WINTER TURNIP RAPE IN MIXED CROPPING: ADVANTAGES AND DISADVANTAGES

DOCTORAL THESIS

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ACADEMIC DISSERTATION

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ABSTRACT

Winter turnip rape is a biennial, cold-hardy crucifer oilseed. A problem associated with winter turnip rape, in addition to occasional poor overwintering is early sowing time in July, when farms are short of available land. Even though establishing winter turnip rape by undersowing with a cereal was suggested to farmers in 1950’s, the method did not gain popularity. The reason for the abandoning of the methods was cereal lodging, which resulted in winter turnip rape growing trough lodged cereal and difficulting cereal harvest.

The aim of this study was to determine if winter turnip rape can be established by undersowing with different spring cereals without deteriorating cereal and winter turnip rape yields. It was also studied, if cutting the vegetative leaves of winter turnip rape in autumn could be performed without affecting the yield and whether the composition of leaf material was nutritionally acceptable to be used as forage. Additionally, the ability of winter turnip rape to function as a mineral nitrogen scavenging catch crop was studied.

Field experiments were conducted at Viikki experimental farm, University of Helsinki, Finland during 2009 – 2011. In the first experiment, winter turnip rape was either undersown with spring cereal or as pure stands. Cereals were six-row barley, two-row barley, oat and wheat. When using normal winter turnip rape density (150 seeds/m²) in mixed stands, cereal density was reduced by 20%. With high winter turnip rape density (300 seeds/m²), normal commercial cereal sowing density was used. Pure stands of winter turnip rape were established either in the normal sowing time in the end of July, or already in May. One third of the winter turnip rape plots were cut after cereal harvest to simulate forage harvest. In the second experiment, winter turnip rape was established either by undersowing with six-row barley or as a pure stand after barley harvest. Pure stands of six-row barley were included, with one of them left to stubble and the other ploughed after harvest and subsoil as well as topsoil samples were gathered from all plots. Experiments were conducted in randomized complete block design.

Winter turnip rape yield and its quality was not compromised due to undersowing with a cereal, when the overwintering conditions following cereal harvest were favorable (I). However, after overwintering in conditions where soil remained thawed under snow cover, winter turnip rape yield was decreased. Decrease was most prominent in plots established in May either as pure stands or undersown with a cereal.
Cutting the winter turnip rape stands in autumn decreased seed yield in the following year without exceptions (I). Winter turnip rape leaf forage has very high crude protein content and low crude fibre content. Fibre content is higher in forage taken from mixed stands due to cereal stubble. The glucosinolate content of winter turnip rape leaf forage is comparable to other forage crucifers.

Cereal yield was not decreased by the undersown winter turnip rape and quality, namely protein content of wheat, was only slightly affected (III). Seed yield of six-row barley and oat was increased by the undersown winter turnip rape, indicating a facilitative interaction between the species. Leaf area index of mixed stands was higher than that of pure stands, but there was no correlation between leaf area index and land equivalent ratio of cereal and winter turnip rape yields. Undersown winter turnip rape decreased subsoil nitrate content effectively in late autumn under conditions that favored mineralization (II).

The results suggest that winter turnip rape can be established by undersowing without decreasing its yield and that cereal yield is not decreased by the undersown winter turnip rape. Some cultivars of barley and oat may even benefit from the undersown winter turnip rape possibly due to root interactions forcing cereal roots to deeper, nutrient-rich soil layers. Even though winter turnip rape is nutritionally suitable as forage, autumn forage cuts should be avoided, if the intention is to produce an acceptable seed yield. Winter turnip rape seems to be an effective catch crop during autumn months, when high precipitation may lead to leaching of soil nitrate. This can be seen not only as reduction of soil nitrate, but also in the substantial amounts of nitrogen that are held in winter turnip rape tissues in autumn. The reduction in subsoil nitrate due to cultivation of undersown winter turnip rape has practical value in mitigating leaching losses of high latitude crop production.
LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following original articles. In the text, the articles are referred to by their Roman numerals. The articles are reprinted with the permission of the publishers.


CONTRIBUTIONS

Publication I

All authors contributed to the research plan of the study. The experimental work, measurements and laboratory analyses were carried out by Antti Tuulos with guidance to forage analysis by Seija Jaakkola. Statistical analysis of the data was done by Antti Tuulos under guidance of co-authors and Dr. Jarkko Isotalo. Antti Tuulos was responsible for the writing of the manuscript and incorporation of the input of other authors.

Publication II

All authors contributed to the research plan for this investigation. The experimental work, measurements and laboratory analyses excluding soil analysis were carried out by Antti Tuulos. Guidance to soil sampling and sample preservation was given by Markku Yli-Halla. Statistical analysis of the data was done by Antti Tuulos with guidance from Frederick Stoddard. Antti Tuulos was responsible for the writing of the manuscript and incorporation of the input of other authors.

Publication III

All authors contributed to the research plan. The experimental work, measurements and laboratory analyses as well as statistical analyses were carried out by Antti Tuulos with guidance from co-authors and Dr. Jarkko Isotalo. Antti Tuulos was responsible for the writing of the manuscript and incorporation of the input of other authors.
1. INTRODUCTION

1.1 Winter turnip rape in Finland

Turnip rape [Brassica rapa L. ssp. oleifera (DC.) Metzg.] is a cruciferous oilseed crop and the non-bulbing form of turnip (Kimber and McGregor 1995). Both annual spring cultivars and biennial winter cultivars exist. Brassica rapa is the oldest cultivated species in genus Brassica. Traces of it have been found from West Europe, North Africa, China and India dating back 2000 years (Kimber and McGregor 1995). The origin of Brassica rapa is thought to be in Near East, Central Asia, or Mediterranean area (Vavilov 1949) and it has probably evolved from a biennial wild form (Kimber and McGregor 1995). Cultivation of Brassicas started in Europe in middle ages, but it is not known for certain, when the species were first used for vegetable oil. Earliest applications were lamp oil and soap. In the 19th century, the high (25 – 30%, Dorrell and Downey 1964) erucic acid (13-docosenoic, 22:1) containing oil was found out to be an appropriate lubricant in steam engines that were constantly exposed to water (Kimber and McGregor 1995). It was only after World War II, when the use of Brassicas for edible oil increased in western countries (Kimber and McGregor 1995). Since 1960’s, the cultivation of Brassica oilseeds has multiplied several folds (Figure 1.) with most increase in Europe and Canada (FAO 2014). The increase of vegetable oil consumption has doubled in industrial countries and three folded in developing countries since 1960’s due to increased welfare and the decline in animal fat consumption, driven by awareness about the negative health impacts of saturated fatty acids (Kearney 2010). The consumption of vegetable oils is expected to increase also in future (Kearney 2010).

Due to its short stem during rosette stage, winter turnip rape is better adapted to cold temperatures during winter than oilseed rape (Torssell, 1958). Hence, winter turnip rape is cultivated in areas too cold for oilseed rape. On the other hand, oilseed rape also requires a longer growing period than turnip rape (Mäkelä et al. 2011). Winter turnip rape is a relatively new crop in Finland. First cultivation experiments with winter turnip rape were conducted in 1945 in the agro-economic test facility, located in Tikkurila, southern Finland. The year 1950 was the first year, when larger scale commercial cultivation began in Finland. Area sown to winter turnip rape by 5 400 farmers was nearly 5000 hectares with northernmost cultivations located in Oulu area, just above the 65th latitude (Valle 1951a). Only three years later, in 1953, the area sown to winter turnip rape reached its peak at 17 380 hectares and from this point on, winter turnip rape virtually replaced all other oil crops such as linseed (Linum usitatissimum L.) and
poppy (Papaver somniferum L.) in Finland for the rest of the 1950’s (Lööf 1960). The increase in the cultivated area sown to winter turnip rape was rapid due to the demand for oilseeds in the new plant oil extraction facility that started in 1951 in Raisio, southwest Finland (Anon. 1951).

Cultivars used in the 1950’s were of German or Swedish origin. It was soon discovered, that many of these cultivars were not hardy enough for the Finnish winter. The cultivar with best overwintering ability was Svalöfs ‘Rapido’, which remained as the hardiest cultivar at least to the mid-70’s (Kivi 1976). Even though breeding of domestic winter turnip rape cultivars had begun already in 1955 (Kivi 1960), it was not until 1972, when first Finnish cultivar, ‘Kulta’ was released by Hankkija Cooperative Wholesale Society. This was due to the lack of appropriate breeding material, namely cultivars that could tolerate the conditions of Finnish winter (Kivi 1976). Release of ‘Kulta’ did not improve winter turnip rape cultivation in Finland, as oilseed production had already started to shift towards the use of spring cultivars (Figure 2.), and the cultivation on winter turnip rape practically ceased for the next three decades.
The interest to winter turnip rape in the early years of 1950’s was based on promising results with the earliest practical experiences in 1948 and 1949. The average yield in those years was 1000 kg/ha, with highest yields being 2 200 kg/ha (Valle 1950). However, after the turn of the decade, the problems with winter turnip rape overwintering became evident. Between the years 1950 and 1954, the overwintering percentage of winter turnip rape declined heavily. Poor overwintering was attributed to high precipitation before winter combined with poor drainage of the soils as well as to fungal infections and the breaking of tap root due to frost heaving in some cases (Valle 1955). Though overwintering was not always successful, the early sowing time in July caused a problem as well. Based on the results of sowing time experiments, Valle (1953) concluded that the most reliable timing for winter turnip rape seeding in Finland was the second half of July as later sowing would reduce the seed yield in the following year (Valle 1953). As other crops grown could not be harvested by this time of the year, viable options for winter turnip rape establishment included sowing after ley, fallow or harvested winter turnip rape (Valle
1953). Sowing winter turnip rape after winter turnip rape was soon not
recommended as it proved to be unreliable method and increased the risk
of pests and diseases (Valle 1953). Sowing after ley proved to be unreliable
as well, because it delayed the sowing of winter turnip rape in case dry hay
was harvested from the field in July. Decomposing of ley also used up soil
mineral nitrogen (N) and if the tillage was not properly done, grass seeds
left to soil germinated simultaneously with winter turnip rape leading to
competition and difficulties in harvest (Valle 1954). Due to these factors,
sowing after fallow became known as the most reliable method, but in turn
caused economic losses to farmers, as tilling of the fallow was laborious and
the soil could not be used during the early part of the growing period and
thus resulted in no income. Undersowing winter turnip rape already in
spring with a cereal was also attempted in 1950 (Valle 1951). Even though
undersowing was recommended to farmers, only a small proportion of
farmers actually tried it and it seems that the method was abandoned only
few years after its introduction.

