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Doctoral Dissertation

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Abstract

The disadvantages associated with invariable cereal cropping, concern about nutrient leaching and the price of nitrogen (N) fertilizer have increasingly become the subjects of discussion during recent decades. An undersown crop, which grows together with a main crop and post-harvest, could address such disadvantages. The aim of this study was to gain knowledge needed to develop undersowing for Finnish conditions in the interests of optimizing cereal production and meeting environmental goals. Studies were made on the effects of undersown species and management practices on biomass and N yield of undersown crops, grain yield of spring cereals and soil nitrate levels.

In total, 17 plant species were undersown in spring cereals during the field experiments carried out between 1991 and 1999 at four sites in south and central Finland. After analysis of preliminary results, eight species were studied more thoroughly. Two legumes, one grass species and one grass-legume mixture were included in long-term trials in order to study annually repeated undersowing. Simultaneous broadcasting of seeds instead of specific undersowing was also studied. Moreover, seeding rates of undersown crops and N fertilization application rates during annually repeated undersowing were researched. Italian ryegrass (*Lolium multiflorum* Lam., IR) absorbed soil nitrate N (NO_3-N) most efficiently in autumn and timothy (*Phleum pratense* L.) in spring. The capacity of other grass species to take-up N was low, or it was insufficient considering its negative effect on grain yield. Red clover (*Trifolium pratense* L.) and white clover (*Trifolium repens* L.) were well suited to annually repeated undersowing, supplying fixed N for cereals without markedly increasing the risk of N leaching. Autumn oriented growth rhythms of the studied legumes were optimal for undersowing, whereas those of grasses were less well suited despite variation in the trait among species. All species were compared according several critical features required of an undersowing system.

A model of an adaptive undersowing system was outlined in order to emphasize allocation of measures according to needs. After defining the goal of undersowing, many decisions need to be made. When the primary consideration is reduction in N leaching, a mixture of IR and timothy is advantageous. Clovers represent suitable replacements for N fertilization because their positive residual effect is greater than the negative effect of increased competition. A mixture of legume and nonlegume is a good choice when increased plant diversity is the main target. Seeding rate is an efficient means for adjusting the levels of competition and N effects. Broadcasting with soil covering equipment can be used to establish an undersown crop. In addition, timing and method of cover crop termination play an important role in the outcome. Continuous observation of the system is needed as, for instance, ambient conditions significantly affect the growth of an undersown crop and N release from crop residues can increase over the long term.

Keywords:
Catch crop, cereal, clover, cover crop, grass, interseeding, leaching, legume, nitrogen, soil ammonium nitrogen, soil nitrate nitrogen, undersowing

Aluskasvien käyttö pohjoisissa oloissa: vaikutus kevätviljan jyväsatoon ja nitraattitypen huuhtoutumisen riskiin

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Tiivistelmä

Viime vuosikymmenten aikana yksipuolinen viljanviljely on lisääntynyt, huoli ravinteiden huuhtoutumisesta kasvanut ja typen hinta noussut. Aluskasvi, viljelykasvin kanssa yhdessä ja sen korjuun jälkeen kasvava kasvi, voi lievittää kyseisiä ongelmia. Tutkimuksen tavoitteena oli kehittää aluskasvien käyttö hyvin kevätviljan viljelyn yhteyteen sopivaksi, pellon kasvukuntoa ja ympäristöä hyödyttäväksi menetelmäksi. Satovasteen lisäksi typen hallinta oli tärkeässä asemassa menetelmän toimivuutta arvioitaessa.

Kaikkiaan 17 kasvilajia kylvettiin kevätviljojen aluskasveiksi vuosina 1991 - 1999 neljällä koepaikalla Etelä- ja Keski-Suomessa. Kahdeksan lajia valittiin tarkemman tutkimisen kohteeksi. Vuosittain toistettua aluskasvien käyttöä tutkittiin kahdella apila- ja yhdellä heinäkasvilla sekä yhdellä apilan ja heinän seoksella. Myös erillisen aluskasvin kylvön korvaavia hajakylvöratkaisuja tutkittiin. Lisäksi tutkittiin typpilannoituksen määrää vuosittain käytetyn aluskasvin yhteydessä sekä aluskasvien siemenmääriä. Viljan jyväsato, aluskasvin kuiva-aine- ja typpisato sekä maan nitraattitypen määrä olivat erityisesti kiinnostuksen kohteena.

Tutkimus osoitti aluskasviksi kylvetyillä palkokasveilla olevan hyvät edellytykset sitoa ilmakehän typpeä ja vapauttaa sitä seuraavan kevätviljan käyttöön. Vastaavasti heinäkasveilla on edellytykset estää typen huuhtoutumista keräämällä nitraattitypeä (NO_3-N) maasta. Soveltuvuus aluskasviksi sekä vaikutukset pääkasvin kasvuun ja typen kiertoon olivat kuitenkin suuresti lajista riippuvaisia.

Westerwoldin raiheinä (*Lolium multiflorum* Lam. *var westerwoldicum*) ja syysvehnä (*Triticum aestivum* L.) vähensivät huomattavasti viljojen jyväsatoa mutta keräsivät silti huonosti typpeä syksyn aikana. Italianraiheinäkin (*Lolium multiflorum* Lam.) alensi pääkasvin satoa mutta vähensi tehokkaasti nitraattitypen määrää maassa. Monivuotiset heinälajit haittasivat yksivuotisia vähemmän pääkasvia, mutta keräsivät heikohkosti typpeä syksyllä. Luotettavimmin kasvanut timotei (*Phleum pratense* L.) keräsi typpeä tehokkaasti seuraavana keväänä.

Puna-apila (*Trifolium pratense* L.) ja valkoapila (*Trifolium repens* L.) sopivat toistuvaan käyttöön ja luovuttivat typpeä viljalle lisäämättä olennaisesti typen huuhtoutumisen riskiä. Apiloiden myönteinen vaste viljan jyväsatoon oli suurempi kuin kilpailun aiheuttama kielteinen vaikutus. Näyttää siltä, että valkoapila ja nurmimailanen (*Medicago lupulina* L.) jonkin verran lisäävät typen huuhtoutumisen mahdollisuutta seuraavana keväänä, mutta puna-apilan aiheuttama riski on pieni. Palkokasvien syksyyn painottuva kasvu oli eduksi aluskasvikäytössä. Heinäkasvien kasvurytmi sopi menetelmään huonommin, mutta lajien välillä oli eroja.

Westerwoldin raiheinä ei luovuttanut toistuvastikaan viljeltynä oleellisia määriä typpeä viljakasvin käyttöön. Syy saattoi alhaisen typpipitoisuuden lisäksi olla se, että kuuden vuoden aluskasvijakso oli liian lyhyt kumuloituvan vasteen syntymiseen. Ulkomaisissa tutkimuksissa havaittu ajan mittaan lisääntynyt typen vapautuminen on kuitenkin syytä ottaa huomioon vuosittain toistuvassa heinäkasvien aluskasvikäytössä, etenkin kun heinien typpipitoisuus vaihtelee suuresti lajeista ja kasvuoloista riippuen.

