown legumes produced less biomass and absorbed less N than pure legumes, but the total biomass, legumes and cereal together, increased compared to pure cereal crops. With undersown lee gumes, 93–177 kg N/ha, 16–20 kg P and 98–153 kg K/ha was returned to soil. In the tested common green manure legumes as pure sows, 114–196 kg N, 17–24 kg P and 89–144 kg K/ha was returned to soil every year. Green manures with high nutrient concentrations and low C/N ratios have a great impact on their value as fertilizer in crop production. Compared with other legumes, bird's-foot trefoil is not suitable as a green manure crop.

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III

Talgre, L., Lauringson, E., Roostalu, H., Astover, A., Makke, A. 2009.
PHYTOMASS FORMATION AND
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Phytomass formation and carbon amount returned to soil depending on green manure crop

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Abstract. The trials were carried out during the 2004–2006 growing seasons at the Department of Field Crop and Grassland Husbandry of the Estonian University of Life Sciences. Various green manures and ensuing cereals were studied in respect of phytomass formation and quantity of C returned to soil. The highest amount of organic matter was applied by red clover (8.91 Mg ha^{-1}) and lucerne (8.41 Mg ha^{-1}), and the lowest by unfertilized barley. The total phytomass of pure sowings of barley ranged, depending on the nitrogen fertilizer norm, from 6.55 to 11.54 Mg of dry matter per hectare, of which the grain yield constituted 37.3–43.2%. Sowings of lucerne and red clover added 3.44–3.82 Mg C ha^{-1} to soil, while sowing of bird's-foot trefoil supplemented 1.99 Mg C ha^{-1}. Preceding crop determined the phytomass of ensuing crops and the amount of C returned to soil. The amount of C of the oats grown after clover was 5.32 Mg C ha^{-1}, whereas 3.28 Mg C ha^{-1} was returned to soil. Lucerne pure sowing resulted in 3.17 Mg C ha^{-1} returned to soil. When oats were preceded by barley (without manure), 2.53 Mg C ha^{-1} was returned to soil.

Key words: green manure, soil fertility, carbon, soil organic matter, humus content

INTRODUCTION

One of the factors that limit the yield of field crops is low humus content, especially in South Estonia, where humus content is below 2% in 40–60% of the total cultivated area (Järvan et al., 1996). Among the most important factors influencing soil fertility is humus, the organic matter contained in soil. Soil fertility is closely linked to soil organic matter (Roose & Barthes, 2001) and depends to a large extent on the use of organic fertilizers, in both organic and conventional cultivation; green manure crops have an important role in crop rotation (Lauringson et al., 2000). In favourable conditions, bioproduction of green manure crops may exceed 10 Mg ha^{-1}, of which 2–3 Mg ha^{-1} of humus is formed as a result of the humification process (Piho, 1973). The organic matter applied to soils improves their humus condition, which in its turn improves soil structure as well as its physical and hydrophysical characteristics.

Organic matter has a favourable effect on the soil biota and the biological activity of soil. The concentration of organic C and N appear to be good indicators of soil quality and productivity (Reeves, 1997). Many agricultural systems in industrialized countries induce low contents of soil organic carbon (Dick & Gregorich, 2004; Riley & Bakkegard, 2006). The amount of carbon returned to soil depends on the quantities of nitrogen fertilizer and the crop (Talgre et al., 2009). The more organic matter and carbon is applied to soil, the more humus is formed.

Increasing the soil fertility and maintaining it at an optimum level is one of the key factors in sustainable agriculture. In organic farming, growing legumes would be the main method of enriching soil with nutrients. The green mass that has been ploughed in improves the soil with organic matter, and as a result of microbiological activity, nutrients consumable by plants are released.

The aim of the present study was to investigate the influence of various green manures and ensuing cereals in respect of phytomass formation and quantity of C returned to soil.

MATERIALS AND METHODS

The trials were carried out during the 2004–2006 growing seasons at the Department of Field Crop and Grassland Husbandry of the Estonian University of Life Sciences. Random block-placement in 4 replications was used (Hills & Little, 1972). The size of each test plot was 30 m^2. The soil type of the experiment area was sandy loam Stagnic Luvisol in the WRB 1998 classification. The mean characteristics of the humus horizon were as follows: C_{org} 1.1–1.2 %, N_{tot} 0.10–0.12%, P 110–120 mg kg^{-1}, K 253–260 mg kg^{-1}, pH_{KCl} 5.9, soil bulk density 1.45–1.50 Mg m^3. The thickness of the ploughed layer was approximately 27–29 cm. Soil analyses were carried out at the laboratories of the Department of Soil Science and Agrochemistry. Plant analyses were conducted at both the Department of Soil Science and Agrochemistry of EMU and at the laboratories of the Estonian Agricultural Research Centre. Acid digestion by sulphuric acid solution was used to determine the N content in plant material. The Dumas Combustion method was used to determine the content of carbon in the plant biomass.

The field experiment was established in 2004 using the following variants of green manure crops and fertilization:

Variant A) legume pure sowings (i) red clover (*Trifolium pratense)*, (ii) lucerne *(Medicago sativa)*, (iii) bird's-foot trefoil *(Lotus corniculatus)*;

Variant B) spring barley (*Hordeum vulgare* L.) with undersowings of (i) red clover, (ii) lucerne, (iii) bird's-foot trefoil, (iv) Westerwold ryegrass *(Lolium multiflorum westerwoldicum)*;

Variant C) spring barley with mineral fertilizer rates (i) N_0 – the control variant (ii) N_{50}, (iii) N $_{100}$ (every year with cereal sowing).

The 2004 cover crop was spring barley *cv. "Arve"*. Succeeding crops in 2005 were oats (*Avena sativa* L.) *cv.* "*Jaak*", and in 2006, spring barley (*Hordeum distichon* L.) *cv.* "*Inari"* in 2006. The seed rate of germinating grains of cereals was 500 m^{-1} every year. Green manure pure crops were sown according to the following norms: red clover 15 kg ha^{-1}, lucerne 13 kg ha^{-1}, bird's-foot trefoil 12 kg ha^{-1}, Westerwold ryegrass 10 kg ha^{-1}. The seeding rates of undersowings were reduced by half. In all variants, barley straw and the biomass of legumes were ploughed into the soil (20–22 cm). Samples of aboveground biomass were taken before harvesting the cereals and the root mass was taken from 10–60 cm in depth. In variants with undersowings (B), the aboveground biomass of green manure crops was measured twice: first, during harvesting; and secondly, the aftermath mass was taken before autumn ploughing. The aboveground biomass of pure sowings and the root mass of leguminous crops were measured before ploughing.

The experimental area belongs to the South Estonian upland agroclimatic region, where the average annual sum of active air temperatures is 1750–1800°C, and total precipitation is 550–650 mm (Tarand, 2003). The amount of precipitation during the vegetation period (from May to September), compared to the average, varied through the trial: it was above average in 2004, similar in 2005, but below average in 2006. The analysis of variance (ANOVA) was used in the statistical analysis of trial results.