1.2 Mixed cropping

In mixed cropping and intercropping two or more crop species are grown
simultaneously on the same field. The aim of mixed cropping is to improve
the efficiency of resource use in agriculture. Due to the higher number of
plants per unit area radiation capture (Keating and Carberry 1993), water
use (Morris and Garrity 1993a) and nutrient utilization (Midmore 1993,
Morris and Garrity 1993b) become more efficient. Mixed cropping is the
oldest form of systemized agricultural production (Plucknett and Smith
1986) and has been widely adopted in the tropics (Francis 1986,
Vandermeer 1989), though it has recently gained interest also in irrigated
temperate croplands with relatively short growing seasons (Li et al. 1999).
Common mixed crops include various cereal—legume mixtures e.g. oat—
vetches mixtures (Lauk and Lauk 2009), wheat—pea mixtures (Ghaley et al.
2005) and maize—faba bean mixtures (Li et al. 1999) as well as cereal—
cruciferous oilseeds mixtures (e.g. Singh et al. 1991, Subedi 1997). The
reason for legumes being popular in mixed cropping applications is their
symbiosis with atmospheric N₂ fixing rhizobia, which excludes the need to
apply extra fertilizer for the legume (e.g. Andersen et al. 2004). Mixed
cropping applications have been used in the northern latitudes as well,
including ley mixtures, small grain cereal-pea mixtures (Harper 1983) and
establishing leys by undersowing to a cereal (Känkänen and Eriksson 2007,
Känkänen et al. 2001).
In mixed cropping, the growth of component species is altered due to competition for water, light and nutrients. However, the interactions between species are complex and due to this, plants may alter their growth by partitioning to other organs instead of dying. It is worthwhile to consider that interactions may happen between aboveground plant parts as well as between root systems. Root systems of different species often avoid each other and on the other hand, competition for water and nutrients occurs between belowground plant parts (Silvertown 1982).

Species with a large tap root may affect negatively the growth of shallow-rooted species, such as cereals as the large rooted species exploits the soil from water and nutrients more efficiently than shallow rooted species (Harper 1983). However, competition for resources changes during the growing season. Early in the season, competition occurs for water and nutrients, but at later stage light becomes the limiting factor due to increase in leaf area in the canopy. The severity of competition and the final proportions of species in a canopy at the end of the season are also affected by the original densities of species at the beginning of the season. The properties of component species and their ability to utilize resources will determine which will become dominant. Additionally, the environmental conditions, such as precipitation and temperature may affect the outcome during the growing season by favoring one or more of the species in an intercrop. For example, a deep rooted species may overcome a highly competitive shallow rooted species by accessing moisture deep in soil during times of low precipitation which restricts the growth of the shallow rooted species (Vandermeer 1989). Fortunately, the competitive effect of dominating species can also be alleviated by sowing them later than the other crops (Andersen et al. 2007). Competition exists between crops in mixed cropping applications as well as between crops and weeds (Vandermeer 1981). However, it is possible for different plant species to coexist, providing that the species have different nutritional requirements, different tolerance for allelochemicals or most importantly the species differ in their time of highest need for resources (Zimdahl 2004). Thus, it is important to select species that differ from each other in their growth habit and compete with each other as little as possible in an intercropping system (Vandermeer 1989). Likewise, it is important to select the sowing times and densities of the component species carefully in order to maximize mixed stand productivity (Davies et al. 1986).

Mixed cropping may improve the sustainability, productivity and in some cases the yield of field crops (Vandermeer 1989, Fukai and Trenbath 1993). The resource use of mixed stands differs from pure stands, due to higher amounts of mineral nutrients removed with the yield (Midmore 1993,
Morris and Garrity 1993a). This leads to increased nutrient use efficiency in a nutrient rich environment or increased need for external nutrient inputs, if the yield of mixed stand is restricted by nutrient supply in soil (Midmore 1993). Likewise, radiation use efficiency in mixed stands is improved due to higher leaf area as in a dense canopy only small fraction of radiation reaches soil surface (Keating and Carberry 1993). However, despite the high radiation use efficiency, production in a dense, heavily shaded canopy may decrease after a point where shade respiration exceeds assimilation (Black 1963). Water use is improved in mixed stands as well, since evapotranspiration and evaporation from soil and leaf surface are reduced due to lesser air movement in canopy and soil remaining cool due to increased shading (Morris and Garrity 1993b). Additional benefits of mixed cropping include in many cases smaller amount of weeds and reduced occurrence of diseases and pests, because host plants are difficult to detect in a mixed stand and in some cases mixed stands increase the abundance of natural enemies of insect pests (Trenbath 1993, Altieri and Liebman 1986), which may be a result of diverse cropping systems providing more cover as well as alternative prey or host species than monocrops (Altieri and Letourneau 1982).

Common full intercrops involve species that are sown and mature at the same time, which enables simultaneous harvest of the species. However, mixed crops are most productive, when the time required for maturing differs between the component species. Relay intercropping is a practice, where two crops grow simultaneously in the same area for some part of their life cycle. Typically in relay intercropping, the second component crop is sown considerably later than the first crop, usually at the reproductive stage of the first crop, but before the harvest of it (Francis 1986). Harvest time of the crops in relay intercropping differs, leaving the later maturing crop time to utilize resources without competition (Fukai and Trenbath 1993). The practice enables the growing of two crops in areas, where growing season is not long enough for two crops to be grown consecutively. Other factors influencing the productivity of mixed crops include weather, soil type and pests.

Studies concerning mixed cropping of cereals and cruciferous oilseeds are scarce in the western world. However, in India (Singh et al. 2014), Pakistan (Khan et al. 2014), Nepal (Subedi 1997) and Ethiopia (Adamu and Kemelelew 2011), cereal—crucifer mixed or intercropping is a common practice. Singh et al. (1991), Singh and Gupta (1993), Subedi (1997), Khan et al. (2005), Khan et al. (2014) and Wang (2007) cover mixed crop experiments with spring wheat and an annual oilseed crucifer in full intercropping arrangements. In these experiments, wheat yield was decreased and wheat
was more affected than crucifer. As the crucifers in the mixed stands were annual, they reproduced earlier or simultaneously with wheat. This undoubtedly leads to increased competition, even with lower than normal crucifer sowing ratios. As some of the crucifers grew taller than wheat (e.g. Singh et al. 1991), they also received more radiation than any undercrop would have, and probably also shaded wheat effectively. Reasons for reduced wheat growth and yield include lower phosphorus uptake by wheat when grown with *Brassicas* under acidic conditions (Wang et al. 2007). In some of these reports (Singh et al. 1991, Singh and Gupta 1993), considerably high (2:1 or higher) wheat—crucifer sowing ratio gave better wheat yields. In addition, row intercropping gave better yields than mixed cropping with plants randomly arranged (Singh and Gupta 1993, Khan et al. 2014). There are also differences between oilseed crucifer cultivars in their competitive ability, as according to Wang et al. (2007) out of two oilseed rape cultivars only one decreased wheat yield markedly in mixed cropping. On the other hand, cereal-crucifer intercropping may improve barley growth (Bellostas et al. 2003) or yield (Varma and Taneja 1980, Merker et al. 2013), indicating, that barley is suitable to be cropped with crucifers.

Oilseed crucifers seem to suitable to be cropped with cereals. Singh et al. (1991) reported that yield of Indian mustard (*Brassica juncea* L. Czern.), was only slightly affected by full intercropping with wheat. Row intercropping seems to give higher yields than mixed cropping (Khan et al. 2014), assuming that the sowing or row ratios in mixed cropping or intercropping with a cereal do not differ greatly from pure stands of crucifer crops. Nordestgaard (1982) reported that winter oilseed rape undersown to two-row barley produced less yield than pure stands after overwintering in relay intercropping. The yield decrease was 17 – 21 % on the low yielding oilseed rape cultivar and only 12 – 13 % on the high yielding cultivar. Most of the reduction was likely caused by hypocotyls being damaged during barley harvest (Nordestgaard 1982).

### 1.3 Dual purpose cropping

Dual purpose cropping or double cropping is another attempt to improve production efficiency mainly in mixed production farms that have crops and livestock. In dual purpose cropping, forage is harvested or grazed from a crop, before the onset of generative growth stage (Kirkegaard et al. 2008). Several crop species are known to be suitable for dual purpose cropping, including cowpea (*Vigna unguiculata* (L.) Walp.) (Singh et al. 2003), oilseed rape (Kirkegaard 2008) and cereals such as barley (*Hordeum vulgare* L.),
oat (*Avena sativa* L.) and triticale (*X Triticosecale rimpai* Wittm. ex A. Camus) (Bonachela et al. 1995, Francia et al. 2006, Royo 1997). Successful dual purpose crop should have an adequate period of growth between the forage harvest and initiation of flowering (Kirkegaard et al. 2008). In temperate regions this can be achieved even with spring sown cereal or oilseed rape (Francia et al. 2006, Kirkegaard 2012, Royo 1997), but under Boreal climate the growing season is too short for the aforementioned practice. In general, autumn sown crops are more appropriate for dual purpose cropping, especially if they are sown earlier than usual (Dann et al. 1983).

As an alternative to single cultivars, mixtures of spring and winter cultivars of same species could be used in order to achieve adequate forage yield without compromising the following seed yield. A rapidly growing spring wheat cultivar in a mixture would ensure a high forage yield, while the seed yield of winter cultivar would not be affected by defoliation, if done before early jointing (Davidson et al. 1990). Sowing the crop a few weeks earlier than usual is common in dual cropping with cereals and oilseed rape (Epplin et al. 2000, Kirkegaard 2012), even though early sowing might induce drawbacks to crop growth in the form of pest and disease outbreaks due to crop staying longer in the field (Epplin 2000, Sprague et al. 2010 and 2013). It seems that in many dual-purpose cropping systems, the biggest challenges lie in determining the optimal sowing time as well as for forage harvest. Early forage harvest or grazing is likely to be suitable, if the intention is to produce a high seed yield. Oilseed rape and wheat seed yield is not compromised if grazed early, during the vegetative stage (Kirkegaard et al. 2012, Epplin et al. 2000), before stem elongation. As oilseed rape produces more biomass than is needed for its full yield potential, defoliation during the early growth stages does not necessarily decrease seed yield (Kirkegaard et al. 2012).