Viljelytoimet voivat ratkaista aluskasveista saatavat hyödyt. Heinien kylvötiheys ei saa olla suuri, jotta viljan jyväsato ei pienene liikaa. Sen sijaan apiloiden siemenmäärät voivat olla suurehkoja suurten typpisatojen varmistamiseksi. Hajakylvö multaavien laitteiden avustamana toimii hyvin. Lannoitetypen lisääminen vähentää palkokasvien biomassaa, pienentäen typpivastetta seuraavalle kasville. Typpirikkaille kasvintähteille suositeltu myöhäinen syysmuokkaus sopii menetelmään, mutta timotein kasvu yli talven tehostaa jäännöstypen keräämistä. Keväisen maahan muokkaamisen merkitystä typen kierrolle ei kuitenkaan selvitetty, vaan se edellyttäisi uusia tutkimuksia.

Aluskasvien käyttö ja hyöty riippuvat monesta tekijästä. Ensin on päätettävä, halutaanko sitoa typpeä ilmasta vai kerätä sitä maasta, vai onko monimuotoisempi viljely ja ajan mittaan paraneva maan kasvukunto päätavoite. Italianraiheinän ja talvehtivan timotein seosta voidaan käyttää, kun suuret typen huuhtoutumisesta aiheutuvat haitat ovat pelättävissä. Lannoitekuluja pienennetään apiloiden avulla. Esimerkiksi puna-apilan ja timotein seos on hyvä valinta, kun tavoitellaan samaan aikaan monimuotoisuutta, typpihyötyä ja pientä huuhtoutumisen riskiä. Typpivasteita ja viljaan kohdistuvaa kilpailua voidaan säädellä siemenmäärien avulla.

Mukautuva aluskasvimenetelmä perustuu systeemin toteuttamiseen alkutilanteen ja tavoitteen pohjalta. Käytännön toteutus edellyttää toistuvaa harkintaa olosuhteiden ja toteutuneen kasvun perusteella sekä ajan mittaan myös maan paranevan kasvukunnon huomioimista. Kuten aluskasvimenetelmä vaatii jatkuvaa säätöä maatiloilla, voidaan väitöskirjaan luotua mukautuvan aluskasvimenetelmän teoreettista mallia kehittää tutkimuksen ja kokemuksen avulla.

Avainsanat:
aluskasvi, kevätvilja, jyväsato, typpi, huuhtoutuminen, kylvötapa, siemenmäärä

List of original publications

The thesis consists of the following papers, which are referred to by their Roman numerals in the text.

I Känkänen, H., Eriksson, C., Räkköläinen, M. & Vuorinen, M. 2001. Effect of annually repeated undersowing on cereal grain yields. Agricultural and Food Science in Finland 10: 197-208.

II Känkänen, H., Eriksson, C., Räkköläinen, M. & Vuorinen, M. 2003. Soil nitrate N as influenced by annually undersown cover crops in spring cereals. Agricultural and Food Science in Finland 12: 165-176.

III Känkänen, H. & Eriksson, C. 2007. Effects of undersown crops on soil mineral N and grain yield of spring barley. European Journal of Agronomy 27: 25-34.

IV Känkänen, H., Mikkola, H. J. & Eriksson, C. 2001. Effect of sowing technique on growth of undersown crop and yield of spring barley. Journal of Agronomy and Crop Science 187: 127-136.

List of abbreviations

BNF	biological nitrogen fixation
C	carbon
DM	dry matter yield
IR	Italian ryegrass
N	nitrogen
N-%	N concentration
NH_4-N	ammonium N
NO_3-N	nitrate N
NRV	N-fertilization replacement value
SMN	soil mineral N
SOM	soil organic matter
WR	westerwold ryegrass

Contents

1 Introduction

1.1 Invariable cereal cropping impairs sustainability

Increase in intensive cropping during the past century, favouring short rotations, monocropping systems and omitting green manure crops, has impacted negatively on soil fertility and the environment (Karlen et al. 1994). Invariable cropping is the prevailing system and in Finland a growing trend in land area devoted to spring cereals has occurred, exceeding 50 % of the total cultivated area in 2008 (ANON 2009), for the first time in history. Furthermore, cereal cropping is strongly emphasized in the southern and western parts of the country. If there are breaks in monocropping, they are usually represented by turnip rape (*Brassica rapa* L. subsp. *oleifera* DC.) or oilseed rape (*Brassica napus* L. subsp. *oleifera* DC.). Karlen et al. (1994) indicated that the effects of this development are often site-specific, but include decreased soil organic matter (SOM) content, degraded soil structure, increased soil erosion, increased need for external inputs and increased surface and groundwater contamination. According Breland and Eltun (1999), soil from forage rotations contained more organic C, total C, total N and microbial biomass than soil from a conventional arable rotation, and the negative effects on the soil health indicators were counteracted by return of organic matter through animal and green manures. Moreover, diversifying cereal cropping by introducing new crops into rotations can have long-term effects, as after a rather rapid start decomposition of plant material takes several years (Jenkinson 1997).

Increasing SOM with animal manures is often not feasible in conventional arable farming and neither is dedicating a growing season solely to a green manure crop. Rather, solutions that include commercial crops are desired for developing more versatile cropping systems. Sometimes an introduced cropping system can promote greater efficiency, such as that represented by intercropping, for which total yields compare favourably with corresponding to sole crops (Jensen et al. 2005). As reported by Jensen et al. (2005), intercropping of cereals and grain legumes can result in fewer weeds and reduced incidence of plant diseases. Olson et al. (1986) reported that interseeding of alfalfa (*Medicago sativa* L.) and rye (*Secale cereale* L.) in corn (*Zea mays* L.) reduced disease and insect attack, in addition to improving soil structure and N supply. In the latter cropping system there is however only one main commercial crop and the interseeded crop should disturb it as little as possible, but should confer some benefits. Such a situation corresponds to the undersowing system detailed in this dissertation.

1.2 Nitrogen: resource, cost and risk

Nitrogen (N) is a macronutrient, and one of the major yield-limiting nutrients for crop production worldwide (Fageria 2009). According Olson et al. (1986), fertilizer N has contributed more towards increasing yields of grain crops since the 1950s than any other single factor. On Finnish mineral soils N fertilization usually markedly increases spring cereal yields by up to 100 kg ha^{-1}, but according to Esala (1991), an additional 40 kg N ha^{-1} has a rather small effect on yield quantity, although it still substantially increases the protein content of wheat (*Triticum aestivum* L.) grains. The total N input to all fields, including that from organic manures, decreased from 160 kg ha^{-1}

at the beginning of the 1990s to almost 120 kg ha^{-1} in 2005, mainly because of the decreased use of mineral N fertilizers (Salo et al. 2007). The trend shows the influence of both decreased profitability in crop production and the Finnish Agri-Environmental Programme, which has set the maximum N application rates for most crops since 1995.