RESULTS AND DISCUSSION

The vegetation period and the competitiveness of the green manure crop influence the biomass of herbage. The total phytomass of pure sowings of barley constituted 6.55–11.54 Mg of dry matter per hectare depending on the nitrogen fertilizer norm, of which the root mass constituted 17.7–20.4% and the grain yield 37.3–43.2%. The phytomass of mixed sowings returned to soil varied from 7.72 to 8.25 Mg ha^{-1}, the root mass constituted 18.6–33.3%. The lowest total phytomass of legume pure sowings was observed in bird's foot trefoil with only 4.64 Mg ha^{-1}, while that of red clover and lucerne was 8.91 Mg ha^{-1} and 8.41 Mg ha^{-1}, respectively (Fig. 1). Root mass constituted 42.2–51.6% of the total phytomass in these legume pure sowings. Roots may also be important C sources to soils which contribute to soil C sequestration (Hogberg & Hogberg, 2002).

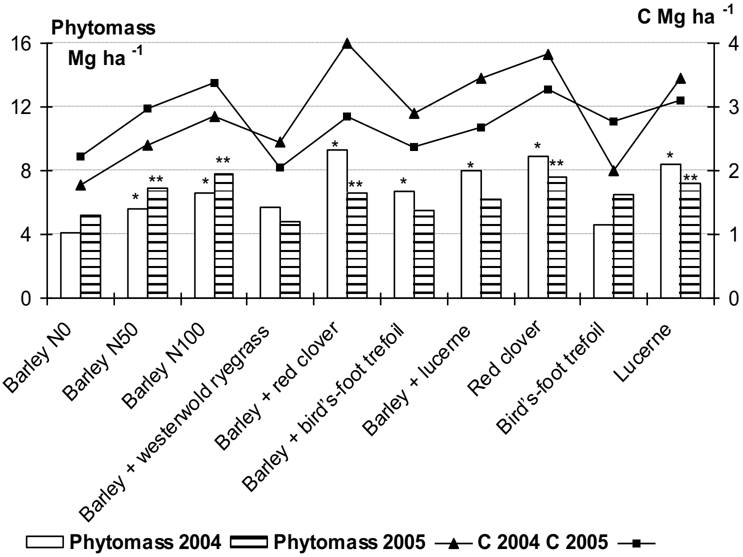

Fig. 1. Quantities of dry matter (Mg ha^{-1}) and carbon (Mg ha^{-1}) applied to soil in 2004, 2005.

* significant at $P<0.05$, respectively, in 2004 and ** significant at $P<0.05$, respectively, in 2005

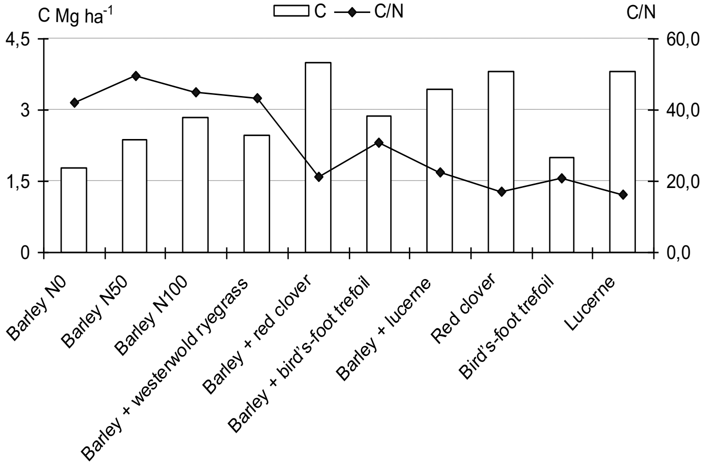

Fig. 2. Quantities of carbon (Mg ha^{-1}) and the C/N ratio of organic matter at the application into soil with biomass (2004).

In an unfertilized barley field, 1.75 Mg C ha^{-1} was applied to soil with straw, weeds and roots, the biomass C/N ratio being 41.9. With undersowing of barley and ryegrass, 2.02 Mg C ha^{-1} was applied to soil, with the C/N ratio of 43.5. Undersowing of red clover and lucerne with barley straw and roots gave 3.45–3.96 Mg C ha^{-1} .With the pure sowing of leguminous green manure crops, 1.99–3.82 Mg C ha^{-1} was applied to soil (Figure 2). The amounts of carbon and nitrogen were significantly smaller with undersowing and pure sowing of bird's foot trefoil. Decomposition of organic matter in soil is largely determined by its C/N ratio. The usual recommended range for C/N ratios at the start of the composting process is about 30/1 (Ghaly et al., 2006). The C/N ratio of the organic matter varied considerably. The C/N ratio was more than 60 in barley straw and 18–23 in the biomass of legumes. The following year, oats were used as the succeeding crop. Its yield and capability to form biomass were dependent on the preceding crop and the amount of N applied to soil. The trial variant N_{100} gave the largest amount of oats biomass and carbon, with 3.4 Mg C ha^{-1} returned to soil. In the previous trial variant, 2.4 Mg C ha^{-1} was returned to soil with straw, which equals the amount of carbon returned to soil with unfertilized oats. The biomass of the undersowing of red clover and lucerne had a significant effect on the formation of oat biomass. Following the undersowing of clover and lucerne, the amount of carbon returned to soil with oat biomass was 2.8 Mg C ha^{-1} and 3.4 Mg C ha^{-1}, respectively. 3.3 Mg C ha^{-1} was returned to soil with straw and roots of oats after the pure sowing of clover (Fig. 1).

In the second year with barley as succeeding crop, 2.53–3.61 Mg C ha^{-1} was returned to soil, depending on the trial variant. The amount of carbon returned to soil was up to 1.1 Mg ha^{-1} greater with mineral nitrogen and green manure as compared to unfertilized barley. As a result, it can be concluded that the organic matter remaining in soil from green manure crops has a long-lasting effect on soil fertility.

Considering the fact that 20% of the carbon that was applied to soil is incorporated into humus, and 1–2% of the soil humus or carbon stores (45.3 Mg C ha^{-1}) is mineralized per year (Piho, 1973), it is evident that in case straw is applied to soil, the humus balance remains negative if the barley yield is low. On a cereal farm where only stubble and roots are applied to soil after harvesting, two to three times more humus is lost than formed (Talgre et al. 2009).

CONCLUSION

The amount of organic material and C left in the soil was affected by the crop grown. It was the highest in the pure sowing of legumes: red clover – 8.91 Mg ha^{-1} dry matter and 3.82 Mg C ha^{-1} , and the lowest in the sowing of non-fertilized barley – 4.1 Mg ha^{-1} dry matter and 1.77 Mg C ha^{-1}. Taking into consideration the total input of biomass, leguminous green manure crops show a three times narrower C/N ratio of the organic matter compared to cereal crops or cereals undersown with ryegrass. Thus, in both organic and conventional cereal farming where animal manure is not used, green manures are the only means for retaining and improving soil fertility.