Duration of grazing also affects the seed yield, lighter grazing is advisable near the onset of stem elongation as the grazing may delay the beginning of spring oilseed rape flowering (Kirkegaard et al. 2012). In some cases, under favorable weather and soil conditions, grazing spring cultivars might even improve the seed yield, due to reduced lodging of the shorter stands, as shown with oilseed rape and winter wheat (Kirkegaard et al. 2012, Kelman and Dove 2009). Whether the crop should be grazed lightly or not depends on the relative price of the forage and seed yield. Heavier grazing could be feasible, if forage price is expected to be high compared to the value of seed yield (Epplin et al. 2000).
The decision between grazing and mechanized harvesting probably depends on available equipment and the time when feed is required. However, mechanized harvesting may have some benefits compared to grazing. Mechanized harvesting may reduce the risk of plant disease outbreak in the field, as the crop is not exposed to trampling and the duration of mechanized harvest is normally shorter than duration of grazing, which improves crop recovery (Sprague et al. 2010 and 2013). Excessive grazing of the leaves may also damage the crop too much, and therefore at least with oilseed rape, the smallest leaves in a rosette near ground level will remain intact with mechanized harvest (Kirkegaard et al. 2012), assuming that the cutter bar is adjusted properly.

1.4 Catch crops

Nitrogen (N) is a plant nutrient that is taken up by plants in large quantities, as 1.5 to 5.0% of plant dry weight is N. Most of plant N (80 – 90 %) is found in plant proteins (Novoa and Loomis 1981). It is usually the most limiting nutrient in agricultural as well as in natural ecosystems. In soils, N can be found in organic forms (urea, amino acids and other organic constituents containing N) forms and inorganic forms such as nitrate (NO$_3^-$-N), ammonium (NH$_4^+$-N) and dinitrogen (N$_2$) (Crawford and Glass 1998). In most soils, within the 0 – 100 cm layer, approximately 1 – 2 total kg/m$^2$ N can typically be found (Batjes 1996). Plants can take up N in various forms, but NO$_3^-$-N and NH$_4^+$-N are the most important sources of N. Preference to NO$_3^-$-N or NH$_4^+$-N is dependent of plant species and its growth stage. Usually plant growth is increased when fertilized with a mixture of both NO$_3^-$-N and NH$_4^+$-N, but some species are intolerant to NO$_3^-$ (Havlin et al. 2005). NO$_3^-$-N is taken up by plants rapidly and is highly soluble in soil. Unfortunately, due to the high solubility of NO$_3^-$-N, it is easily leached from soils.

Majority of N in soils is in soil organic matter, which consists of the remains of dead plants and animals (detritus), as well as from micro-organisms living in soil. Organic matter is a subject to mineralization, which is the microbial degradation of organic material. If the amount of N in the organic matter exceeds the requirement of microbes (i.e. the organic matter has a low C/N ratio), surplus N is released as NH$_4^+$ (Robertson and Groffman 2007). This NH$_4^+$ can be fixed to clay minerals by cation binding, taken up by plants or it can be degraded by soil microbes for energy (Havlin et al. 2005). As a result of microbial degradation of NH$_4^+$, NO$_3^-$ is released. NO$_3^-$ can be taken up by plants or it may be leached from soil profile. It may also
be turned into a gaseous form through denitrification, which is a form of anaerobic respiration of microbia or it can be immobilized to soil microbial biomass (Havlin et al. 2005). Immobilization of $NO_3^-$ is performed by microbia, which require the N for their amino acid synthesis when disintegrating organic matter with a high C/N ratio. The C/N ratio of the organic matter under microbial attack is what determines whether N is immobilized to or mineralized from the organic matter. Generally, C/N ratios higher than >35:1 result in immobilization and ratios lower than 25:1 result in mineralization of N (Heal et al. 1982). Both mineralization and immobilization can, however, occur simultaneously in a soil (Robertson and Groffman 2007) as soils are usually highly heterogeneous in their composition.

Nitrogen can be lost from the cycle in soils through leaching of nitrate and volatilization of gaseous forms of nitrogen produced by denitrification (Havlin et al. 2005). In an agricultural system, removal of plant biomass also removes nitrogen from the cycle. N inputs to soil come from plant residue, manure and also from biological and industrial fixation of atmospheric N (Havlin et al. 2005). Biologically and industrially fixed N are the major sources of N in agricultural systems (Galloway et al. 2004), with lesser amounts of N derived from atmosphere through lightning and rainfall.

N and phosphorus (P), which leach from agricultural soils, are the most important reason of eutrophication of waters. Other anthropogenic sources, such as sewage waste and gaseous emissions play a minor role in the amounts of nutrient load. Most important cause of eutrophication in marine environments is increase in available N, whereas P is the limiting factor of primary production in most freshwater ecosystems (Smith et al. 1999, Hessen et al. 1997). It is estimated, that globally in early 1990’s 48 Tg of N/a, including natural and anthropogenic sources is transported to estuaries via rivers (Galloway et al. 2004). Increase in riverine N transport from 1860 is 78%, and it is mostly caused by increases in fertilizer and biologically fixed N inputs to agricultural soils. In 2050 the riverine N transport to estuaries is expected to be approximately 62 Tg of N/a (Galloway et al. 2004). In Finland, agriculture is responsible for N export of 45 000 Mg/a to rivers, which is approximately 38% of the total export (Lepistö et al. 2006). Most of the N load comes from southern, western and southwestern parts of Finland, which are major agricultural areas (Lepistö et al. 2006). Of the total N export, approximately 32% ends up in lakes and 65% to estuaries (Lepistö et al. 2006).

N losses from agricultural soils are affected by various factors, including mineralization rate, temperature, precipitation, tillage, soil type, soil
organic matter content as well as amount and type of nutrient inputs. An easy and commonly used predictor of potential N losses is the N balance, which is calculated as the remainder of N inputs and N removed from the field with harvest. The method has limitations, due to the complexity of condition depending N interactions and transformations in soil, and therefore the N balance is applicable only as a long term predictor, with inadequate accuracy in the annual scale (Salo and Turtola 2006). Mineralization rate depends on soil moisture and temperature, of which, temperature plays a major role (Sierra 1997, Guntiñas et al. 2012) as higher soil temperatures result in higher mineralization rates if soil moisture is not severely limited. Optimum temperature for mineralization is in the range of 20 – 25 °C (Guntiñas et al. 2012), but mineralization occurs in temperatures as low as -6°C (Clark et al. 2009). This indicates that mineralization occurs even during the cold autumn and winter in the high latitudes (above 60° N) of Finland. Mineralization occurs even in low soil moisture conditions above plant wilting point (1500 kPa) (Sierra 1997). Hence, low soil moisture content does not play a significant role in N mineralization in the high latitudes, where precipitation exceeds evaporation. In addition to the presence of $\text{NO}_3^-$ in soil, leaching requires water movement through soil (Di and Cameron 2002). Average annual precipitation in Finland is 500 – 650 mm with autumn being the season with highest amounts of rain (FMI 2014). Precipitation or irrigation during times when free $\text{NO}_3^-$ is found in soil leads to leaching of $\text{NO}_3^-$ to deeper soil layers (Goulding et al. 2000, Yläranta et al. 1993), and eventually to groundwater. $\text{NO}_3^-$ is also transported to watersheds due to surface runoff, which in Finland is on the average 300 mm p.a. (Kuusisto 1992). Subsurface draining of fields also contributes to the N leaching, as under Finnish conditions renovating of subsurface drainage may double the amounts of leached N from a clay soil (Turtola and Paajanen 1995). Excess moisture in soil can also, however increase amounts of mineral N in soil, as waterlogging accelerates mineralization (Waring and Bremner 1964), even though the magnitude of mineralization depends on soil type (Wang et al. 2001). Generally, mineralization is slower in fine textured soils (Ladd et al. 1981) due to the organic material being inaccessible to microbial decomposition when absorbed on clay surfaces (Craswell and Waring 1972a). On the other hand, waterlogging may also reduce immobilization of N (Wang et al. 2001), which increases the risk of leaching. Most of the leaching occurs between growing periods, as crop uptake reduces the amount of free $\text{NO}_3^-$ in soil during growing seasons (Di and Cameron 2002). Due to this, only 1-4% of N in spring fertilizer application is leached, whereas in autumn, the fertilizer N loss of 20% has been measured when fertilizing winter wheat in autumn under Finnish conditions (Jaakkola 1984). Cereal crops took up 41-66% of
N-15-labelled fertilizer during a four year period in Finland (Yläranta et al. 1993), with majority of the uptake taking place in the first year. The amount of spring application fertilizer N residues in soil in autumn can be expected to be insignificant for leaching in the autumn, as Lindén et al. (1992b) found that after optimal N fertilization of barley, there was only 3 kg/ha of mineral N more in the soil at yellow ripeness than in the corresponding unfertilized treatment. Soil tillage increases net mineralization of organic matter in soils (Craswell and Waring 1972b, Powlson 1980), as increased air spaces in soil create conditions more favorable to mineralization and the soil particle surfaces are exposed to microbial activity. Different tillage methods affect leaching as well, since ploughing results in higher net mineralization than stubble cultivation (Møller Hansen and Djuurhuus 1997), due to the more intensive effect of ploughing to soil structure and air space volume. Therefore, under Finnish conditions, total N leaching through subsurface drainage water from a ploughed clay soil was observed to be on the average 7.2 kg/ha/a, which was 57% higher than total N leaching from a harrowed soil (Koskiaho et al. 2002). The timing of tilting affects leaching also. Tilling in autumn increases leaching when compared to tilling in spring, due to increased precipitation and drainage in autumn months (Møller Hansen and Djuurhuus 1997). Mineralization due to tillage has been higher in soils with high clay content (approximately 20% clay) than in soils with low clay content (less than 5% clay), indicating that soils high in clay have high potential for denitrification and retaining organic material (Craswell and Waring 1972a, Simmelsgaard 1998, Di and Cameron 2002). The organic matter retaining ability of clays is a result of several factors, but among the most important ones are the cation bridging between clay particles and organic matter and the ability of clays to stabilize organic matter into micropores inaccessible to microbes (Oades 1988). Drainage is slower in fine-textured soils compared to coarser soil, which also slows down leaching (Di and Cameron 2002). Additionally, tilling in organic matter, such as plant residue or manure, increases mineralization. Whether that leads to leaching, depends on the time of tillage, prevailing weather conditions and sowing of a subsequent crop (Arnott and Clement 1966, Møller Hansen and Djuurhuus 1997, Velthof et al. 2010). Mineralization potentials of different crops vary, with grass and legumes typically resulting in higher amounts of mineralized N than cereal straw (Powlson 1980). This is due to variability in C/N ratio between different plant species and plant parts, as tissues with a very high C/N ratio (approximately above 35) typically results in net immobilization of N (Jensen et al. 2005). Manure applications usually increase leaching compared to fertilizing with inorganic fertilizers, as the N in manure is released over a several months due to the temporary immobilization of
substantial proportion of the N. Because of this, N from manure is released also after the crop has seized to actively take up N (Thomsen et al. 1997, Simmelsgaard 1998, Kirchmann and Bergström 2001, Basso and Ritchie 2005). Applications of manure or compost tend to increase soil organic matter content in the long term (Eghball 2002, Edemeades 2003, Petersen et al. 2003, Ginting et al. 2003,) and hence, potential for mineralization.