In conventional farming, N is mainly added to the soil through application of inorganic fertilizers, whereas in organic farming farmyard manures and legumes are used. However, in conventional arable farming use of biological N fixation (BNF) could be enhanced. In this respect, interest in green manuring has increased during recent years because of increased fertilizer prices. Legumes incorporated into crop rotations are familiar as sources of N, and Varvel and Wilhelm (2003), for example, reported that 65 to 80 kg N ha^{-1} year^{-1} is supplied by soybean (*Glycine max* L.) for the subsequent non-legume crop in a 2-year rotation, according to the results of two long-term trials on rainfed and irrigated soils in the Midwestern USA. They commented on the need to reduce fertilizer N applications to avoid loss of N and unnecessary input costs. On the other hand, Salo et al. (2007) estimated the input of N via BNF in Finland to be only 3 – 7 kg ha^{-1} year^{-1}, considering the total agricultural area.

The cycle of N in a soil-plant system is dynamic, and the state of N varies. More than 90 % of the N in most soils occurs in the form of organic matter, and while this form protects N from losses it is not available to plants (Fageria 2009). However, according Nordic research undertaken by Lindén et al. (1992), a 1 % increase in the SOM content of the 0-20 cm soil layer increased the net N release on average by 5 kg ha^{-1} from early spring to the yellow ripeness stage of a cereal, although variation among sites was substantial. The organic form of N, similarly to the N in crop residues, should be mineralized to nitrate (NO_3^-) and ammonium (NH_4^+), together mineral N, before it is taken up by plants. NH_4-N is oxidised through nitrification to NO_3-N, which is easily leached under conditions of heavy rainfall (Fageria 2009) or when water surplus otherwise occurs, including snow melt in spring (Turtola and Kemppainen 1998). Although substitutes for mineral fertilizers are desired, Dahlin et al. (2005) reported that organic nutrient sources generally represent an increased risk for N losses to the environment because soil microbial activity leads to N release that is out of synchrony with plant nutrient demand. They further emphasized the need to improve the means of directing N release from organic nutrient resources. N depletion occurs in different ways, and this study focuses on leaching of NO_3-N, which means both loss of N for use by cultivated crops and contamination of waters from leaching.

The total amount of soil mineral N (SMN) shortly after harvest, which is considered to be at risk of leaching, varies considerably within Europe according to agricultural practices and environmental conditions, and may range from less than 20 kg to over 200 kg N ha^{-1} (Schröder 2001). SMN in Finland is normally at the lower end of the scale, although high contents are found, especially after manure application (Esala 2002). In special cases SMN content can be very high, as reported by Paasonen-Kivekäs and Ylihalla (2005), >400 kg SMN ha^{-1} in the 0 – 240 cm profile, with substantial concentrations in the deepest layers in acid sulphate soils characteristic of the western coastal areas of Finland. Concerning the more usual situation in Finnish arable farming, which this study represents, Sippola and Yläranta (1985) reported that SMN at 0 to 100 cm in spring in a heavy clay and a peat soil ranged from 22 to 27 kg ha^{-1} and 45 to 78 kg ha^{-1}, respectively.

According to Sippola and Yläranta (1985), concerning conventional cereal farming on common soil types in southern Finland, the SMN contents in spring were higher than after a previous cereal harvest. The change during autumn and winter is however not easily predictable, as in addition to farming system, soil type and cultivated crops, conditions greatly affect the N mineralization from soil and crop residues. For instance, in the circumstances of a cold winter, net N mineralization following the spring thaw can provide a significant share of the total NO_3-N, as concluded by DeLuca et al. (1992), according to results of freeze-thaw studies with soils representing various types and land uses. On the other hand, high N mineralization in soils in autumn was emphasized by Rankinen et al. (2007), who reported that the non-growing season from autumn to spring accounted for 40 – 98% of simulated annual N leaching from agricultural fields in southwestern Finland, representing both conventional and organic cereal production, and conventional cattle and pig husbandry. Moreover, the N leaching was emphasized in the period between harvest and soil frost occurrence in late autumn.

Notwithstanding that moderate SMN contents are common in arable farming in southern Finland, their effect on the environment can be notable as N is the limiting factor for algal growth in the major part of the Baltic Sea (Granéli et al. 1990, Kivi et al. 1993). Moreover, reducing the N loss is also important in cereal farming because most losses are discharged directly from coastal areas and also through rivers into the Baltic Sea (Valpasvuo-Jaatinen et al. 1997). This leads to eutrophication of costal waters according to Rekolainen et al. (1995), who reported that the total N load per ha of arable land was 10 – 20 kg per year. Salo and Turtola (2006) measured N loss on two runoff fields in southern and western Finland where the average annual leached N was 10 – 16 kg ha^{-1}, although on sandy soil up to 100 kg N ha^{-1} was leached when slurry was applied to frozen soil. On clay soil receiving mineral N fertilizers only, they recorded losses of 2 to 40 kg N $year^{-1}$. The decrease in gross N balance (N input minus harvest of N) from 110 kg ha^{-1} in 1990 to 60 kg ha^{-1} in 2005 in Finland (Salo et al. 2007) would be expected to reduce N leaching. However, as management practices, crop rotations and soil hydrological conditions also play an important role, annual N balance seems not to be an axiomatic indicator of N leaching (Salo and Turtola 2006), although Rankinen et al. (2007) established a positive correlation between N balance and simulated N leaching.

Although since the 1960s concern has focused on phosphorus in the context of freshwater lakes and although nutrients discharged into surface waters have markedly decreased (Räike et al. 2003), a decrease in non-point source loading is required. Liikanen (2002) emphasized the need for reduced nutrient losses because eutrophication and N load increase emission of the major greenhouse gases, methane and nitrous oxide, from lakes. According to Rekolainen et al. (2005), a decrease in dissolved inorganic N in lake waters, most probably caused by a decrease in N emissions to the atmosphere, indicates that many large lakes may become N-limited during the later part of growing season. They noted however that agriculture does not make as big a contribution in lake areas as it does in coastal regions.

High nitrate concentration in drinking water is regarded as a significant problem in many areas of Europe (Cepuder and Shukla 2002, Berntsen et al. 2006, Köhler et al. 2006), but in Finland pollution of groundwater caused by agriculture is not an extensive problem, although it does occur occasionally with intensive livestock production (Valpasvuo-Jaatinen et al. 1997). All in all however, every measure that enhances control of N leaching is desirable.

1.3 Cover crops as a tool for risk management

The negative effects of invariable cropping and post-harvest nutrient leaching and erosion can be diminished by growing non-marketable crops between harvest and sowing of the successive commercial crop. According Fageria (2009), the importance of special purpose crops, such as cover crops, catch crops and green manure crops (Table 1), is increasing as a result of the high cost of chemical fertilizers, the increased risk of environmental pollution, and the need for sustainable cropping systems. The uses of these crops vary: conserving water and nutrients, protecting soil from erosion, controlling weeds, and improving physical, chemical and biological properties of soil. Furthermore, as Trenbath (1993) reported, there is often less damage by pests and diseases during intercropping compared with sole cropping. A cover crop can protect against some organisms when grown together with the main crop.