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IV

Talgre, L., Lauringson, E., Makke, A. 2010.
AMOUNTS OF NITROGEN AND CARBON RETURNED TO SOIL DEPENDING ON GREEN MANURE AND THE EFFECT ON WINTER WHEAT YIELD.
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Amounts of nitrogen and carbon returned to soil depending on green manure and the effect on winter wheat yield

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Abstract. The trials were carried out during the 2006–08 growing seasons at the Department of Field Crop Husbandry in the Estonian University of Life Sciences. A field experiment was conducted to investigate the effect of green manure treatments on the yield and yield quality of winter wheat. The total phytomass of leguminous green manures ploughed into soil in 2007 varied from 10.3 Mg ha^{-1} with the bird's foot trefoil to 13.9 Mg ha^{-1} with the white sweet clover. The root mass of legumes comprised 37–54% of the total biomass. The amount of carbon applied into the soil with the green material and roots of legumes varied from 4.43 Mg ha^{-1} to 5.98 Mg ha^{-1}. The amounts of nitrogen were up to 274 kg of N ha^{-1}. The highest wheat yields were attained in treatments with lucerne and red clover as preceding crops. Compared to the N_0 treatment, the extra yield reached 3.26 Mg ha^{-1} with green manures. Both green manures and mineral fertilizers enhanced the quality of the winter wheat yield, but the results did not vary among different green manures.

Key words: green manure, nitrogen, carbon, grain yield, protein, gluten index, volume weight

INTRODUCTION

One of the key factors in increasing the yield and quality of crops is appropriate manuring. In the present economical situation the sales prices of crops have decreased considerably compared to previous years, whereas the prices of pesticides and fertilizers have risen, leaving the farmers with fewer financial resources. Given the increased prices of mineral fertilizers, leguminous green manure crops have become important organic fertilizers both in organic as well as traditional production due to their ability to bind air nitrogen and carry nutrients (P, K) to deeper plough layers. Biological N fixation is one of the primary sources of N in organic farming (Berry et al., 2002). Some mineral fertilizers used in agriculture can be replaced by green manuring, which reduces the cost of production (Poutala et al., 1994). A high soil N fertility, e.g. from incorporated green manure crops, imply a risk of N leaching (Askegaard et al., 2005). Organic matter content is generally regarded as one of the main indicators of soil quality (Schjønning et al., 2004). Organic matter helps to improve the humus status of soil, thus also improving the soil structure, and physical as well as hydrophysical properties. Abundant application of organic matter into soil has a positive effect on soil biota and the soil's biological activity. Also, the nutrients released from organic matter increase the yield of succeeding crops. Beneficial effects of the preceding crop on water use efficiency and reduction in crop diseases can in some cases account for up to 50% of the yield response of the succeeding crop (Harper et al., 1995).

Green manure crops are most effective in organic farming where the main issues concern the application of nutrients into the soil and growing grains with high-quality properties. One of the major benefits of increasing the soil organic N levels through green-manure crops is an increase in the mid-growing season N mineralisation, which in most cases translates into a higher grain N content (Olesen et al., 2009). In the production of high-quality milling wheat, late manuring with nitrogen is especially important. Under good humidity conditions, the optimum period for late manuring is the heading phase. Manuring stimulates growth in protein content during this period. Nitrogen applied at a later period primarily enhances gluten content in wheat (Järvan et al., 2007). Applying the total amount of nitrogen fertilizer at the beginning of the growing period could result in superfluous vegetative growth, lodging and decrease in the yield and quality of wheat (Brown et al., 2007). With green manure, large amounts of nitrogen are applied into the soil, but nitrogen is released gradually because organic matter is decomposed over a long period of time. With green manure, crops are provided with nitrogen throughout their growing period. Research has shown that 82–84% of the red clover's effect is realized in the first year, and 16–18% in the second year as an after-effect (Viil & Võsa, 2005).

MATERIALS AND METHODS

The trials were carried out during the 2006–08 growing seasons in the Estonian University of Life Sciences, Institute of Agricultural and Environmental Sciences (58°23′N, 26°44′E). The size of each test plot was 30 m^2, with 4 replications. The soil was sandy loam Stagnic Luvisol in the WRB 1998 classification. The mean characteristics of the humus horizon were as follows: C_{org} 1.3–1.4 %, N_{tot} 0.10–0.11%, P 3.3–3.5 mg $100g^{-1}$, K 15-17 mg $100g^{-1}$.

Plant analyses were conducted at both the Department of Soil Science and Agro-Chemistry of EMU and the Estonian Agricultural Research Centre laboratories. Acid digestion by sulphuric acid solution was used to determine N, P, and K content in plant material. The Dumas Combustion method was used to determine the content of carbon in the plant biomass. The crude protein (CP) concentration in feed was determined using the Kjeldahl procedure. Wet gluten content (WGC) and gluten index (GI) were determined by ISO 21415-2:2006. Yield (Y), 1000 kernel weight (TKW) and volume weight (VW) was calculated as the average of 8 replications (2 from each plot).

The preceding crop in 2005 was spring barley. The field experiment was established in 2006 using the following variants of green manure crops and fertilisation:

Variant A) spring barley (*Hordeum distichon* L.) with undersowings of (i) red clover (*Trifolium pratense)*, (ii) lucerne *(Medicago sativa)*, (iii) hybrid lucerne *(Medicago media)*, (iv) bird's-foot trefoil *(Lotus corniculatus)*, (v) white sweet clover *(Melilotus albus)*

Variant B) spring barley with mineral fertiliser rates (i) N_0 – the control variant (ii) N_{100}, (with cereal sowing); the same, for 2007.

The succeeding crop winter wheat (*Triticum aestivum*) "Ramiro"was sown at the beginning of September 2007. The seed rate of germinating grains of cereals was 500 m^{-1} every year. Green manure crops were sown according to the following norms: red clover 7.5 kg ha^{-1}, lucerne 6.5 kg ha^{-1}, hybrid lucerne 10 kg ha^{-1}, bird's-foot trefoil 6 kg ha^{-1}and white sweet clover 18 kg ha^{-1}. In 2006 barley straw was removed. In the beginning of August 2007 the biomass of legumes and barley straw were ploughed into the soil. Samples of the aboveground biomass (0.25 m^{-2} from each plot) were taken before harvesting the cereals. The root mass was taken from 0–30 cm in depth (by 10*20 cm frame from each plot), washed, dried and weighed. Biomass from the undersowing samples was separated into leguminous and cereals.

In variants with undersowings (A) the aboveground biomass and the root mass of leguminous crops were measured before ploughing.

The vegetation period of 2006 had a high temperature regime and low precipitation. The first half of the vegetation period (up to 31 July) was very dry, with only half of the average precipitation in Estonia. In 2007, the average temperature was higher whereas the average precipitation was lower than in previous years. The drought reached its peak in August. The average temperature of the 2008 vegetation period was lower than in many previous years. Drought in spring and high average precipitation in August had an influence on the yield and quality of wheat.

The analysis of variance (ANOVA) was used to evaluate the impact of the experimental variants on the yield and yield quality.

The relationship between the C/N ratio (y) and the nitrogen content (x, %) of the organic matter is reflected in the following regression equation:

$$y\ (C/N) = 42.977x^{-1.0035},\ R^2 = 0.99;\ p < 0.000.$$

The objectives of the trial include examining the capacity of the second vegetation year leguminous green manures to form biomass; analyzing the amount of nitrogen and carbon returned to soil, and determining the effect of these factors on the yield and quality of the succeeding crop.

RESULTS AND DISCUSSION

In 2007 barley pure sowings, the amounts of nitrogen returned to the soil with straw and roots were 39 kg ha^{-1} and 57 kg ha^{-1} on the background of N_0 and N_{100} respectively. The respective amounts for carbon were 1.83 and 2.62 Mg of C ha^{-1}. The phytomass returned to the soil in barley sowings was 4.26 and 6.10 Mg of dry matter ha^{-1} on the background of N_0 and N_{100} respectively.