N may also be mineralized from organic material on soil surface when not incorporated into soil (Arnott and Clement 1966, Saarijärvi et al. 2004). As the mineralized N on soil surface is subjected to precipitation, ploughing in manure may also reduce N leaching compared to leaving it on soil surface (Eghball and Gilley 1999). Ploughing in manure also reduces ammonia (NH₃) emissions, which can be reduced 80 – 90% by immediate incorporation after application (Webb et al. 2010). In addition to leaching, N may be lost through volatilization, when anaerobic bacteria reduce NO₃⁻-N to nitrous oxide (N₂O). Anaerobic conditions due to high soil moisture combined with available NO₃⁻-N may lead to losses of N in the form of N₂O over 10 kg of N/ha/a (Regina et al. 2013, Sheehy et al. 2013), even though the average N₂O-N emission from agricultural soils in Finland is less than 3 kg/ha (Regina et al. 2013). In the cropping of annual plants in boreal conditions, N₂O emissions were increased due to the long winter without vegetation covering the soil. Mild temperatures during winter months may increase these emissions further (Regina et al. 2013). On the other hand, N losses of surface application of manures and fertilizers may also be increased by surface runoff in compacted soils (Turtola and Kemppainen 1998).

Due to the concerns over degradation of aquatic environments and its possible impact on biodiversity as well as economy, measures against nutrient flow from agricultural environments have been made in Finland and in the rest of the European Union. These actions include setting limits to amounts of N and P applied through inorganic and organic fertilizers, as well as to the time of their application (European Commission 2013). For example, the net N balance calculated from N inputs, N in harvested yield and ammonia volatilization in Finland showed a decrease of 44% from 1990 to 2005 due to restricted use of N fertilizers (Salo et al. 2007). However, in addition to limiting N and P inputs to agricultural systems, another approach to alleviate eutrophication is to reduce the flow of nutrients from agricultural systems into watercourses. European Commission’s Codes of Good Agricultural Practice (European Commission 1991) encourage maintaining the soil covered with green vegetation during rainy periods, when NO₃⁻-N is likely to leach. Green vegetation actively takes up NO₃⁻-N from the soil and thus acts as catch crop.
Catch cropping involves the use of soil nutrient scavenging plant species between actual crops. Catch crops scavenge N from soil and fix it into their biomass (Dinnes et al. 2002). When fixed to living plant tissue, N is not prone to leaching. Catch crops are occasionally associated with cover crops, which can indeed function as catch crops as well. However, the term “cover crop”, refers mostly to crop covering soil and reducing water and wind erosion (Dabney 1998).

As N fertilizer production and transportation prices are highly dependent on energy cost, using commercial fertilizers has become more expensive to farmers in the 21st century (Huang 2009). Catch crops may improve the sustainability and economy of crop production, since the scavenged nutrients can be made available for the next main crop by incorporating the catch crop into soil in the following spring (Thorup-Kristensen and Nielsen 1998), and the amount of external N inputs can be correspondingly decreased. Catch crops are highly suitable in reducing $\text{NO}_3^-$-N leaching in production systems that rely on organic fertilizers, as organic matter mineralizes also at times when no yield producing crop is present in the field (Kirchmann and Bergström 2001). Species with a large root system can ameliorate soil structure by the formation of macropores and by stabilizing soil. Higher aggregate stability may reduce the leaching of soil-derived N (Nissen and Wander 2003), but aggregate stability is often associated with increased amount of macropores which increases the leaching of fertilizer N (Di and Cameron 2002, Nissen and Wander 2003). Species that have been studied for their catch crop properties include, for example, small grain cereals and legumes (Kaspar et al., 2012, Francis, 1998, Eichler et al., 2004), ryegrass (*Lolium perenne* L. and *Lolium multiflorum* Lam.) (Thomsen, 2005, Francis 1998, Lemola et al. 2000), and several crucifers, such as fodder radish (*Raphanus sativus* L. var. *oleiformis*), oilseed rape [*Brassica napus* L. ssp. *oleifera* (Moench.) ] and mustard (*Sinapis alba* L.) (Henriksen et al., 2007, Dean and Weil, 2009.).

There are differences between plant genera and species in their efficacy as a catch crop. The most suitable species for catch cropping tend to be fast growing with large root systems (Lainé et al. 1993). Rooting depth is more important than root frequency (Thorup-Kristenssenn 2001) in terms of $\text{NO}_3^-$-N depletion, as $\text{NO}_3^-$-N leaches rapidly to deeper soil layers due to precipitation in autumn and snow melt in spring. Leguminous species that have been used as catch crops tend to have lesser potential to scavenge soil N than cereals or crucifers (Dabney et al. 2001), due to slow root growth. Grasses and crucifers are known to be efficient catch crops, which can reduce the amount of soil mineral N. Henriksen et al. (2007) reported that both ryegrass and crucifer mixture catch crops depleted soil inorganic N in
autumn, when compared to undisturbed soil. According to Eichler et al. (2004), among nine different catch crops (oil radish, yellow mustard, buckwheat \(Fagopyrum\ esculentum\) Moench), phacelia \(Phacelia\ tanacetifolia\) Benth., Westerwold ryegrass \(Lolium\ multiflorum\) Lam. var. westerwoldicum Wittm.), serradella \(Ornithopus\ sativus\) Brot., pea \(Pisum\ sativum\) L., lupin \(Lupinus\ luteus\) L.) and raphanobrassica \(Raphanus\ sativus\) \(L.\times\) \(Brassica\ oleracea\) L.), oil radish and raphanobrassica had highest uptake of mineral N from soil. Dean and Weil (2009) found that rye, oilseed rape and radish all depleted soil N in Northeast US. By decreasing soil mineral N, catch crops also reduce N leaching. Thomsen (2005) stated that overwintering ryegrass could reduce \(NO_3^-\)N leaching up to 76 % under Danish conditions. Similarly, under Finnish conditions, Lemola et al. (2000) reported a reduction of 27 – 52% in N leaching when Italian ryegrass was used as an undersown catch crop. Other grasseous species seem to work as well since Kaspar et al. (2012) observed a reduction of 48 % in drainage \(NO_3^-\)-N content, when rye \(Secale\ cereale\) L.) was used as a catch crop. However, whether the catch crop overwinters or not affects the N status of the soils in spring. If the catch crops die during winter, the N is released from dead plant tissues early in spring (Dean and Weil 2009, Henriksen et al. 2007). Van Schöll et al. (1997) found out that 20% of N in soil incorporated plant material is mineralized in ten weeks at temperature as low as 1°C and Magid et al. (2001) stated that 25 – 40% of N in incorporated plant tissues is mineralized in 35 days at 3°C. N mineralized from dead catch crop tissue may be lost before even an early sown spring crop can utilize it (Dean and Weil 2009). Even though some leaves of a winter-hardy crop may also die during winter, the plant may take up some of the N released from leaves in the spring (Dejoux et al. 2000). Therefore, under climate with sub-zero winter temperatures, a winter hardy catch crop would probably inhibit \(NO_3^-\)-N leaching most efficiently.
1.5 Aims of the present study

This study was conducted to investigate whether undersowing with a spring cereal is an eligible establishing method for winter turnip rape and what effect does the establishing method have to the yield of winter turnip rape and the cereals. This was done in order to find an alternative to the present practice of sowing winter turnip rape as pure stands in July, which has proven to be problematic due to the lack of available farmland in July. Additionally, the effect of winter turnip rape leaf harvest to winter turnip rape yield and the nutritional values of leaf forage were investigated to see if winter turnip rape can provide an additional forage supply to production animals. Furthermore, N uptake by differently established winter turnip rape stands was examined to find out if winter turnip rape is an effective catch crop. These results together with the relevant literature are discussed with reference to the view that complications of winter turnip rape production could be improved by adjustments of agronomic practices and that additional benefits can be acquired in the form of a domestic forage supply and saving N from leaching.

The main working hypotheses were:

1. Undersowing does not affect winter turnip rape overwintering or yield, nor is cereal yield decreased by undersown winter turnip rape.

2. Winter turnip rape leaf forage can be harvested without affecting overwintering or seed yield. Nutritional value of the forage is suitable for domestic animals and the amounts of harmful substances are within acceptable limits.

3. Winter turnip rape decreases soil mineral N content throughout the year.
2 MATERIALS AND METHODS

The experimental part of the work is described here as a general outline. It is presented more thoroughly in the original publications (I–III).

2.1 Plant material and experimental site

Field experiments were carried out at the Experimental Farm, University of Helsinki, Finland (60°13’ N, 25°01’ E, 8 m above sea level) between 2008 and 2011. For 2009 – 2011 cultivation method experiments (I, III), the preceding crop was grass ley, whereas the preceding crop in 2008 – 2009 cultivation method experiment (III) as well as in catch crop (II) experiments was barley. In all cases, the soil was ploughed in the previous autumn and harrowed before spring sowing. Soils were of silty clay with slightly acidic pH values and a high C content and belonged to Luvic Gleysols or Luvic Stagnosols in the WRB system (FAO 2006).

The plant material in all experiments consisted of commercial cultivars available in Finland. Winter turnip rape cultivar used in all experiments was ‘Largo’. The six-row barley used in all experiments was ‘Vilde’. In the cultivation method experiments, the two-row barley cultivars was ‘Xanadu’, the wheat cultivar was ‘Zebra’ and the oat cultivar was ‘Marika’. Cultivar properties are given in table 1.