Adding plant material into the soil affects micro-organism activity, which plays a key role in sustaining the fertility and productivity of agricultural soils. According Lupwayi et al. (2004), legumes with high N content increase soil microbial functional diversity and activity, whereas high residue C content improves soil quality by increasing the SOM content. Their conclusion that increasing those positive effects simultaneously would require simultaneous application of a mixture of crop residues of different quality to the soil supports the idea of undersown cover crops. Moreover, while above-ground growth after cereal harvest produces more organic matter and protects soil from autumn rains, growth below the soil surface plays a role in soil quality. According Kunelius et al. (1992), undersown cover crops increased root biomass several fold compared with growing barley (*Hordeum vulgare* L.) alone.

Cover crops can be seen as a substitute for decreased area of leys, which according to Gustafson (1987) reduced mean N leaching up to six times compared with the average losses registered after cereals. Furthermore, long-term use of cover crops can enhance soil productivity. Hansen et al. (2000b) reported a non-nutritional yield

Table 1: Terms used in context of special purpose crops to introduce diversity, improve nutrient management, protect soil, improve soil properties, and diminish environmental pollution.

Cover crop	Covers soil when commercial crops are spatially or temporally unable to do so. Decreases soil erosion and nutrient leaching or improves soil structure and fertility, in particular the N supply for following crops. (The term is confusingly used also to mean a cereal crop that covers a grass crop in the year of establishment preceding production years.)
Catch crop	Often used to describe a crop that absorbs mineral N from the soil and prevents leaching losses to the environment. The term cover crop is often used as a synonym for catch crop.
Green manure crop	Mainly legumes or mixtures of legumes and non-legumes grown to improve the N supply for successive crops.
Intercropping	Simultaneous growing of two or more crop species in the same field. Target is to improve the use of resources when all components are producing yield for harvest.
Undersown crop	A cover crop grown together with a main crop that continues its growth after harvest of the main crop.
Interseeding	A parallel term for undersowing. The term 'insown' cover crop means the same.

response with a previous ryegrass catch crop compared with continuous production of spring-sown crops without catch crops. On the other hand, Blombäck et al. (2003) reported increased SOM content and N mineralization capacity already after 6 years of a ryegrass catch crop, whereas according Berntsen et al. (2006), the consequences of catch crop use for soil fertility and nutrient losses to the environment can only be evaluated on at least a ten-year scale. In addition, Singer and Cox (1988) reported increased main crop yields as a consequence of the positive effects of introducing diversified rotations when they compared continuous corn with rotations including soybean and wheat interseeded with red clover.

Cover or catch crops are often mentioned when agricultural practices aimed at environmentally safe arable farming are introduced (Beaudoin et al. 2005), or when retention of nutrients in the soil-plant system and reduction in the risk of environmental pollution are otherwise concerned (Sturite et al. 2007a). According Schröder (2001), an effective cover crop can decrease NO_3-N leaching to less than 10 kg N ha^{-1} compared with 30-50 kg N ha^{-1} for winter cereals or bare soil in the same rotational position. Köhler et al. (2006) reported catch crops to be the most efficient way to reduce the very high NO_3-N concentrations in the groundwater found in sandy soils in northern Germany.

Cover crops are often recommended for conventional arable farming, and Torstensson et al. (2006) even found that a system incorporating inorganic N fertilizer and a catch crop was superior when comparing the effects of different farming systems according to N leaching loads and N use efficiency. Consequently, control of N could be enhanced with cover crops on cereal production fields, although they, according to Rankinen et al. (2007), exhibited the lowest N leaching among different production types. Knudsen et al. (2006) concluded that catch crops were important tools in reducing N leaching losses both in organic and conventional systems, and to the same extent on dairy farms as on arable farms. Meisinger and Delgado (2002) suggested the use of grass cover crops, adding a legume to a rotation and crops that more fully utilize water resources in soil, as tools for managing N leaching. Need for cover crops is in accordance with the findings of Ekholm et al. (2007), who mentioned lack of vegetation outside the growing season to be one possible reason for no clear reduction in Finnish nutrient loading despite introduction of the EU Agri-Environmental Program over ten years ago.

Grasses and cruciferous crops absorb or catch N from the soil, and legumes can take N from the atmosphere through BNF. The capacity of plant species to produce biomass and take-up N varies greatly. If the plant takes-up its entire N requirement from the soil, N can become a growth-limiting factor (Fageria 2009). If removal of all easily leached N from the soil is the goal, this can be advantageous. Legumes also absorb N from the soil if available and can thus decrease N leaching also (Karlsson-Stresse et al. 1996, Vyn et al. 2000, Arlauskiene and Maiksteniene 2008), although according to Garand et al. (2001) red clover interseeded in spring wheat did not act as an N catch crop after cereal harvest. In any case, the ability of legumes to fix N from the atmosphere represents an opportunity for productivity increases, but also a challenge for utilizing the fixed N in a crop rotation. Legumes have been reported widely to be superior in providing N to the subsequent crop, even when undersown (Vyn et al. 1999, Garand et al. 2001, Talgre et al. 2009), and therefore represent an alternative to application of mineral fertilizer N. Similarly as N mineralization differs widely among legumes (Müller et al. 1988, Kirchmann and Marstorp 1991), there are great differences in N release among non-legume species, both when material is incorporated into the soil (Jensen 1992) and when crops are allowed to overwinter (Sturite et al. 2007a).

An option to improve retention or release of N is to adjust the composition of a cover crop by using mixtures of species, e.g. grass and clover as reported by Dahlin et al. (2005). Studying both legumes and non-legumes in same cover crop experiments has not been common however, and there has been little effort made to investigate how they function together in a mixture. Furthermore, efforts towards adapting cover crops in crop rotations at a system level according to various needs and changing circumstances are quite rare, although a comprehensive report on catch crops was produced by Thorup-Kristensen et al. (2003) and the role of cover crops in reduction of NO_3-N leaching in Europe was covered in an EU project (Schröder 2001). This study was established in order to fill the knowledge gap on undersowing in cereal farming, particularly in Finland.

1.4 Undersowing, a solution for cool climate

According to Schröder (2001), when sown in early August, cover crops can be grown over virtually all of Europe. However, when sown later, which would normally be the case after cereal harvest, the temperature sum during autumn is insufficient for satisfactory growth in the northern regions of Europe. Undersowing into the main crop instead of sowing after harvest has proved to be a suitable method for establishing a cover crop at northern latitudes (Jensen 1991, Alvenäs and Marstorp 1993), which enables immediate uptake of residual N by the cover crop after harvest of the main crop (Breland 1996) or increase in available N for the successive crop (Wallgren and Lindén 1994). Consequently, at its best undersowing can improve control of SMN and particularly inhibit N leaching, as Andersen and Olsen (1993) found for spring undersown ryegrass on four Danish soils, when it reduced soil NO_3-N in early winter fourfold compared with a crop sown after barley harvest. However, in the case of two crops grown together, the main crop may absorb less N and even N-uptake of the subsequent commercial crop can be reduced (Martinez and Guiraud 1990). This makes evaluation of cover crop effects complicated from the perspective of both the environment and economics.