The total phytomass of leguminous green manures ploughed into soil in 2007 varied from 10.3 Mg ha^{-1} with the bird's foot trefoil to 13.9 Mg ha^{-1} with the white sweet clover. The phytomass of hybrid lucerne was 12.5 Mg ha^{-1}. The formation of legume mass is influenced by various factors. The trials have shown that red clover is more stable and resistant to unfavourable conditions than other legumes (Talgre, et al., 2009a, 2009b). White sweet clover and lucerne are more sensitive to climatic and agrotechnical factors.

The root mass of legumes comprised 37–54% of the total biomass. The amount of carbon applied to the soil with the green material and roots of legumes varied from 4.43 Mg ha^{-1} (bird's foot trefoil) to 5.98 Mg ha^{-1} (white sweet clover). The amount of nitrogen returned to the soil was dependent on the leguminous crop; up to 274 kg of N ha^{-1} were applied into the soil (Fig. 1) based on the treatment. Earlier research has also proved that leguminous crops can bind 200–300 kg of N ha^{-1} per year (Viil & Võsa, 2005; Talgre, et al., 2009b). The biological production of green manures, as well as the amounts of nitrogen they bind and the C/N ratio of organic matter vary according to the crop species, soil and farming techniques. The decomposition of organic matter in soil is largely determined by its C/N ratio. The smaller the C/N ratio of organic matter and the greater its nitrogen content, the more nitrogen is released into soil from green manure mineralisation (Kumar & Goh, 2002). The C/N ratio of the applied organic matter varied significantly. The C/N ratio of barley straw and the aboveground biomass of leguminous crops were 65–69 and 20–23 respectively.

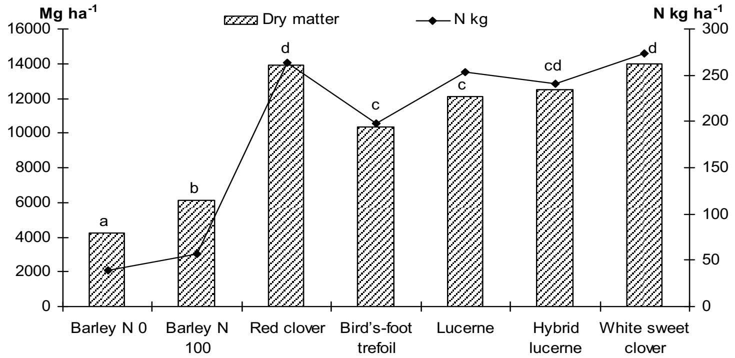

Figure 1. Quantities of dry matter (Mg ha^{-1}) and N (kg ha^{-1}) applied into soil in 2007. Means followed by the same letter are not significantly different ($P < 0.05$).

In the 2007 trial, winter wheat was sown as a succeeding crop. Despite the drought in spring, the conditions were favourable for the yield formation of winter crops, though the quality of the yield was influenced by the rainy harvesting period. Aside from weather, other factors that may influence the yield of winter wheat are crop variety and nutrient supplies. Traditionally, winter wheat is known by its higher yield potential and spring wheat by better baking quality (Swenson, 2006).

The highest wheat yields were attained in treatments with lucerne and red clover as preceding crops. Compared to the N_0 treatment, the extra yield reached 3.26 Mg ha^{-1} with green manures. After the use of bird's foot trefoil, the yield was equal to the treatment in which 100 kg of mineral nitrogen had been applied (Fig. 1). Also Maiksteniene and Arlauskiene (2004) show that the highest wheat yield is attained when wheat is grown after lucerne as a preceding crop, the yield being 18.5% higher than after clover. Higher grain yields are usually associated with lower protein concentration (Blackman & Payne, 1987). Protein is a primary quality component of cereal grains. Protein content can be increased with higher nitrogen fertilizer norms (Peterson, 1976). In the present trial, protein content increased compared to the N_0 treatment, but remained lower than the protein content of wheat (13–15%). The protein content of wheat grains was 11.7–12.8% on the background of green manures, and had a lower level in the treatment where hybrid lucerne and bird's foot trefoil had been grown as preceding crops. Protein content is positively correlated with wet gluten content (Fredericson et al., 1998) which is strongly influenced by the growing environment (Grausgruber et al., 2000). The trial also showed that the wet gluten index increased according to a rise in protein content. One of the most used criteria of wheat quality is volume weight, which is an indication of the density and soundness of the wheat. Volume weight is influenced by many factors, including fungal infection, insect damage, kernel shape and density, agronomic practice and the climatic and weather conditions (Gaines et al., 1997). In the trial, the volume weight remained low. After the application of green manures, the volume weight of all treatments was higher than the volume weight of the N_0 treatment (Table 1).

Table 1. Yield and yield quality of winter wheat *Ramiro* depending on preceding crop.

Preceding crop	Y (Mg ha^{-1})	TKW (g)	VW (gl^{-1})	CP (%)	WGC (%)	GI (%)
Barley N0	2.89	29.8	753	9.4	x	x
Barley N_{100}	5.78	40.0	796	12.9	30.8	55
Red clover	5.95	40.3	801	12.2	23.3	88
Lucerne	6.15	40.8	802	11.9	23.0	87
H. lucerne	5.98	40.6	800	1.7	22.8	92
Sweet clover	5.39	39.8	800	12.2	24.6	98
Bird's foot trefoil	5.78	40.4	799	11.8	22.5	91
LSD $_{0.05}$	582	1.4	5.3			

x – non-washable

Kernel weight, usually expressed in grams per 1000 kernels, is a function of kernel size and density. Kernel weight increased in all treatments compared to the N_0 treatment, but there was no plausible difference between green manure treatments.

Wet gluten, obtained my mixing flour and water, increases the volume of bread. Grains should contain at least 26% of wet gluten, with the best wet gluten content being 28–29%. Wet gluten content in grains was increased both with mineral fertilizers as well as on the background of the after-effect of green manures, but remained below the norm in all treatments. Kangor et al. (2007) have also shown that wet gluten content increases both with root as well as foliar fertilization.

Gluten index is used to measure the quality of wet gluten: the optimum index is 60–90 and the satisfactory index, 41–59. In treatments where green manures were grown as preceding crops the gluten index rose by 33–43 units as compared to the N_{100} treatment. The increased gluten index is an indication of the higher quality of wet gluten and enhanced baking properties.

CONCLUSION

The biological production of green manures, as well as the amounts of nitrogen they bind and the C/N ratio of organic matter, vary according to the crop species. The highest phytomass and amount of nitrogen returned to soil was obtained by growing white sweet clover and red clover; the lowest respective results were obtained with bird's foot trefoil. The winter wheat yield was lower after white sweet clover than after other leguminous preceding crops despite the highest amount of nitrogen applied into the soil. This is probably due to the slower decomposition of white sweet clover. The highest wheat yields were attained in treatments with lucerne and red clover as preceding crops. Both green manures and mineral fertilizers enhanced the quality of winter wheat yield, but the results did not vary among different green manures.