The weather varied between years in 2008 – 2011. April and May in all years were warmer than long term average. June and July in all years were very close to long term average temperatures, with the exception of July 2010, which was considerably warmer than long term average. August and September had temperatures near long term average in 2008 and 2009, but in 2010 both months were slightly warmer than long term average. In 2008, exceptionally dry May was followed by a wet June and a dry July. Precipitation in June and July 2009 was considerably higher than long term average, followed by a rather dry August and September. In 2010 precipitation was close to average with the exception of a rather dry October. The snow cover in 2009/10 and 2010/11 was exceptionally deep, but the difference between years was that in 2010/11, permanent snow fell to unfrozen ground keeping the soil unfrozen during winter months.
Table 1. Properties of the cultivars used in the experiments in 2008-2011. Values are estimated variety means.

<table>
<thead>
<tr>
<th>Plant species</th>
<th>Cultivar (Breeding company)</th>
<th>Yield, kg/ha</th>
<th>1000 seed weight, g</th>
<th>Oil content, %</th>
<th>Protein content, %</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter turnip rape</td>
<td>Largo (SW Seed, SWE)</td>
<td>1318</td>
<td>2.6</td>
<td>43.9</td>
<td>22.7</td>
<td>Kangas et al. 2006</td>
</tr>
<tr>
<td>Six-row barley</td>
<td>Vilde (Graminor AS, NOR)</td>
<td>5470</td>
<td>42.0</td>
<td>64.1</td>
<td>12.3</td>
<td>Laine et al. 2014</td>
</tr>
<tr>
<td>Two-row barley</td>
<td>Xanadu (Nordsaat Saatzucht GmbH, GER)</td>
<td>5292</td>
<td>47.8</td>
<td>67.1</td>
<td>12.3</td>
<td>Laine et al. 2014</td>
</tr>
<tr>
<td>Wheat</td>
<td>Zebra (SW Seed, SWE)</td>
<td>5261</td>
<td>39.9</td>
<td>79.6</td>
<td>12.7</td>
<td>Laine et al. 2014</td>
</tr>
<tr>
<td>Oat</td>
<td>Marika (Graminor AS, NOR)</td>
<td>5716</td>
<td>39.3</td>
<td>55.1</td>
<td>13.1</td>
<td>Laine et al. 2014</td>
</tr>
</tbody>
</table>
2.2 Experimental design

2.2.1 Cultivation method experiments (I and III)

The cultivation method experiments were conducted in a split plot design with four replicates. Combinations of plant species and densities (Table 2) were the main plots and autumn forage cuts as sub plots. Plots were sown 13 May 2008, 5 May 2009 and 15 May 2010 with additional winter turnip rape pure stand plots sown on 31 July 2008, 30 July 2009 and 31 July 2010. Fertilizer (80 N kg/ha) was applied at the time of sowing and also after winter turnip rape overwintering (80 N kg/ha). Sowing was done with a Wintersteiger TC2700 plot seed drill (Wintersteiger AG, Ried, Austria). Cereals and fertilizer was sown with the first pass to the depth of 50 mm and winter turnip rape was sown with the second pass to the depth of 20 mm. After the sowing, the plots were rolled with a Cambridge roller. Seeds of cereals were top dressed against fungal diseases and the seed of winter turnip rape against insect pests. Cereal diseases and insect pests were controlled chemically during the first growing season. Winter turnip rape weeds were controlled chemically after overwintering and insect pests were controlled chemically during winter turnip rape flowering.

2.2.2 Catch crop experiments (II)

The catch crop experiments were conducted as a randomized complete block design with four replicates. The four different treatments are given in table 2. Plots were sown on 13 May 2009 and 25 May 2010 and winter turnip rape pure stand plots 24 July 2009 and 23 July 2010 with a plot seed drill similarly to cultivation method experiments. Fertilizer (80 N kg/ha) was applied only simultaneously with sowing in May and the plots were rolled afterwards. Barley seeds were top dressed against fungal diseases and the seed of winter turnip rape against insect pests. Diseases, pests and weeds were controlled chemically similarly to cultivation method experiments.
2.3 Sampling and measurements

2.3.1 Plant growth and yield

Cereals and winter turnip rape were harvested with a plot combine at maturity (I, II, III). Seed yield and thousand seed weight of cereals and winter turnip rape were measured (I, II, III). Cereal test weight was determined with a grain analysis computer (Dickey-John GAC 2000, Dickey-John Corp., Illinois, USA) and cereal grain protein content (II, III), and barley fibre and starch content (II) as well as winter turnip rape oil and protein content (I) were determined with a near infra-red analyzer (Perten DA 7200, Perten Instruments AB, Segeltorp, Sweden).

One-third of the winter turnip rape plots in cultivation method experiments were cut to simulate forage harvest in autumn 2009 and 2010 and three treatments (double density winter turnip rape monocrop sown in May, double density winter turnip rape mixed crop with oat and normal density winter turnip rape sown in July) were chosen for forage analysis (I). Forage primary dry matter and ash content were determined. N and carbon (C) content were analyzed with a dry combustion method and protein content was derived from N content by multiplying it with 6.25 (Jones 1941). Organic matter digestibility analysis was performed according to Jaakkola et al. (2009) and neutral detergent fibre analysis according to Van Soest et al. (1991) (I).

Cereal stand density in cultivation method experiments (III) was determined after cereal establishment at growth stage 13 (Zadoks 1974) and head density was determined at growth stage 89 in 2009 and 2010. Cereal harvest samples were collected randomly from each plot at maturity and plant weight, seed number, seed weight, and number of heads per plant was measured in 2009 (III). Harvest index was calculated from the weight of plants and seeds. In 2010 measurements from cereal flag leaves (n = 10) were taken with a SPAD (Single Photon Avalanche Diode) meter (SPAD-502, Minolta Ltd., Osaka, Japan) at growth stage 55 (III).

Winter turnip rape stand densities were determined three times in the first growing season and after overwintering (I). Five winter turnip rape plants per plot were collected in autumn 2009 and 2010 before permanent snow and the plants were fractioned and dried (I). Winter turnip rape harvest samples were collected at maturity and number of branches per plant, weight of seed per plant and dry weight per plant were determined. Winter turnip rape harvest index was calculated from the weight of plants and weight of seeds (I).
Table 2. Treatments, sowing densities, species, and measurements in the original papers.

<table>
<thead>
<tr>
<th>Paper</th>
<th>Stand types</th>
<th>Species</th>
<th>Measurements</th>
</tr>
</thead>
</table>
| I     | Winter turnip rape pure stands (150 seeds/m²) sown in July  
Winter turnip rape pure stands (300 seeds/m²) sown in May and July  
Mixed stands of winter turnip rape (150 seeds/m²) and cereal (-20% of normal density)  
Mixed stands of winter turnip rape (300 seeds/m²) and cereal (normal density) | Winter turnip rape  
Two-row barley  
Six-row barley | Winter turnip rape seed yield  
Oil and protein content |
| II    | Winter turnip rape mixed stands (150 seeds/m²) with six-row barley (500 seeds/m²)  
Winter turnip rape (150 seeds/m²) sown after barley (500 seeds/m²) harvest  
Barley (500 seeds/m²), left to stubble after harvest  
Barley (500 seeds/m²), ploughed after harvest | Winter turnip rape  
Six-row barley | Topsoil and subsoil  
NO−3 and NH4+ content |
| III   | Cereal pure stands normal density  
Mixed stands of winter turnip rape (150 seeds/m²) and cereal (-20% of normal density)  
Mixed stands of winter turnip rape (300 seeds/m²) and cereal (normal density) | Winter turnip rape  
Two-row barley  
Six-row barley | Cereal biomass  
Seed weight and number  
Number of spikes |
<table>
<thead>
<tr>
<th></th>
<th>Oat</th>
<th>Wheat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain yield</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test weight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000 grain weight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grain protein content</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPAD values</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cereal densities</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leaf area index</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* a = Normal sowing density for two-row barley and wheat was 600 viable seeds/m² and for six-row barley and oat 500 viable seeds/m²
Leaf area index (LAI) was measured from stands with canopy analysis equipment (SunScan SS1 with a BF3 sunshine sensor, Delta-T Devices Ltd., Cambridge, UK) three times in each growing season. Land equivalent ratio (LER) for mixed stands of cereal and winter turnip rape was calculated based on the yields of the cereal and winter turnip rape.

2.3.2 Catch crop soil samples

Soil samples were collected to study soil $NH_4^+$-N and $NO_3^-$-N content under different crops and cultivating methods. Topsoil samples were gathered from each block in 2009 and 2010 and subsoil samples in 2010 before sowing in order to determine pre-sowing soil nutrient status (II). From both experiments, three sets of soil samples were gathered from topsoil (0 – 20 cm) and subsoil (30 – 50 cm) in August, after barley harvest in October, before soil froze and in the April of the following spring. Sample size was 0.5 liters and the samples were stored at -20 °C before analysis. Soil samples were analysed at Suomen Ympäristöpalvelu Oy, Oulu, Finland according to SFS-EN ISO 13395 and SFS-EN ISO 11732 standards.

$NH_4^+$-N and $NO_3^-$-N were extracted from soil samples with 2M KCl for 1h with extraction ratio of 1:5. Soil nitrogen species ($NH_4^+$-N, $NO_3^-$-N and the total amount of $NO_3^-$-N and $NO_2$-N) were determined spectrophotometrically from extracts with automated flow injection analyzer (FOSS-TECATOR FiaStar5000, Hillerød, Denmark).