Undersowing as a cover crop solution is however not restricted to regions with a cool climate, but can be a useful tool for diversifying crop rotations everywhere, as recommended by Singer and Cox (1998) for the eastern USA, for example. Consequently, in central Europe a higher temperature sum required for cover crop growth has been reached by undersowing in corn instead of sowing after harvest (Schröder et al. 1996). Climate change obviously further increases the need for using cover crops in northern Europe, as under conditions of higher precipitation, especially heavy rains, and shorter and warmer winters, there will be an increased risk of leaching of both plant protection chemicals and fertilizer nutrients and of soil erosion (Peltonen-Sainio et al. 2009). Increase in the temperature sum does not necessarily improve conditions for post-harvest cover crop growth, but the growth-limiting day-length in northern latitudes may maintain the need for undersowing instead of sowing after harvest.

Undersowing may be justifiable also when aiming at good soil cover for controlling erosion and weeds already during the early growth of the main crop, where intensively grown crops with wide row spacing are cultivated (Abdin et al. 1997). According to Hollander et al. (2007) however, even then it is very difficult to combine adequate weed suppression with an acceptable level of yield reduction in the main crop. When two or more crops draw on the same resources, nutrients, water and light, there will inevitably be competition for these resources (Andersen et al. 2007). Consequently, with small-grains in northern Europe, it is better if the growth of an undersown crop is moderate until harvest in order to minimize competition with the main crop. However, undersowing can also be seen as an alternative for replacing a commercial crop with a green manure crop, as discussed by Abdin et al. (1997) regarding interseeding cover crops between corn rows to maintain the soil without sacrificing yield of the grain crop. According to the literature referred to for this dissertation, undersowing has been reported to decrease the yield of the main crop greatly, slightly or not at all, depending on the species of both the main and cover crop, cultivation practices and weather conditions. Consequently, and because of only few published results (Kauppila 1983, Varis & Kauppila 1992), there was an evident need for experiments to support decisions for using undersown cover crops in Finnish arable farming.

According to a tentative ideotype described by Karlsson-Stresse et al. (1996), an undersown cover crop should withstand competition from the main crop, but not grow too robustly before harvest of the main crop. However, after harvest it should grow vigorously and have good frost and winter hardiness together with a well-developed root system. Furthermore, a good cover crop should not easily become a weed or transmit or allow multiplication of pests and pathogens that could attack and damage the main crops in a rotation. Avoiding increased disease and weed pressure was the reason why crucifer crops were rejected in this study despite being used as cover crops elsewhere (Vyn et al. 1999, Thorup-Kristensen et al. 2003). Oilseed crops are a desired and intrinsic choice for commercial crops when crop rotations on Finnish arable farms become further diversified. As far as other non-legumes in cover crop studies are concerned, reported results mainly focus on ryegrasses, which were included also in this study, but were compared with other grass species. More species were studied here than in most other cover crop studies.

A common goal for interseeded crops is good establishment, requiring sufficient air and moisture at a suitable seed depth (Decker et al. 1973), with minimal interference with the main crop. As seeding rate via plant number affects the relative portions of biomass production between two species in a mixed crop (Paynter and Hills, 2009), it apparently represents a means for adjusting the competition between an undersown and a main crop. However, as seeding rates of cereals have become fixed according to the requirements for pure stands, the seeding rate of an undersown crop has to be the adjustable component and should be set as low as possible, not least because it represents an extra cost in cereal farming. If the realized plant density is too low however, take-up of N from the soil or fixing it from the atmosphere remains at a low level. Studies of seeding rate of cover crops are rare (Kauppila 1983, Kvist 1992), and this gap in the knowledge was considerable before the field studies described here were undertaken.

As delayed undersowing has been shown not to be beneficial for the system (Kvist 1992, Ohlander et al. 1996), and because sowing the main crop in a living mulch is challenging because of substantial competition (Williams and Hayes 1991, Bergkvist 2003, Carof et al. 2007), this study included undersowing simultaneously or as soon as possible after cereal sowing. Furthermore, although often used, separate drilling represents an extra cost compared with simultaneous seeding. Comparative studies in this context are rare, especially when broadcasting is combined with seed covering equipment. As broadcasting small seeds has been reported both to improve (Øyen 1991) and impair (Hare et al. 1989) establishment and to have no effect (Sheaffer and Marten 1992) compared with drilling, studying sowing technique was deemed justifiable and was done in the field experiments described in paper IV.

Timing of cover crop termination has been reported to be essential for N release, and earlier Nordic results of decreased N leaching risk with delayed incorporation of N-rich plant material (Kirchmann and Marstorp 1991, Breland 1994, Känkänen et al. 1998) were taken into account. Although timing of incorporation was not a variable in the field experiments, it is discussed as several studies further emphasized its importance for N leaching (Magid et al. 2001, Korsaeth et al. 2002, Lahti and Kuikman 2003) and a range of residual effects on the subsequent crop were reported (Känkänen et al. 1999, Lahti and Kuikman 2003, Ball et al. 2007, Talgre et al. 2009).

Most cover crop studies are based on breaking an invariable rotation once, whereas long-term experiments with repeated use of cover crops are quite rare. Repeating the annual or biennial experiments at least once is however important, as e.g. Müller (1988) found the loss of cover-crop-derived N and uptake of it by a subsequent crop varied greatly between years. Furthermore, the effect of a cover crop can change in the long run according to the results from long-term experiments (Hansen et al. 2000a, Beaudoin et al. 2005), which provide a valuable perspective for considering the results of the annually repeated undersowing in this study (paper I and II) and emphasize the importance of continuous evaluation of needs and measures when undersowing is adapted to cereal cropping.

1.5 Objectives of this study

The purpose of this thesis was to gain knowledge needed to develop undersowing for Finnish conditions in the pursuit of production and realize environmental goals. Effects were studied of undersown species and management practices in spring cereal farming, especially on biomass and N yield of undersown crops, grain yield of spring cereals and soil nitrate. Depending on whether the undersown crop was a legume or non-legume, the main requirement was to either fix N for cereals or catch N from the soil to prevent leaching. In both cases, however, a major goal was to reduce leaching risk and a maximise transfer of the N released from the cover crop to a successive cereal crop. Species and undersowing techniques with minimal negative effects on the main crop, and which ensured good cover crop growth after cereal harvest, were desirable. Another important target of this study was investigation of effects over a longer time period with undersowing being repeated on an annual basis.