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Biomass production and nutrient binding of catch crops

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Abstract

The trials were carried out during the 2008–2010 growing seasons at the Estonian University of Life Sciences’ Department of Field Crop Husbandry. The experiments were performed to measure the amount of biomass produced by catch crops and how effectively they bind the soil nutrients. The experiment was performed four times on a *Stagnic Luvisol* (*LVst*). The catch crops were white mustard, fodder radish, faba bean, winter oil rape, winter oil turnip, Italian ryegrass, pea, rye and phacelia. The amount of biomass that catch crops produced differed significantly from year to year. Sowing time had a great effect on biomass production, with August having the greatest sum of effective temperatures. The best nutrient binders were pea and beans. In better growth years these crops bound 50–100 kg ha^{-1} N, 7–10 kg ha^{-1} P, 40–60 kg ha^{-1} K. Of *Brassicaceae*, white mustard and fodder radish produced the highest biomass, used up to 9 kg ha^{-1} P and up to 82 kg ha^{-1} K (2010, fodder radish) in the biological cycle of organic matter. The catch crops did not reduce soil NO_3-N and NH_4-N content compared to the control fields without catch crops variant.

Key words: catch crops, biomass, nitrogen, potassium, phosphorus, C:N ratio, spring wheat yield.

Introduction

In recent years, many research groups from various countries have taken an interest in finding new ways of reducing the loss of plant-accessible soil nutrients during vegetation-free periods. It is known that the mineralization of organic matter takes place in periods before or after growing seasons (Powlson, 1993; Vos, Van der Putten, 2001); autumn ploughing also increases the risk of reducing nitrogen amounts because of leaching (Davies et al., 1996).

One way to reduce nitrogen leaching is to use a crop rotation system which leaves some of the fields covered with plants for the winter. Along with growing winter cereals or perennial grasses, one could also grow intermediate crops, i.e. catch crops.

The research interest in growing catch crops and green manures is not new, but the use of such crops has decreased (Renius, Entrup, 2002). A catch crop may absorb residual N up to 200 kg ha^{-1} N and thus reduce N available for leaching and denitrification. The N uptake by the catch crop may depend on plant species, sowing date (determined by the harvest time of the previous crop), amount of available soil N and weather conditions (Van Dam, 2006).

In addition to reducing nutrient leaching, catch crops improve soil quality by adding organic matter (Lord, Mitchell, 1998), avoiding topsoil erosion (Thorup-Kristensen et al., 2003), reducing the loss of organic matter, inhibiting pest/disease infestation and reducing weeds. Plants from the *Brassicaceae* family are able to produce glycosinolates (both in their roots as well as their above-ground parts), which inhibit root rot (Ilumäe et al., 2007). Therefore growing catch crops in a crop rotation system with cereals is of great importance, because it reduces the environmental stress on the soil and disrupts the disease development cycles. However, when choosing catch crops, it is important to avoid growing biologically similar species together too often, to prevent transferring common pests and diseases. Recently, it has also been speculated that catch crops may influence the degradation potential of the soil for pesticides (Thorup-Kristensen et al., 2003).

The most common catch crops are *Brassicaceae*: fodder radish, white mustard, oilseed rape and turnip, but also cereals (rye), Italian ryegrass and phacelia. These catch crops are able to bind free nitrogen in the soil. Leguminous plants, which have the added advantage of binding nitrogen from the air, are also grown as catch crops. The efficiency of binding air nitrogen depends on the length of the growing season, crop rotation system and manuring (Peoples et al., 2001).

Catch crops are usually sown late in the summer, immediately after main crop harvesting and usually after cereals, but it is becoming more common to sow them on early vegetable and legume (bean, pea) fields as well. The earlier the catch crops are sown, the more effective they are. Their growing period requires at least 50 days, a daily temperature of 9°C and a total amount of precipitation of 150–200 mm per growing season for their normal development (Küpper, 2000).

The catch crops are ploughed into the soil shortly before the ground freezes. After incorporation of the crop into the soil, N mineralization starts, so that, with good timing, part of the mineralized N may become available for the next main season crop allowing reduction of the N application for that crop (Vos, Van der Putten, 2001). Some researchers (Stenberg et al., 1999) have found that late autumn ploughing or spring ploughing reduces the risk of N leaching.

Experiments were performed in the trial fields to study the amount of biomass formed by catch crops, how they bind nutrients and their effect on the plant available N in the soil. The purpose was to find the most optimal catch crop species for Estonian conditions.

Materials and methods

The trials were carried out during the 2008–2010 growing seasons in the Department of Field Crop Husbandry at the Estonian University of Life Sciences (EMU), Institute of Agricultural and Environmental Sciences (58°23′ N, 26°44′ E). The trial was repeated four times on a *Stagnic Luvisol* (*LVst*) (by WRB classification), the humus layer of which has the following characteristics: C_{org} 1.1–1.2%, N_{tot} 0.10–0.12%, P 110–120 mg kg^{-1}, K 253–260 mg kg^{-1}, pH_{KCl} 5.9, soil bulk density 1.45–1.50 Mg m^{-3}, the depth of ploughing layer was 27–29 cm. Soil analyses were carried out at the laboratories of the Department of Soil Science and Agrochemistry, EMU.

Barley cv. 'Inari' was used as the preceding crop. The field was prepared and catch crops were sown with a Kongskilde sowing machine (row width 12.5 cm) immediately after the barley harvesting: on 25 August in 2008, 14 August in 2009 and 2 August in 2010.

The catch crops were sown according at the following rates: winter oil turnip (*Brassica rapa* L. var. *silvestris*) cv. 'Largo' and winter oilseed rape (*Brassica napus* L. var. *oleifera*) 8 kg ha^{-1}, fodder radish (*Raphanus sativus oleiformis*) cv. 'Adios' 22 kg ha^{-1}, white mustard (*Sinapis alba* L.) cv. 'Condor' 18 kg ha^{-1}, pea (*Pisum sativum* L.) cv. 'Clarissa' 180 kg ha^{-1} (80 seed m^{-2}), faba bean (*Vicia faba* L.) cv. 'Jõgeva' 280 kg ha^{-1} (40 seeds m^{-2}), Italian ryegrass (*Lolium multiflorum* Lam.) cv. 'Talvike' 25 kg ha^{-1}, rye (*Secale cereale* L.) 210 kg ha^{-1} and phacelia (*Phacelia tanacetifolia* Benth.) cv. 'Stala' 11 kg ha^{-1}. The aboveground biomass of catch crops and the root mass were measured before ploughing. Samples of above-ground biomass were taken from 1 m^{-2} and the root mass from 0–30 cm depth (4 replications). The samples were dried and weighed. According to the length of the growing period, the catch crops were ploughed into the soil in the 2nd–3rd ten-day period of October. Ploughing depth was 22–24 cm. Before ploughing, the catch crops were neither ground nor crushed.

Soil samples to measure NO_3-N and NH_4-N content were taken during the catch crop growing period and in the spring before tillage (Table 2) from the 20 cm depth. NO_3-N and NH_4-N were determined in 2 M KCl soil extracts by "FIAstar 5000".

The effect of catch crops was monitored by growing spring wheat cv. 'Mooni' (2009, 2010). Plant analyses were conducted at the Department of Soil Science and Agrochemistry of EMU. Acid digestion by sulphuric acid solution (Methods of soil…, 1986) was used to determine P and K content in the plant material. Total nitrogen, carbon and sulfur content of oven-dried samples (separately in undeground and aboveground biomass) were determined by dry combustion method on a "vario MAX CNS" elemental analyzer ("Elementar", Germany).