2.4 Statistics

Data was subjected to analysis of variance using PASW 18 (IBM, Armonk, New York, USA) (I, II, IV). Post hoc analysis was reformed with Sidak method (I), Tukey’s test (II) or with LSD test (III). For correlations (II), Pearson’s correlation coefficient was used.
3. RESULTS AND DISCUSSION

3.1 Growth in mixed stands

3.1.1 Winter turnip rape

Germination in double density (300 seeds/m²) winter turnip rape stands was lower than in normal density (1500 seeds/m²) stands (I). Thus, it is possible that winter turnip rape seedlings or germinating seeds inhibited the establishment of the rest of the seeds, similarly to oilseed rape as observed by Moore and Guy (1997) and Yasumoto et al. (2011). Also Scarisbrick et al. (1982) observed a reduction in establishment percentage in higher sowing densities, but reasons for the phenomenon were not discussed. Due to the self-inhibition or intra-species competition of winter turnip rape, extremely high sowing densities, such as 300 plants/m² (I), should be avoided (I). Also, if winter turnip rape is similar to winter oilseed rape in this aspect, higher seeding rate combined to early sowing may lead to yield reduction (Boelcke et al. 1991) as well as increased seed cost (Scarisbrick et al. 1982). However, some of the pronounced thinning after establishment in both 2009 and 2010 growing seasons could be attributed to inter-species competition, which undoubtedly was more intense in mixed stands with normal cereal density and high winter turnip rape density than in other stand types due to higher total plant stand density (Silvertown 1982). Further thinning occurred during the winter months in both years. Severe reductions in stand density were observed after winter 2010/11 (I), possibly due to inadequate cold hardening (Kacperska and Szaniawski 1993) or plant respiration under snow cover (Jamalainen 1978, Waalen 2014), as the soil did not freeze before permanent snow. Increased respiration under snow cover reduces carbohydrate reserves, and thus decreases winter hardiness (Waalen 2014). However, in both springs 2010 and 2011, the observed winter turnip rape densities in most cases were above 30 plants/m², which is considered to be the threshold for successful overwintering of a winter oilseed (Mendham et al. 1981). Highest densities after overwintering were in the double density plots, but in 2010 the yields were similar between different plant stand types (I), indicating that stands with low plant density compensated their yield, similarly to winter oilseed rape (Mendham et al. 1981, Leach et al. 1999, Lääniste et al. 2008) or spring turnip rape (McGregor 1987). On the other hand, high density stands probably had fewer silique and therefore fewer seeds per plant as shown with oilseed rape by Scarisbrick et al. (1982). These factors most likely resulted in the uniform yields across the different stand types in 2010 (I).
The winter turnip rape pure stand sown at normal time in July to normal density had higher root, hypocotyl and leaf biomass before overwintering than most other stand types. The only exception was the high density monocrop sown in May in 2009 (I). However, the higher biomass of winter turnip rape pure stands did not yield better in the following year (2010). In the autumn 2010, no differences in the biomass of plant parts between different plant stand types we observed. However, the plants had gathered more biomass before winter than in 2009, possibly due to more favorable weather conditions during summer (I).

3.1.2. Leaf area index of cereal-winter turnip rape stands

The LAI was affected by stand type and the differences were evident at all measurement points in 2009 and at the first measurement point in 2010 (III). Highest values were measured generally in dense mixed stands and on some occasions, also the sparse mixed stands had higher LAI values than pure stands. The LAI values and land equivalent ratio LER did not correlate, indicating that LAI cannot be used to predict the outcome of mixed stands when the component species mature at significantly different times. The mixed stands having generally higher LAI values than pure stands in 2009 indicates that the plant stands did not suffer from resource limitation, such as lack of nutrients or water. However, in 2010, the LAI values were similar across different plant stand types and leaf area growth was limited due to lack of resources, most likely moisture as June and July 2010 were drier than long-term average. The increase in LAI almost ceased between the June and mid-July measurements (III). The LAI values were generally lower in 2010 than in 2009, probably due to limited moisture. In 2009, the LAI values in mixed stands were considerably high, as mean LAI for all field crops is 3.6 (Asner et al. 2003) and optimum LAI for mixed stands is 5 (Kasanaga and Monsi (1954). Therefore it is possible, that the net assimilation rate in the plant canopy was restricted by the cereal shading winter turnip rape. However, as winter turnip rape has a horizontal growth habit during vegetative phase similarly to sugar beet (Beta vulgaris L. ssp vulgaris var. altissima Döll), the radiation is likely to be distributed evenly to leaf surfaces, and used efficiently. Therefore, as neither the yield of cereals nor the yield of winter turnip rape was decreased by mixed cropping, the high LAI’s did not decrease stand production (III).
3.2 Yield

3.2.1 Growth and grain yield of cereals with undersown winter turnip rape

Cereal yields were affected by the year with highest yields in 2008 and lowest in 2010 (III). In 2008 the yields of most of the cereals did not vary between stand types. An exception was oat mixed stand with normal density winter turnip rape that had 29% or approximately 2000 kg higher yield than oat pure stand. Likewise in 2009, six-row barley sown with high density winter turnip rape yielded 50% or approximately 2400 kg more than six-row barley pure stand (III). In catch crop experiments, no differences in six-row barley yield were detected between treatments (II). However, pure stands of other cereals yielded higher than mixed stands with low cereal sowing density. In 2010, no differences in yield were detected between stand types. The yields of cereals in high density mixed stands not being lower indicates, that winter turnip rape does decrease cereal yields. This is in contrast to cases with full intercropping arrangements where similarly to current work, cereals experienced competition throughout the growing season and as a result cereal yield decreased (Känkänen and Eriksson 2007, Karlsson-Strese et al. 1998). On the other hand, some barley cultivars have low competitive ability against weeds, which allows the weeds to develop substantially higher biomass than when grown with high competitive ability barley cultivars (Didon and Hansson 2002). Despite of their low competitive ability, some barley cultivars are still able to produce high grain yields in the presence of weeds (Didon and Hansson 2002). Therefore, cereal cultivar properties may allow the establishment of other species without the cereal experiencing significant yield losses. Lower yields in 2009 in low sowing density mixed stands may well be a result of the cereal sowing density itself. Higher yields of oat and six-row barley in mixed stands indicate a facilitating effect of winter turnip rape (III). Beneficial effects of crucifers on cereals are rare in literature, but have been reported by Merker et al. (2010), Varma and Taneja (1980) and Bellostas et al. (2003). Merker et al. (2010) reported a 5% or approximately 260 kg increase in barley average yield over three years, when field cress [Lepidium campestre (L) W.T. Aiton] was grown in relay intercropping with barley. Varma and Taneja (1980) reported a 42% or 1100 kg/ha increase in barley seed yield when grown as a full intercrop with Indian mustard. Based on the current findings and the previous reports, it is likely that in some cases undersown crucifer increases the yield of certain cereals hundreds of kg/ha or more. However, as the effect may not be constant or it is difficult to detect, recommendations regarding undersowing of winter turnip rape in order to increase cereal yields cannot
be made at this stage. Other non-legumes inducing a positive influence to barley yield in mixed cropping include chicory (*Chicorium intybus* L.) and cocksfoot (*Dactylis glomerata* L.) (Karlsson-Strese 1998). Hauggaard-Nielsen et al. (2001) and Hauggaard-Nielsen and Jensen (2005) suggested that intercrop root competition in topsoil may force the roots of the species to explore soil profile extensively and deeper than in pure stands. This may be the case in winter turnip rape-oat/six-row barley mixed cropping. Oat or six-row barley with its fast initial root growth (Whitely and Dexter 1982) utilizes the nutrients of applied fertilizers efficiently early in the growing season. As crucifer root growth rates increase in later growth stages (Thorup-Kristensen 2001), winter turnip rape possibly causes a nutrient depletion in upper soil layers forcing the cereal roots to grow downwards to deeper soil layers and hence, accesses more nutrients and water. Andersen et al. (2014) also found that growing red beet in mixtures increased the production of roots, which also leads to greater volume of soil being explored by roots. The subsoils in the area are known to be relatively rich in mineral N (Šimek et al. 2011), but whether this applies to current experiments (III) is not known. On the other hand, crucifers are known to excrete organic acids or acid phosphatase from their roots to soil increase the solubility of phosphate (Hoffland et al. 1989, Tadano and Sakai 1991, Zhang et al. 1997). It is possible, that increased phosphate availability due to crucifer root exudates in soil under mixed stands of winter turnip rape and cereal may have affected the cereal as well. Alternatively, the presence of winter turnip rape root exudates may have altered the soil microflora and the proportions of plant growth enhancing rhizobacteria as it is well known that plant species have a significant effect to the composition of rhizobacterial communities in soil (Micallef et al. 2009). An attempt to confirm a complementary effect of a crucifer to a cereal would therefore require at least the sampling and analysis of subsoil for mineral N and plant available P as well as their movement to plants, recording the changes in soil pH, measurement of rooting depth, number of roots of both species and the screening of soil microflora.

The reason for other cereals not benefitting from undersown winter turnip rape is not clear (III). However, barley root systems vary between cultivars (Wahbi and Gregory 1989, Hockett, 1986), and the two-row barley cultivar used in the experiments has a longer growing time than the six-row cultivar (Laine et al. 2014). These differences may explain why six-row barley benefitted from undersown winter turnip rape whereas the two-row cultivar did not. Additionally, barley cultivars that produce many tillers are more affected by competition than low tillering cultivars, such as the six-row cultivar (III). These factors may explain the better performance of six-
row barley cultivar when compared to two-row cultivar. The wheat low density mixed stands producing less yield than pure stands in 2009 may be explained not only by the low sowing density itself, but also by the fact that several crucifers, such as Indian mustard, toria (Brassica rapa L. ssp. dichotoma (Roxb.) Hanelt) and oilseed rape are known to decrease wheat yield when undersown (Wang et al. 2007, Singh et al. 1991, Subedi 1997). The competition between crucifer and cereal in the work of Wang et al. (2007), Singh et al. (1991), Subedi (1997) is, however, quite intensive as both crops reproduce almost simultaneously in a full intercropping arrangement. By altering cereal and winter turnip rape sowing densities and amount of N fertilizer input, the outcome of mixed stands could possibly be improved. Increasing N inputs could increase the yield of cereal in a mixed stand (Charles 1962), but on the other hand could also lead to the suppression of the other crop (Andersen et al. 2005). Also, as demonstrated by Jokinen (1991) in barley variety mixtures yield advantage of mixtures seen at lower sowing densities and N input levels is lost when sowing density and N input levels are increased. This is due to the increased dominance of certain barley varieties sown in high densities under conditions of abundant N supply.

Cereal flag leaf SPAD values in 2010 did not differ significantly between stand types in any of the cereals (III), and were above the threshold value indicating N deficiency (Peltonen et al. 1995). Likewise, only wheat protein content was slightly affected by winter turnip rape (III). This indicates that winter turnip rape has a negligible effect to cereal N nutrition and a weak competitive effect to cereals. With a moderate fertilization level, an undersown crop with low competitive ability does not affect cereal protein content (Charles 1962). Furthermore, the idea of winter turnip rape being a weak competitor to a cereal is supported by the weight of cereal plants and seeds, number of seeds as well as number of spikes and panicles not being affected by undersown winter turnip rape (III).