The objectives of the present investigation were to:

- Quantify accumulation of N in above- and below-ground biomass of undersown legume and non-legume cover crops, and thus gauge their suitability for fixing and catching N under Finnish conditions.
- Investigate growth dynamics of undersown crop species, competition with the main cereal crop, and plant biomass N and soil inorganic N dynamics from grain harvest onwards.
- Quantify net effects of annually repeated undersowing on cereal grain yield.
- Investigate effects of sowing technique, seeding rate, N fertilization rate and timing of plant biomass incorporation on target parameters.
- Generate a principled framework for adaptive management of undersown crops in order to encourage positive effects on crop production and the environment.

Effects of annually repeated undersowing with legume or grass cover crops on spring cereal grain yields and SMN content, and in particular N leaching risk through soil NO_3-N, were reported in papers I and II. As the need for alternative undersown crops occurred during the first experiment, a species experiment was conducted. The aim of the work constituting paper III was to identify undersown crops that effectively absorb soil N or fix atmospheric N without increasing N leaching risk and with minimal negative effects on the main crop. The influence of N fertilization rates and seeding rates were investigated for papers I and II, and III, respectively. Sowing technique was investigated for paper IV, by comparing standard separate drilling with different simultaneous broadcasting methods. As an overall perspective this thesis discusses the principles of an undersowing system as adapted to the needs of cereal cropping for various aims and under various conditions.

2 Materials and methods

The experimental part of the work is described here in general terms. Detailed descriptions can be found in the original publications (I-IV).

2.1 Theme and experimental sites

The experiments were conducted at MTT Agrifood Research Finland to study the suitability of different species for undersowing in spring cereals, and the effects of undersowing when examined over a single or several year basis. Special attention was paid to sowing technique, seeding rate and N fertilization rate in the context of undersowing. Effects on establishment, plant biomass and N yields, cereal growth and yield, and soil N were studied. The experiments were conducted in 1991 - 1998 in Pälkäne (61°20'N, 24°13'E, sandy loam to loamy sand) and Laukaa (62°25'N, 26°15'E, silt loam) (paper I and II), in 1995 - 1999 in Jokioinen (60°49'N, 23°28'E, different soil types) (III), and in 1994 – 1997 in Vihti (60°25'N, 24°24'E, clay loams) (IV). Spring cereal species were barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.) and wheat (*Triticum aestivum* L.) in papers I and II, and barley in papers III and IV.

2.2 Experimental design

In total, 17 plant species were undersown during the experiments. However, several species were rejected following one to three years of experimentation, and eight species were studied more thoroughly (Table 2). Experiments were designed as split-plot trials with N fertilization rates (I and II), seeding rates (III) or rolling after undersowing (IV) as the main plots, arranged as a randomized complete block with three (I and

Table 2: The eight most thoroughly studied undersown crop species, and experimental years and papers in which the species were included. The species is marked with "x" if it was included when seeding rate, annually repeated undersowing with different N fertilization rates or sowing technique was studied.

			Studied cultivation methods		
Undersown crop	Paper	Years	Seeding rate	Annual use and N rate	Sowing technique
White clover (*Trifolium repens* L.)	I - III	1991 - 1999	x	x	
Red clover (*Trifolium pratense* L.)	I - IV	1991 - 1999	x	x	x[d)]
Black medic (*Medicago lupulina* L.)	III	1995 - 1999	x		
Timothy (*Phleum pratense* L.)	III	1995 - 1999	x		
Westerwold ryegrass [a)]	I - III	1991 - 1999	x	x	
Italian ryegrass (*Lolium multiflorum* Lam.)	III	1997 - 1999	x		
Winter wheat (*Triticum aestivum* L.)	III	1995 - 1999	x		
Meadow fescue (*Festuca pratensis* Huds.)	I - IV	1991 - 1997	(x)[b)]	x [c)]	x[d)]

[a)] (*Lolium multiflorum* Lam. *var westerwoldicum*)
[b)] Not included in analysis because it was rejected after the initial years.
[c)] In a mixture with red clover.
[d)] A mixture of red clover and meadow fescue.

II) or four (III and IV) replicate blocks. The split-plot treatments, undersown crops (I-III) or undersowing technique (IV), were randomised among the subplots within each main plot.

N application rate treatments (I and II) were 0, 30, 60 and 90 kg N ha^{-1}. Seeding rate treatments were termed low, standard or high (paper III: Table 1), where the standard seeding rate was determined based on knowledge of each species when grown in mixtures and in pure stands. The low seeding rate was half the standard rate and the high seeding rate was double the standard rate. In the rolling treatment (IV) the soil was either rolled independently after undersowing with a continental Cambridge roller, or not, whereas in other trials rolling was done before and after undersowing. When N application rate was not an experimental treatment, N was applied at slightly lower rates than those recommended to prevent lodging, ranging from 70 to 90 kg ha^{-1}. The seeding rates for cereals were those normally used in Finland, except in sowing technique trials, where 100 seeds m^{-2} less than normal was used.

Undersowing was normally done soon after the cereal was sown, across the cereal rows to a depth suitable for each species, and at the same row distance of 12.5 cm as for the main crop. The tested alternative sowing techniques are explained in paper IV, page 128. After harvesting the cereal crop in August or September, straw residues were collected to ensure good growth potential for the undersown crop. When soil was autumn ploughed (I and II), it was done in late October to ensure a sufficiently long growing season for the undersown crops. The other trials ended in late autumn of the year of establishment (IV) or in the succeeding spring (III), and no incorporation of the cover crop was done. Correspondingly, no effects on successive crops were studied for papers III and IV.

Weather conditions were monitored especially carefully during the experiments reported in papers I and IV, where air temperature and precipitation values are presented according the critical periods for establishment and growth, and N release and leaching (Table 1 in both papers).

2.3 Establishment and growth

In the sowing technique trials (IV), the number of undersown plants (from two areas of 0.25 m^2 in each plot) was recorded five times during the growing season. On the first date the number of barley plants was also counted. Plant samples (from 0.25 m^2 per plot) were taken at cereal harvest (III and IV) and at the end of the growing season (I – IV). These included above-ground material of the undersown crop at both times and of barley the first time. At the second plant sampling, root samples from the 0–25 cm soil layer were also taken (I and II, and III at the standard seeding rate). The root samples were taken manually (25 x 25 cm surface area) during the first three years (I and II) and mechanically (12.5 x 12.5 cm surface area) in later years. As roots were washed manually in the first three years (I and II), some loss of roots and incomplete removal of soil were possible. After that, washing with a root washer ensured contamination-free soil and minor root loss, although small amounts of other organic matter remained in samples after separation with forceps. Shoot and root samples were dried in an oven, and dry matter yields (kg ha^{-1}) were recorded. The root biomass was not sorted on a single plant basis. N contents (%) of roots and mixed above-ground biomass of the cover crop and weeds were measured (I – III).