Research data was processed by using analysis of variance and correlation analysis. The differences between treatments are shown as standard error. To describe the growth period, the sum of effective temperatures (above 5°C) and precipitation average (mm) was used (Table 1).

Table 1. The sum of effective temperatures and precipitation during catch crops' growth period

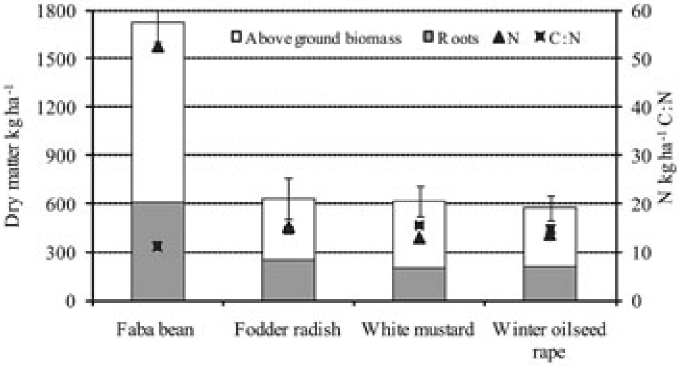
Year	Sum of effective temperatures, degree-days	Precipitation mm	Growth period/days
2008	352	134	72
2009	427	207	60
2010	602	225	72

Results and discussion

Since cereals are prevalent in modern crop rotation systems, barley cv. 'Inari' was chosen as the preceding crop before the catch crop for Estonian conditions. As a cultivar of medium height, it provides a sufficiently long growing period for the catch crop.

From year to year, there were great fluctuations in the quantity of catch crop biomass produced and depended on the sum of effective temperatures during the growing season ($R = 0.63$). Especially significant positive correlations were detected between biomass of fodder radish and sum of effective temperatures ($R = 0.88$). In 2008, because of the weather conditions, the crop was harvested at the end of August. As the sum of effective temperatures was low in August and September (about 30ºC lower than the average from 1948–2007), the catch crops produced a modest amount of biomass. The rather long duration of the growing period (until the end of October) did not compensate for the low temperatures. The total biomass of catch crops varied from 570 kg ha^{-1} for winter oil rape to 1720 kg ha^{-1} for faba bean, which bound 13–52 kg ha^{-1} N (Fig. 1). In fodder radish, 39% of the total biomass consisted of roots; for other crops the roots had a smaller share in the resulting biomass. Previous research (Thorup-Kristensen, 2001) has shown that fodder radish forms a strong taproot with a well-spread system of side roots, which enables it to uptake water and nutrients from lower soil layers and to improve soil structure.

The decomposition of organic matter depends largely on the C:N ratio and their overall amount. The smaller the C:N ratio of organic matter and the greater its nitrogen content, the more nitrogen is mineralised into soil from green manure (Kumar, Goh, 2002). The C:N ratio of the applied organic matter varied from 13 (bean) to 18 (white mustard and winter oilseed rape). When organic matter is decomposed by microorganisms in the conditions like these, no soil nitrogen is used in the decomposition process and nitrogen is immediately available for the main (following) crop.



Note. Vertical bars denote standard deviation.

Figure 1. Biomass of catch crops, N and C:N ratio in 2008

The ability of catch crops to bind P and K nutrients for the main crop has been less studied. Although both catch crops and green manure have an effect on nitrogen loss and its availability for catch crops, long term studies of catch crops and green manure in the context of nutrient depletion have shown that they cannot improve access to phosphorus and potassium in poorer soils (Pedersen et al., 2005; Jensen et al., 2006). This may be a result of smaller biomass production by catch crops on poor soils. Nevertheless, it has been shown (Thorup-Kristensen et al., 2003), that catch crops and green manures take up soil P and thus convert it from inorganic to organic form. Some species may have especially high P uptake capability, e.g., by forming particularly long root hairs. Upon incorporation of the residues into the soil the plant P is released slowly and is not as susceptible to leaching and precipitation as inorganic P fertilizers.

In 2008, field bean was the most effective binder of phosphorus and potassium in the experiment – 4.5 kg ha^{-1} P and 33 kg ha^{-1} K (Fig. 2). The phosphorus and potassium amounts did not change significantly and were 1.8–2.1 kg ha^{-1} P and 10.8–11.6 kg ha^{-1} K, accordingly.

Vos and Van der Putten (2000) have found that rye and fodder radish bound between 4 and 9 kg ha^{-1} P and 21–45 kg ha^{-1} K when grown as catch crops, if their biomass was 400 to 900 kg ha^{-1}. Bigger biomass enables them to bind more nutrients. The levels of P and K in a plant depend on species, growth stage and part of the plant. There is more potassium in young parts and more phosphorus in aboveground parts than in the roots.

In 2009, field bean had the largest biomass – 2160 kg ha^{-1} (35% was roots) but pea biomass was not significantly smaller (20% roots). Fodder radish (38% roots) and white mustard (28% roots) had an equal biomass – 1600 kg ha^{-1}. Winter oil turnip had a biomass of 1395 kg ha^{-1} (40% roots). The biomass of Italian ryegrass was significantly smaller. *Brassicaceae* returned into soil 28–37 kg ha^{-1} N. Legumes that are able to bind nitrogen from the air as well, deliver about 67 kg ha^{-1} N into soil (Fig. 3), but their disadvantage was high seed rate and price.

The C:N ratio in the biomass that was ploughed to the soil varied from 13 (bean and pea) to 33 (Italian ryegrass). Depending on crop type and amount of biomass, in 2009 catch crops returned to the nutrient cycle from 12 (Italian ryegrass) to 51 kg ha^{-1} K (bean) and 7.3 kg ha^{-1} P (pea). In 2009, Italian ryegrass was the least effective in binding phosphorus (total biomass only 620 kg ha^{-1}) – 1.6 kg ha^{-1} P (Fig. 4).

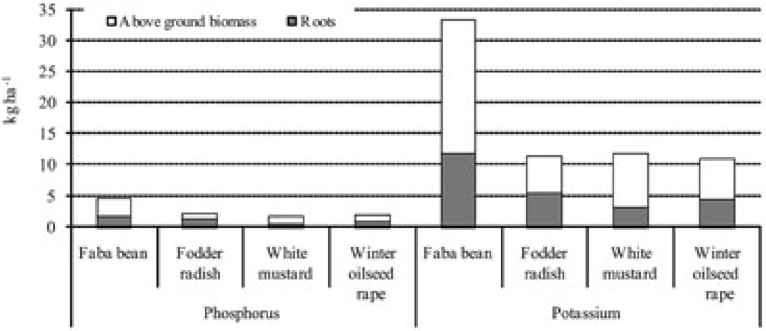
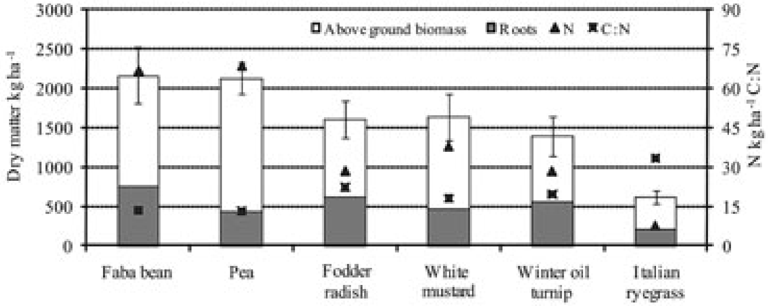


Figure 2. Quantities of P and K in 2008 (ploughed into soil with catch crops biomass)



Note. Vertical bars denote standard deviation.