### 3.2.2 Seed yield of winter turnip rape

Winter turnip rape seed yield and its quality in 2010 did not differ between plant stand types (I). Thus, winter turnip rape can be established as a mixed crop with cereals, as long as overwintering conditions remain favorable. As the undersown winter turnip rape is basically relay intercropped, it grows majority of its life cycle in conditions free of competition from cereal and this seems to be adequate for the production of a normal seed yield. However, in 2011, the winter turnip rape stand sown to double density in
July outyielded the other stand types. This can be interpreted so that under less favorable overwintering conditions, sowing at the normal time in July seems to be most reliable establishing method for winter turnip rape (I). The yield reduction in 2011 compared to 2010 can be attributed mostly to the poor overwintering of the plant stands. Winter turnip rape plants had more biomass in autumn 2010 than in autumn 2009, but the yield was poor in 2011 (I). It is likely, that the overwintering conditions have a more important role in the yield formation than plant size in autumn has. Even though the seed yield did not differ between plant stand types in 2010, there were differences in the number of seeds per plant, which provides further evidence of the crop compensating the yield in sparse stands. However, in the experiments the winter turnip rape pure stands were sown in July after a fallow period (I). The soil being as a fallow and not cropped may have affected the growth of winter turnip rape pure stands before overwintering through better N availability in soil as preceding crops are known to deplete mineral N from deeper soil layers, which affects the growth of succeeding crops (Thorup-Kristensen 1993). As the cereal seed yield and straw were removed from the plots, there was also a considerably small amount of organic material from which N could have mineralized for the use of remaining winter turnip rape. These factors may have also contributed to the lower seed yields of winter turnip rape stands established by undersowing in 2011.

The oil content of winter turnip rape seeds correlated negatively to protein content in both 2010 and 2011 (I). This phenomenon is well documented with oilseed rape (Zhao et al. 1993, Brennan et al. 2000, Rathke et al. 2005, Gunasekera et al. 2006), in which the increase in protein content to the detriment of oil content is usually a result of spring N application and moisture stress during flowering. Increasing N application tends to increase the protein content (Brennan et al. 2000) and low rainfall and high temperatures after anthesis decrease oil content (Gunasekera et al. 2006).

### 3.2.3 Forage yield of winter turnip rape

Forage yields of winter turnip rape were in the range of 1000 – 3000 kg of dry matter/ha (I). The forage yield was highest in the monocrop sown to normal density in July, probably because it did not experience competition from cereals. Additionally, early sowing of forage crucifers does not improve forage yield (Harper and Compton 1980), which explains why the forage yield of early sown winter turnip rape did not exceed the yield of the one sown in July (I). The forage yield of high density monocrops was also
lower than forage yield of the normal density monocrop. In the catch crop experiment in 2009, the leaf biomass of undersown winter turnip rape was 1756 kg/ha and the one sown after barley harvest 1076 kg/ha, but the differences were not significant (I).

The two monocrop forages differed in their composition from oat-winter turnip rape mixed stand forage (I). The monocrop forages had approximately 30% higher D-value, at least 45% higher crude protein and about 60% higher crude fat content than the forage from mixed crop stand (I). On the other hand, the monocrop forages had at least 22% lower dry matter content, at least 60% lower NDF-value and at least 55% lower crude fibre content than the mixed stand forage (I). The differences between stand types can be attributed to the oat stubble that was included to the mixed stand samples. The high protein content and low crude fibre content of winter turnip rape forages may lead to poor utilization of protein (Thomas et al. 1980, Bowman et al. 1991, Rinne et al. 1997). Additionally, such composition of forage increases the risk of frothy bloat of ruminants (Cole et al. 1945, Wang et al. 2012). Thus, winter turnip rape monocrop forage should be used as a protein supplement and fed mixed with forages of high fibre content. The glucosinolate content of the ‘Largo’ winter turnip rape leaves, was 3 – 20 μmol/g DM (I), which is comparable with other forage Brassicas (Barry 2013). Therefore, the winter turnip rape forage seems to be suitable for ruminant nutrition. However, as glucosinolate decomposition products are harmful to ruminants, ensiling could be used in order to reduce the amount of glucosinolates in crucifer forage (Fales et al. 1987, Vipond et al. 1998). Ensiling can reduce the amount of glucosinolates approximately 90% (Fales 1987), and the reduction is assumed to be caused by breakdown of glucose and sulphur containing structures of the compounds by microbial enzymes. Additionally, the high moisture and temperature in ensiled forage may promote the autolysis of glucosinolates (EFSA 2008).

Cutting the leaves of double density winter turnip rape stands for forage resulted in sparser stands after overwintering (I). This was most evident in double density winter turnip rape monocrop stands. Even though the density in mixed stands sown to normal winter turnip rape density was not affected by forage cuts, the yield was affected in almost every stand type. The severe yield reductions in stands with forage cuts (2010, 20%; 2011, 62%) correspond to work by Kirkegaard et al. (2008), Bonachela et al. (1995) and Francia et al. (2006), who concluded that cutting leaves for forage reduces seed yield in oilseed rape and cereals. In addition to cutting of the leaves, leaf removal may have contributed to the poor performance of the cut stands, as the N in winter killed leaves contain could have been
scavenged and exploited by the crop in spring, if similar to oilseed rape in this aspect (Dejoux et al. 2000). However, the forage cuts were taken very late in autumn in both 2009 and 2010 (I). An earlier forage harvest might improve the overwintering of the cut stands (Kirkegaard et al. 2008), to the detriment of forage yield.

3.3. Soil N uptake by winter turnip rape

Soil $NO_3^-$-N and $NH_4^+$-N amounts did not differ between treatments in either of the soil layers (0 – 20 cm, 30 – 50 cm) or years (2009, 2010) after barley harvest (II). However, before the onset of winter, differences between treatments in topsoil and subsoil $NO_3^-$-N content were evident in both years (II). In 2009, both topsoil and subsoil $NO_3^-$-N was more abundant in the ploughed plots than in the other treatments, indicating that ploughing increased N mineralization. This is consistent with the findings of Arnott and Clement (1966) and Powlson (1980), who observed an increase in N mineralization after tillage. Ploughed barley plots being distinguishable from the other treatments is likely the result of the high mineralization potential of the soil, as it contained high amounts of organic matter, which reflected also to the high C content of the soil: 3.8 – 5.3% in topsoil and 2.2 – 3.3% in subsoil. These findings were similar to Šimek et al. (2011), who found total C content of over 4% in the plough layer and about 2% or more in the subsoil of fields located in proximity of current experimental site. In 2010, the soil $NO_3^-$-N results were similar to 2009 in topsoil, with the exception of barley left to stubble not differing from ploughed plots in the amount of $NO_3^-$-N (II). However, as a result of winter turnip rapes $NO_3^-$-N uptake, the plots with winter turnip rape sown simultaneously with barley had less $NO_3^-$-N in subsoil than both barley stands, the ploughed and the one left to stubble. There was over 50% less $NO_3^-$-N in topsoil and 60 – 80% less $NO_3^-$-N in undersown winter turnip rape compared to ploughed barley plots. Differences in soil $NO_3^-$-N content correspond to the amount of N in winter turnip rape biomass, which in the undersown crop was over 70 kg of n/ha. Differences being more evident in 2010 than in 2009 is a consequence of initially higher $NO_3^-$-N content of soil in 2010, due to more favorable conditions for mineralization in 2010. In 2009, the rainy summer months promoted waterlogging, which likely led to denitrification and inhibition of nitrification (Mikkelsen 1987). The summer months of 2010 were close to long term average in terms of precipitation leading to higher mineralization rates. The undersown winter turnip rape being more efficient in depleting subsoil $NO_3^-$-N indicates that early sowing of a catch crop is more advantageous than late sowing (II), similarly to findings of
Francis et al. (1998). Crucifers are also known to grow their lateral roots mostly to the depth of 50 cm and below (Thorup-Kristensen 2001). Therefore it is likely that undersown winter turnip rape had more roots in the subsoil than the late sown crop, even though this cannot be confirmed as the lateral roots were not sampled (II).

The amount of $NH_4^+$-N was not reduced in soil by winter turnip rape (II), corresponding to Dean and Weil (2009), who concluded that crucifers do not decrease soil $NH_4^+$-N. On the other hand, $NO_3^-$ is more mobile in soil than $NH_4^+$ and $NH_4^+$ is often held to cation-exchange sites in soil (Robertson and Groffman 2007) making $NO_3^-$ more available to plants than $NH_4^+$. This is of particular importance in agricultural soils, where tillage creates aerobic conditions that favor mineralization of N from soil organic matter. As a result of increased N mineralization and hence increased availability of $NH_4^+$-N, nitrification is accelerated as well, which consequently leads to higher amounts of plant available $NO_3^-$-N in soil (Robertson and Groffman 2007). Amounts of $NO_3^-$-N being higher in spring than in previous autumn in plots with winter turnip rape (II) suggest that N is released from winter turnip rape tissues that died during winter, similarly to oilseed rape (Dejoux et al. 2000) or various grass species (Räty et al. 2010). However, as roots and hypocotyls of the plants remain alive during winter, the plant stores N more efficiently than catch crop species that do not overwinter, such as oat or barley. Additionally, some of the N released from dead tissues may be taken up by the crop in spring, after soil thawing, similarly to oilseed rape (Dejoux et al. 2000). In the spring the measured mineral N species did not differ significantly between the treatments (II), which may indicate, that leaching from soil layers above 50 cm during the spring months compensated the initial differences in soil $NO_3^-$-N content between treatments. As discovered by Thorup-Kristensen (2001), several catch crops, including crucifers, deplete soil $NO_3^-$-N below 100 cm in soil. The current experiments (II) cover soil layers to 50 cm and therefore cannot confirm whether winter turnip rape has effect to leaching also after overwintering.

The plant samples taken in autumn 2009 indicated no significant differences in tissue N content or N uptake per hectare, even though undersown winter turnip rape had gathered 45 kg/ha N and late sown winter turnip rape 27 kg/ha N (II). These amounts are slightly lower than those reported with other crucifers, such as oilseed rape, fodder radish and mustard on other sites that are below 60° latitude (e.g. Francis et al. 1998, Thorup-Kristensen 2001, Dean and Weil 2009), most likely because of the low amounts (less than 30 kg/ha N) of available mineral N in soil in Finland (Sippola and Yläranta 1985).
Nevertheless, the amounts of N in winter turnip rape biomass are comparable with those found with other catch crops in northern Europe. Hansen and Djurhuus (1997) found that perennial ryegrass contained approximately 11 – 38 kg/ha N in its aboveground tissues in late autumn in subsequent years when grown on Danish sandy loam. The average reduction in $NO_3^-$ leaching was 39% (12 kg N/ha/a) when the ryegrass catch crop was used. Similarly, Lemola et al. (2000) reported a reduction of 53% (6.4 kg/ha/a N) in total N leaching from lysimeters when Italian ryegrass was used as a catch crop undersown to barley on a clay soil in Finland. On a sand soil the corresponding reduction was 64% (16.5 kg/ha/a N). The N uptake of Italian ryegrass was approximately 10 – 25 kg/ha/a N, with lesser uptake on fine textured soils. Also, with common ley species including legumes and grasses sown to normal density to various mineral soils in Finland, the N uptake of the crops in late autumn was approximately 21 – 36 kg/ha N with reduction of soil $NO_3^-$-N of up to 60% (Känkänen and Eriksson 2007). These reports show that even moderate crop uptake of N can result in considerable reductions in the amounts of soil mineral N, $NO_3^-$ or leaching in low mineral N conditions. Jaakkola (1984) reported, that in spring barley cropping with moderate fertilization (100 kg/ha N) on a clay soil in Finland, the annual leaching of $NO_3^-$-N varied between 4 and 10 kg/ha N during five subsequent years. However, these amounts are considerably lower than those observed in temperate area cereal and corn cropping on loam and loamy sand soils with generous (200 kg/ha N) N fertilization. Under such conditions $NO_3^-$-N leaching can be 87 – 107 kg/ha N (Shepherd and Lord 1996, Bjorneberg et al. 1996).