2.4 Cereal grain yield

Cereal crops were harvested with a combine harvester at growth stage 92 (Zadoks et al. 1974). After the cereals had been dried in an air stream (+40°C) and sorted, grain yield was measured and calculated in kg ha^{-1} at 15% moisture. In the long-term experiment (I), the effect of undersowing on grain yield was studied in four periods: 1) the first year of undersowing, 2) additional years of undersowing, 3) the first year after the final undersowing year, and 4) the second year after the final undersowing year. For the additional purposes of this thesis, N-fertilizer replacement values (NRV) of undersown crops during period 2 were determined, when it was possible according to the published data in paper I. In order to do this, N-fertilizer response curves as an average and at Laukaa, $y = 18.7x + 2301$ ($R^2 = 0.9461$) and $y = 24.5x + 1701$ ($R^2 = 0.9673$), respectively, were calculated according to grain yields in plots without undersowing (not published in paper I). In the other experiments (III and IV), the effect of treatments on cereal grain yield was studied solely in the year of undersowing.

2.5 Soil mineral N

The effect of undersowing on SMN (kg ha^{-1}) was studied (except IV) by taking soil samples before sowing in spring, at cereal harvest, in late autumn, in early spring before soil thawing and at the start of the following growing season, from soil layers at depths of 0 – 30, 30 – 60 and 60 – 90 cm. However, the sampling procedure varied greatly among and during experiments, and according to the special interest concerning each sampling date. Furthermore, in the long-term experiment, the effect of undersowing on SMN was studied in four periods (II) similarly as explained in the context of the grain yield. Soil samples were extracted with 2 M KCl. The NO_3-N and NH_4-N contents of the extracts were autoanalyzed (air segmented flow analyser, photometric detection) and converted into kg ha^{-1} (Esala 1991). There was variation in sampling procedure. There was also unplanned variation over a few years in the NO_3-N analyses done before winter in the long-term experiments. Such variation interfered with statistical analysis of the results. Information on soil sampling and examination of the soil N data is given in detail in papers I – III.

2.6 Statistics

The models were fitted using the residual maximum likelihood (REML) estimation method. The degrees of freedom were computed using the method described by Kenward and Roger (1997) or approximated using a Satterthwaite procedure if there were zero variance components (Verbeke and Molenberghs 1997) (IV). Accordance of the data with the distributional assumptions of the models was checked graphically. The analyses were performed using the MIXED procedure of SAS/STAT software (Littell et al. 1996) and in paper IV also UNIVARIATE and PLOT procedures (SAS Institute Inc. 1990). The residual analyses were carried out to check the assumptions of the models. The residuals were checked for normality using box plots (Tukey 1977). In addition, the residuals were plotted against the fitted values. Comparisons between means were made using two-sided t-type tests or 95 % confidence intervals (95 % CI).

2.7 Model of adaptive undersowing system

A model of the adaptive undersowing system was created in order to increase the benefits of undersowing. A schematic representation was made to describe decision-making in cultivation, taking into consideration the need for continuous observation, estimation and re-evaluation in the system. It was designed to approach the system from the standpoint of strategic guidelines for either catching N from the soil, fixing it from the atmosphere, or diversifying cereal cropping. The cultivation methods included in the model were based on results reported in original publications and articles cited in this dissertation.

3 Results and discussion

Undersowing is considered to be a positive tool for reducing the detrimental effects of invariable cereal cropping in general, and consequently represents an optional measure to be undertaken in the environmental programme for agriculture in Finland. However, if the system is not well enough understood, failure could ensue in terms of decreased grain yields and negative effects on the environment, or possibly its inadequate use. The effects of undersown crops on arable farming and the environment are highly dependent on implementation, where substantial variation among undersown species represents both possibilities and challenges. Furthermore, there is an apparent need for tailoring the system according the needs, creating an adaptive undersowing system that fulfils precise objectives.

3.1 Differing uptake and release of N among species

3.1.1 Biomass and N yield of shoots and roots

The capacity of crop species to produce biomass and their reaction to growth conditions varied greatly. Italian ryegrass (*Lolium multiflorum* Lam., IR) was superior in dry matter yield (DM), on average 1400 kg ha^{-1} at a standard seeding rate, in comparison with a yield of 400 – 600 kg ha^{-1} for other grasses (III). Substantial differences in growth among species were recorded (Table 3, *C-E*), similarly as reported by Karlsson-Stresse et al. (1996), who indicated high levels of variation in characteristics of several crop species when searching for an ideal crop to undersow. Although biomasses in late autumn in this study were comparable with those of other stud-

Table 3: Features of species undersown with a spring cereal crop. Comparisons between species are made according to measured factors, with contributions from observations and relevant literature.

	Studied factor					
Undersown crop	*A*	*B*	*C*	*D*	*E*	*F*
White clover	L	S	S	M/H[1)]	M	H
Red clover	L	H	S	M	M	H/M
Black medic	L	H/S[1)]	S	M/H[1)]	N	H/S[1)]
Timothy	H	N	H	M	H	L
Westerwold ryegrass	H	N	L	M	N	M[2)]
Italian ryegrass	S	N	M	S	L	L[2)]
Winter wheat	H	N	O	H	L	M[2)]
Meadow fescue	M	N	M	L	M	--

S = superior, H = high, M = medium, L = low or occasional, N = no effect, O = opposite effect, -- = not studied or not evident
A: Capacity to absorb soil N
B: Biological N fixation
C: Autumn oriented growth rhythm
D: Biomass in shoots and roots in late autumn
E: Growth in succeeding spring
F: Rapidity of N release, based highly on literature
[1)] With high seeding rate
[2)] Can vary greatly because of conditions.

ies on average, site-dependent differences were evident. Contrary to us, Kunelius et al. (1992) did not establish differences between biomass production of IR and westerwold ryegrass (*Lolium multiflorum* Lam. *var westerwoldicum*, WR). In addition, their shoot yield in Atlantic Canada, which exceeded 3000 kg ha^{-1}, was double that of IR at high seeding rate reported in (III). On the other hand, Andersen and Olsen (1993) in Denmark found no significant difference between perennial and Italian ryegrass, with above-ground DM intermediate between those of grasses described in this study. We however did establish differences among the perennial grasses, timothy (*Phleum pratense* L.) being the most reliable species, although its shoot yield in late autumn remained much lower than that of annual grasses, at an average of 400 kg ha^{-1}.

The root yield of IR (1450 kg ha^{-1}) was highest, and clearly higher than that of timothy (980 kg ha^{-1}) and WR (680 kg ha^{-1}). As roots make an essential contribution to the effect of green manure crop (Solberg 1995), and in terms of taking-up residual N that would otherwise be leached (Thorup-Kristensen 2006), the result emphasizes the superiority of IR as a biomass producer, although its growth rhythm was not ideal for an undersown crop. Pietola and Alakukku (2005) however found that the root growth rate of IR was high late in the season and concluded that it would be an efficient catch crop after cereal harvest. Thorup-Kristensen (2006) observed a clear increase in root frequency of IR during autumn, although only in the soil layers already containing roots. Timothy is a perennial species with a high root:shoot ratio, which combined with an autumn-oriented growth rhythm increases its value in undersowing. The root sampling depth in our study was shallow, 25 cm, compared with that of Thorup-Kristensen (2006), who measured rooting depth of IR to one meter and even deeper than the 2.5 m for other catch crops. However, as Pietola and Alakukku (2005) found that most of the root biomass was in the upper 20 cm of the soil, it can be expected that our results represent the root biomass and differences among species (Table 4, *I*).