Figure 3. Biomass of catch crop, N and C:N ratio in 2009

In 2009, the sulfur levels in plants were also measured. Sulfur is known to have a positive effect on nitrogen uptake and plant viability. Plants with sufficient sulfur give bigger yields with better quality. Sulfur deficiency has become an important feature of most North European arable cropping systems, due to the greatly reduced sulfur emissions from fossil fuels. Sulfur behaves very similarly to nitrogen in the soil system, and it can easily be lost by leaching in the form of sulfate. Few studies have focused specifically on the effects of catch crops on sulfur retention and availability (Thorup-Kristensen et al., 2003).

Eriksen and Thorup-Kristensen (2002) have found that *Brassicaceae* species, which usually have a high plant S concentration, showed high uptakes of 22–36 kg ha^{-1} S, compared to only 8 kg ha^{-1} S taken up by Italian ryegrass. Data from the current experiment does not support these results. The biggest uptake of sulfur was by pea 7.8 kg ha^{-1} S. Although bean biomass was relatively large, the amount of sulfur uptake was similar to that of *Brassicaceae* catch crops. Biomass from Italian ryegrass returned only 1.5 kg ha^{-1} S to the soil (Fig. 4).

The weather conditions of 2010 made it possible to harvest the barley and sow the following catch crops quite early. The growing period for the catch crops was 72 days, with a total sum of 602 degrees of effective temperatures, resulting in the biggest catch crop biomass for the whole experiment.

In 2010, the total biomass of catch crops (aboveground parts + roots) added from 930 (Italian ryegrass and rye) to 3550 kg ha^{-1} (fodder radish) of organic matter to the soil. Although in previous years white mustard produced about the same amount of biomass as fodder radish, the results were different in 2010. White mustard is a long-day plant; if it is sown early (in the beginning of August), it quickly starts flowering. Flowering reduces root activity and nutrient uptake.

Phacelia is generally considered to be a good catch crop (Brant et al., 2009). Phacelia should be able to create a considerable amount of root mass in a relatively short time, uptaking large amounts of nitrogen. Current results did not support this idea. Although both winter oil turnip and phacelia produced equal amounts of biomass, their root percentages were different: 41% in winter oil turnip, 26% in phacelia. Also, despite the same biomass amount, phacelia bound 1.6 times less nitrogen than winter oil turnip (Fig. 5). Earlier studies (Eichler-Löbermann et al., 2008) have also shown that phacelia contributed to the P supply of the main crops, because it significantly increased the P uptake as well as the readily available P contents in soil.

The amount of nitrogen that was contributed to the soil varied from 10 (Italian ryegrass) to 100 (pea) kg ha^{-1}. Of all *Brassicaceae* crops, fodder radish was the biggest contributor of nitrogen to the soil. The C:N ratio stayed below 30 for all the catch crops, except for Italian ryegrass.

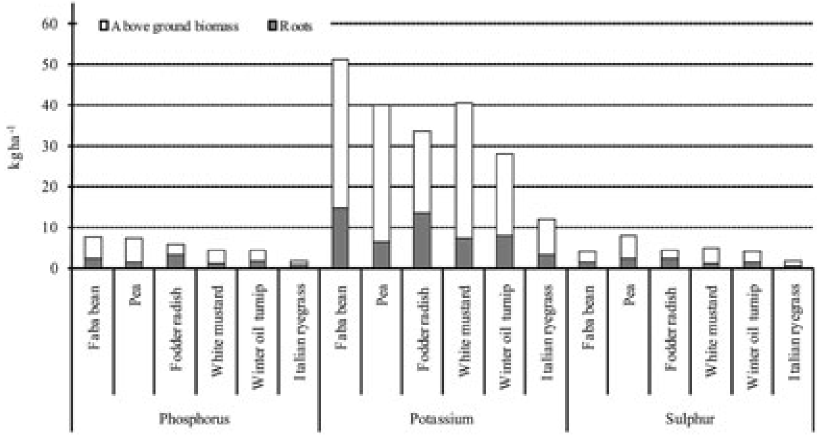
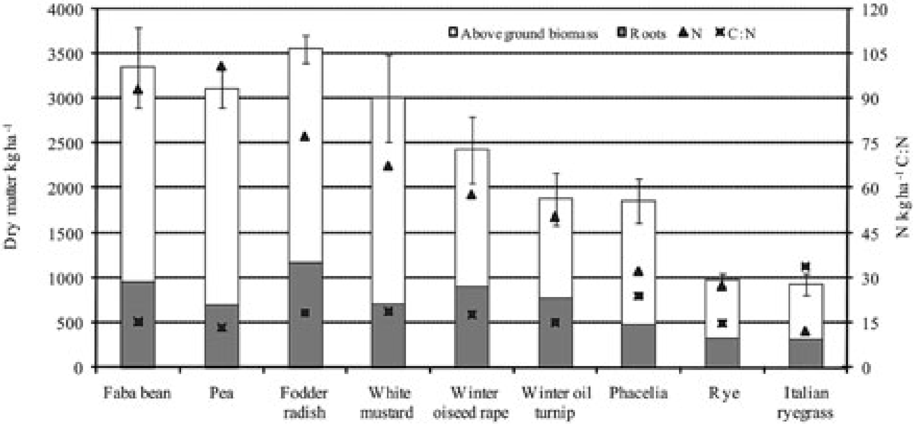


Figure 4. Quantities of P, K and S in 2009 (ploughed into soil with catch crops biomass)



Note. Vertical bars denote standard deviation.

Figure 5. Biomass of catch crop, N and C:N ratio in 2010

In relation to biomass amount, in 2010 the catch crops contributed up to 82 kg ha^{-1} K (fodder radish) and up to 9.9 kg ha^{-1} P (pea) (Fig. 6) to the soil.

In 2009, beans had the greatest effect on the following spring wheat yield, compared to N_0 control field; the spring wheat yield was 590 kg ha^{-1} bigger. Although beans contributed more nitrogen to the soil, the following wheat yield was not significantly different from the wheat yield after growing *Brassicaceae* catch crops. In 2010, the catch crop did not affect grain yields significantly (Fig. 7). An experiment carried out in Sweden also showed that the catch crop did not reduce grain yields significantly in any of the studied years (Stenberg et al., 1999). Muller et al. (1989) found a negative effect of the catch crop on the biomass production of the following crop.