The mineral N content of the soil in catch crop experiments before establishment was slightly higher than amounts observed in other sites in southern parts of Finland and Norway in spring (>40 kg/ha N vs. <30 kg/ha N), but similar to some of the sites in Denmark and Sweden on uncropped, unfertilized soil in nearly corresponding soil layers (Table 3). In the end of the growing season, the mineral N amounts in soil of the catch crop experiments with barley and winter turnip rape were somewhat similar to amounts in uncropped, unfertilized soils (Table 3) in the report of Lindén et al. (1992b). The reason for the slightly higher amounts of mineral N in the soil of current experiments is likely the higher soil organic matter content due to repeated manure applications (Edmeades 2003) on the site during several decades, and to the natively high organic matter content both in the topsoil and subsoil of the former sea sediment. Due to the higher soil organic matter content of the experimental site, there was over 20 Mg/ha of total N in soil in the 0 – 50 cm layer, whereas in the soils sampled from
Nordic countries by Lindén et al. (1992a), the total N content in 0 – 40 cm layer ranged 6 – 11 Mg of total N/ha.

This likely indicates, that amounts of N mineralized in the catch crop experiment during the growing season were higher than in soils of Lindén et al. (1992b), as barley and winter turnip rape took up some of the mineralized N. As the results show, within companion crop barley grain yield 110 – 180 kg/ha N was removed from the field (using a 6.25 conversion factor for protein-to-nitrogen, Jones 1941). Even with a 100% fertilizer utilizing rate assumed, the amounts of N in barley grain yield exceed the amount of N given in fertilizer by 32 – 96 kg/ha N. Majority of the mineral N in the soil of the current experiments was in $NO_3^-$-form. This is consistent with the reports of Sippola and Yläranta (1985), where in three out of four Finnish mineral soils, $NO_3^-$ was the dominant form of mineral N, regardless of whether the soil was sampled in autumn or spring. Similarly, according to Esala (1995), in sandy and clay soil $NO_3^-$-N contributed to 90% of mineral N, and only slight increases in the amounts of NH$_4^+$-N were observed after the soil was freezed, thawed and grinded. In all sampling occasions, $NO_3^-$-N amounts were slightly higher in topsoil compared to subsoil (II), which corresponds to the findings of Esala and Leppänen (1998), who concluded that most of the $NO_3^-$-N in soil is retained in the upper soil layers (approximately 0 – 30 cm), even though substantial amounts can also be leached in cool and rainy conditions.

Precipitation in the boreal region in autumn may rise in future due to climate change (Jylhä et al. 2004). Increased moisture combined with the likely climate change induced temperature elevation would create conditions favorable to mineralization and leaching (Guntiñas et al. 2012). Therefore, if the predicted climate change scenarios are realized, catch crops will play a more important role in soil N manipulation in the high latitudes. With higher than present soil mineral N amounts, differences in soil N between catch cropping and tilled bare soil are likely to be more evident.
Table 3. Soil mineral N in the present experiments and various sites in Nordic countries. Approximate values of Šimek et al. 2011 and Lindén et al. 1992 were drawn from figures presented in those publications.

<table>
<thead>
<tr>
<th>Site, country</th>
<th>Soil texture</th>
<th>Soil layer, cm</th>
<th>Time of sampling</th>
<th>Mineral N, kg/ha</th>
<th>In:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helsinki, FIN</td>
<td>silty clay</td>
<td>0 – 20 spring</td>
<td>harvest</td>
<td>27 – 45</td>
<td>Tuulos et al. (II)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 – 50 spring</td>
<td>harvest</td>
<td>21 – 30</td>
<td>Šimek et al. (2011)</td>
</tr>
<tr>
<td></td>
<td>silty clay</td>
<td>28 – 60 autumn</td>
<td>harvest</td>
<td>15 – 22</td>
<td>Šimek et al. (2011)</td>
</tr>
<tr>
<td></td>
<td>loam</td>
<td>0 – 28 autumn</td>
<td>harvest</td>
<td>10 – 27</td>
<td>Šimek et al. (2011)</td>
</tr>
<tr>
<td>Helsinki, FIN</td>
<td>silty clay</td>
<td>0 – 28 autumn</td>
<td>harvest</td>
<td>32</td>
<td>Šimek et al. (2011)</td>
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<tr>
<td></td>
<td>loam</td>
<td>20 – 40 spring</td>
<td>harvest</td>
<td>60</td>
<td>Lindén et al. (1992b)</td>
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<td></td>
<td></td>
<td>0 – 20 spring</td>
<td>harvest</td>
<td>15</td>
<td>Lindén et al. (1992b)</td>
</tr>
<tr>
<td>Peipohja, FIN</td>
<td>sandy loam</td>
<td>0 – 20 spring</td>
<td>harvest</td>
<td>60</td>
<td>Lindén et al. (1992b)</td>
</tr>
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<td></td>
<td>loamy sand</td>
<td>20 – 40 spring</td>
<td>harvest</td>
<td>10</td>
<td>Lindén et al. (1992b)</td>
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<tr>
<td>Jokioinen, FIN</td>
<td>clay</td>
<td>0 – 20 spring</td>
<td>harvest</td>
<td>15</td>
<td>Lindén et al. (1992b)</td>
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<td>20 – 40 spring</td>
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<td>Lindén et al. (1992b)</td>
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<tr>
<td>Ås, NOR</td>
<td>clay loam</td>
<td>0 – 20 spring</td>
<td>harvest</td>
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<td>Lindén et al. (1992b)</td>
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<td>Lindén et al. (1992b)</td>
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<td>Askov, DEN</td>
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<td>harvest</td>
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<td>20 – 40 spring</td>
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<td>Lindén et al. (1992b)</td>
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<td>0 – 20 spring</td>
<td>harvest</td>
<td>10</td>
<td>Lindén et al. (1992b)</td>
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<td>20 – 40 spring</td>
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<td>Lindén et al. (1992b)</td>
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<td>Everöd, SWE</td>
<td>sandy loam</td>
<td>0 – 20 spring</td>
<td>harvest</td>
<td>25</td>
<td>Lindén et al. (1992b)</td>
</tr>
<tr>
<td></td>
<td>sandy loam</td>
<td>20 – 40 spring</td>
<td>harvest</td>
<td>20</td>
<td>Lindén et al. (1992b)</td>
</tr>
</tbody>
</table>
4. CONCLUSIONS

Winter turnip rape can be undersown without affecting the yields of winter turnip rape and cereal which leads to the conclusion that the first working hypothesis is valid. As long as the overwintering conditions are favorable, the undersown winter turnip rape does not experience yield loss. Overwintering conditions seem to be more important to the outcome of winter turnip rape cultivation than establishing method. However, the winter turnip rape that is established as a pure stand at normal sowing time in July is more reliable when overwintering conditions are harsh. Higher than normal seeding rate is recommended for undersown winter turnip rape, but 100% higher sowing rate is likely to be unnecessarily high.

Cutting winter turnip rape leaves for forages increases the risk of seed yield failing. This leads to the partial rejection of the second working hypothesis, which stated that winter turnip rape leaf forage can be harvested without affecting overwintering or seed yield. However, winter turnip rape leaf forage composition makes it suitable as a high-protein supplement, which cannot be used as sole roughage due to its low fibre content and the amounts of harmful glucosinolates in the forage are within acceptable amounts for ruminants. Therefore, as far as nutritional aspects are concerned, the second hypothesis stating that winter turnip rape forage is suitable to domestic animals and the amounts of harmful substances are acceptable is valid. Winter turnip rape that is intended for forage use can be established in May or July, which offers flexibility for establishment.

Winter turnip rape decreases soil $NO_3^{-}$-N content. However, the working hypothesis stating that winter turnip rape decreases soil mineral N content is valid only partially as effects to soil $NO_3^{-}$-N were observed only in autumn and winter turnip rape has only minor effect to the amounts of soil $NH_4^+$-N. This is probably not a shortcoming, as $NH_4^+$ is fixed to clay minerals in soil and therefore it is not prone to leaching. On the other hand, winter turnip rape scavenges soil $NO_3^{-}$-N effectively and creates reductions in subsoil $NO_3^{-}$-N content up to 80% when compared to ploughed soil. This implies that using winter turnip rape as a catch crop is a valid method for reducing nitrate leaching even in the low mineral N environment of boreal high latitudes.

Spring cereal stands sown to normal density are appropriate companion crops for undersown winter turnip rape and reducing cereal sowing density is not necessary. Six-row barley and oat seem to be most suitable for companion crops as both cereals may benefit from undersown winter turnip rape. LAI is not a suitable measure for evaluating the outcome of
mixed stands with species maturing at different times. However, winter turnip rape—cereal mixed stands do not seem to suffer by the notably high LAI’s.

Winter turnip rape may facilitate certain cereals through what seems to be belowground interactions. It would be wise to study these interactions by studying root growth and various other plant and soil properties of winter turnip rape as pure stands or mixed stands with different cereals. Results could bring more information about crucifer-cereal interactions in general.

Establishing winter turnip rape by undersowing to a cereal seems to be a method worthy of exploring on a farm-scale level. As the method is low-cost and easy to apply, potential benefits exceed the risks. At worst, the winter turnip rape crop is lost due to poor overwintering, but adequate cereal yield is obtained and soil N is salvaged from leaching. At best, normal or close to normal yields of cereal and winter turnip rape are obtained with a single sowing operation.
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