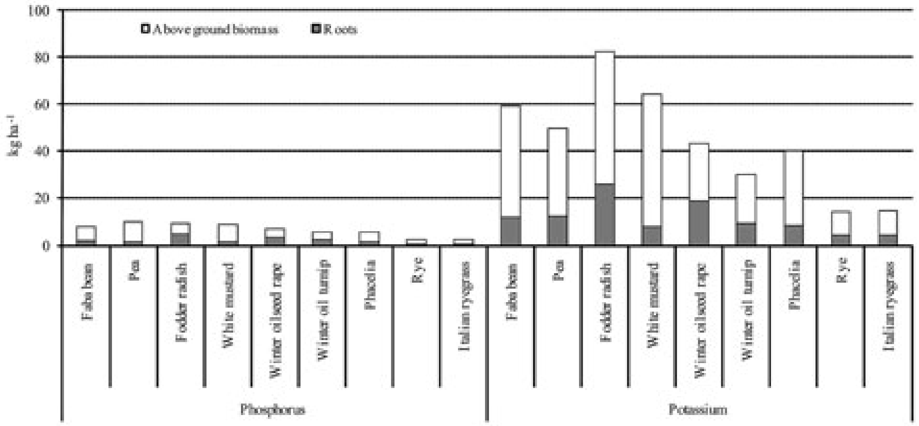
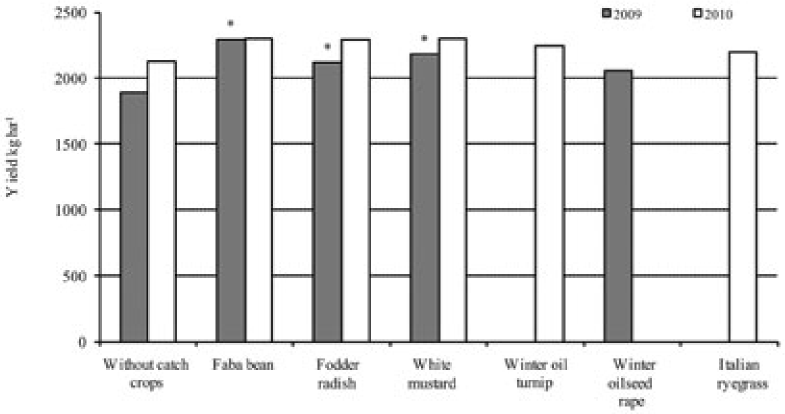


Figure 6. Quantities of P and K in 2010 (ploughed into soil with catch crops biomass)



Note. * – significantly different at $p > 0.05$ significant level, $LSD_{0.05}$ 2009 – 174, 2010 – 259

Figure 7. Grain yield of spring wheat cv. 'Mooni' in 2009, 2010

Soil ammonium and nitrate N content may vary greatly, influenced by soil type and measuring time and cannot be considered a reliable indicator of soil fertility (Kärblane, 1996). The soil cannot retain NO_3-, which is therefore susceptible to leaching. Catch crops should be able to bind available nutrients and biologically usable nitrogen should not leach out during vegetation-free periods. In all soil samples, NO_3-N and NH_4-N content was low when measured.

The nitrate and ammonium nitrogen content that was measured while the catch crops still grew was relatively similar for all the catch crops, but was significantly different for the control treatment. According to literature (Thorup-Kristensen, Nielsen, 1998), catch crops bind soil nitrogen, which should decrease mineral nitrogen content. Conversely, Stenberg et al. (1999) have found that if the growth of catch crops is hindered, nitrate concentrations at 60 cm were higher than those expected in the catch crop treatments. After catch crops, the concentration of available soil N is normally higher in the topsoil layers, with higher amounts of inorganic N in the uppermost soil layers and less in the deeper soil layers (Thorup-Kristensen, Van den Boogaard, 1999). In the current experiment, catch crops did not decrease soil NO_3- and NH_4- content, compared to the control treatment (Table 2).

The reducing effect of a catch crop on nitrate-N leaching is associated with the amount of nitrogen accumulated in the catch crops (Vos, Van der Putten, 2004). Macdonald et al. (2005) have found that catch crops are most likely to be effective when grown on freely drained sandy soils where the risk of nitrate leaching is greatest.

Table 2. Amounts of nitrate N and ammonium N in the soil during the growing period of catch crops and in the spring before tillage

Treatments (2009)	19th October, 2009		21st April, 2010	
	NO_3-N mg kg^{-1}	NH_4-N mg kg^{-1}	NO_3-N mg kg^{-1}	NH_4-N mg kg^{-1}
Faba bean	7.5*	12.5*	9.2*	3.6*
White mustard	6.2	8.8*	5.7	1.7*
Fodder radish	6.3*	9.4*	6.0*	1.0
Italian ryegrass	x	x	5.3	1.2
Control (without catch crops)	4.7	0.7	3.8	0.5

* – significantly different at $p > 0.05$ significance level; x – not determined

Conclusions

1. The effectiveness of catch crops depends on the choice of species, sowing time and main crop harvesting time, as well as on weather conditions during the autumn and winter period. Italian ryegrass and rye produced the least biomass. They also bound less nitrogen than *Brassicaceae* and leguminous crops.

2. Of all the *Brassicaceae* catch crops, the most effective were fodder radish and white mustard, which produced the most biomass and therefore drove more nutrients into the soil.

3. The best nutrient binders were legumes pea and bean. In more favourable growing years (2009–2010) they bound 50–100 kg ha^{-1} N, 7–10 kg ha^{-1} P, 40–60 kg ha^{-1} K. Their disadvantage was high seed rate and establishment costs.

4. The levels of soil nitrogen in nitrates and ammonium were relatively consistent for all the catch crops; growing catch crops did not decrease soil NO_3-N and NH_4-N content compared to the treatment without catch crops.

5. Fodder radish and white mustard proved to be the most optimal catch crops under Estonian weather conditions.

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Tarpinių augalų biomasės augimas ir maisto medžiagų kaupimas

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Santrauka

Bandymai vykdyti 2008–2010 m. vegetacijos laikotarpiu Estijos gyvybės mokslų universiteto Augalininkystės skyriuje. Siekta nustatyti tarpinių augalų užaugintos biomasės kiekį ir dirvožemio maisto medžiagų kaupimo efektyvumą. Bandymas kartotas 4 kartus stagniniame dirvožemyje (IDj). Auginti šie tarpiniai augalai: baltosios garstyčios, pašariniai ridikai, pašarinės pupos, žieminiai rapsai, žieminiai turnepsai, gausiažiedės svidrės, žirniai, rugiai ir facelijos. Įvairiais tyrimų metais augalų užaugintos biomasės kiekis smarkiai skyrėsi. Sėjos laikas turėjo didelę įtaką biomasės augimui, nes rugpjūčio mėnesį buvo didžiausia efektyvių temperatūrų suma. Daugiausia maisto medžiagų sukaupė žirniai ir pupos. Palankesniais augti metais šie augalai sukaupė 100 kg ha^{-1} azoto (N), 7–10 kg ha^{-1} fosforo (P) ir 40–60 kg ha^{-1} kalio (K). Iš bastutinių (*Brassicaceae*) augalų daugiausia biomasės užaugino baltosios garstyčios ir pašariniai ridikai, biologiniame cikle sunaudoję iki 9 kg ha^{-1} P ir 82 kg ha^{-1} K (2010 m. pašariniai ridikai) organinės medžiagos. Tirti tarpiniai augalai dirvožemyje NO_3-N ir NH_4-N kiekio nesumažino, palyginti su laukais be tarpinių augalų.

Reikšminiai žodžiai: tarpiniai pasėliai, biomasė, azotas, kalis, fosforas, C:N santykis, vasarinių kviečių derlius.

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