The clover root DM was higher than shoot DM, as reported by Kunelius et al. (1992) for red clover (*Trifolium pratense* L.). However, the experimental site affected the root yield, and the root yield of white clover (*Trifolium repens* L.) was especially high on sandy soil at Pälkäne in comparison with on the silt loam at Laukaa (II). Also the root:shoot ratio of all species was much higher at Pälkäne. Although there was greater recovery of roots in sandy soil than in loamy soil, on account of the easier separation of roots and soil, characteristics of soil and differences in climate apparently affected root growth, and thus the biomass production was highly dependent on conditions.

The above-ground biomass N concentration (N-%) of black medic (*Medicago lupulina* L.) in late autumn was lower than that of the clovers, 2.8-2.9 and 3.6-3.8%, respectively (III), contrary to the report of Marstorp and Kirchmann (1991). Differing results might be expected as N-% varies during growth (Wivstad 1997) and according to conditions. The N-% of WR (1.2-1.4%) and IR (1.3-1.8%) was lower than that of timothy (2.1-2.4%), contrary to findings of Garnier and Vancaeyzeele (1994), who found that the N-% of annual grasses was higher than that of perennials. They however worked with non-limiting nutrient conditions, and possibly the increased N-limiting growth conditions during these experiments had an effect. Moreover, according to Garnier et al. (1997), the variation among species in both groups of annuals and perennials was high, and the N-% of timothy was among the highest of the perennials.

Differences among species in terms of N-% of roots were similar to those for shoots, al-

Table 4: Differences among undersown species in relation to effects on cereal grain yield and N leaching. Comparisons are made according to measured factors, with contribution from relevant literature for factor *L*.

	Studied factor					
	G	*H*	*I*	*J*	*K*	*L*
Undersown crop						
White clover	H	S	M	N	O	M
Red clover	H	S	M	L	N/O	L
Black medic	H	--	L	M	O	--
Timothy	H	--	H	M/H[2)]	S	--
Westerwold ryegrass	M	M	M	M/H[2)]	N	N
Italian ryegrass	M	--	S	S	N	--[3)]
Winter wheat	L	--	H	L	O	--
Meadow fescue	H	H[1)]	--	--	--	N[1)]

S = superior, H = high, M = medium, L = low or occasional, N = no effect, O = opposite effect, -- = not studied
G: Cereal grain yield in the year of undersowing
H: Cereal grain yield in repeated undersowing
I: Root dry matter yield in late autumn
J: Decreasing soil NO_3-N in autumn
K: Decreasing soil NO_3-N in spring (compared to previous autumn)
L: N leaching risk in the course of time
[1)] According studies in a mixture with red clover
[2)] With high seeding rate
[3)] Increasing risk according to literature

though at a reduced level (II, III), similarly as reported by Hauggaard-Nielsen et al. (1998). Although in a controlled environment similar N-% for roots and shoots has been reported (Wivstad 1997), the N-% values for clover root samples here were nearly half those for above-ground biomass. It is obvious that cereal and weed roots and other organic residues, which were not able to be separated out completely, decreased somewhat the root N-% of legumes. Furthermore, the higher proportion of non-legume material in samples may be the reason for the decrease in root N-% with an increase in N fertilization at Pälkäne, which contrasted with the situation for shoots (II).

The N yield of red clover in late autumn in shoots and roots averaged 30 kg ha^{-1} (I, III). Competition greatly restricted growth in undersowing as N yield from nearly 100 kg N ha^{-1} to over 200 kg ha^{-1} in one growing season was reported for pure red clover stands by Känkänen et al. (1998). Clearly higher N yields following undersowing have however been reported from the southern coast of Finland (Kauppila and Kiltilä 1992, Kauppila and Lindqvist 1992), and the variation here refers to the higher capacity of undersown red clover to produce N through BNF. The N yield of white clover was normally higher than that of red clover (I, III), although N yield of white clover roots remained low at Laukaa (I). Den Hollander et al. (2007a) found that in The Netherlands the total N yield of red and white clover was similar, but differed from those of other clover species, whereas in this study the N yielding capacity of all three legumes differed (Table 3, *B*). The shoot N yield of black medic at a high seeding rate was rather high, 33 kg ha^{-1}, but the root N yield (9 kg ha^{-1}), measured at standard seeding rate, remained low compared with that for clovers (15 kg ha^{-1}) (III).

The highest N yield of grasses, in terms of shoots and roots combined, approached 40 kg ha^{-1} for IR whereas values for timothy and WR remained at about 20 kg ha^{-1} (III). The difference between IR and timothy was mainly because of N in the above-ground biomass. Similarly, Sturite et al. (2007a) measured enhanced uptake of N by IR in comparison with that of perennial meadow fescue (*Festuca pratensis* Huds.) in Norway, although N content of roots did not differ significantly. Capacity of species to absorb N can be ranked (Table 3, *A*), but the realized N yield of grasses depends on available SMN. Andersen and Olsen (1993) reported that N absorption in above-ground material of undersown IR was 16 kg ha^{-1}, but rose to 44 kg ha^{-1} when 50 kg of fertilizer N was added after barley harvest.

3.1.2 Soil nitrate N in late autumn and spring

The average soil NO_3-N content without undersowing in late autumn for the experimental sites was less than 20 kg ha^{-1} in the 0 – 90 cm soil layer, which is a low figure compared with those reported from many other studies (e.g. Hauggaard-Nielsen et al. 1998 in Denmark), although not rare under Nordic conditions (e.g. Solberg 1995 in southeast Norway). Substantial variation (II, III), however, suggests occasional higher N leaching risk. In spite of low average soil NO_3-N content, the considerable influence of the undersown species on the N catching was evident by late autumn (III), as indicated in Table 4, column *J*. IR absorbed two thirds of the soil NO_3-N, which is in accordance with e.g. Martinez and Guiraud (1990), Svensson et al. (1994) and Lyngstad ad Børresen (1996), who reported decreased N leaching with undersown IR. WR absorbed clearly less N and was able to reduce soil NO_3-N content only half that of IR, resulting from an early end to WR growth, reported also by Karlsson-Stresse et al. (1996). Timothy reduced NO_3-N similarly to WR in 0 – 30 cm, but its effect did not reach to the deeper soil layers by autumn. Winter wheat did not reduce soil NO_3-N in late autumn, which was a disappointment considering the N yield of the biomass.

As a perennial grass, timothy has good potential to continue taking-up SMN during the beginning of the succeeding spring (Table 4, *K*). Correspondingly, Sturite et al. (2007a) found significantly smaller winter losses of N associated with perennial meadow fescue than with IR. Furthermore, according Pietola et al. (2009), the root system of timothy develops in spring more intensively than that of red clover and winter wheat, which is in accordance with the differences in soil NO_3-N during spring reported in paper III.

Legumes did not increase the soil NO_3-N in late autumn even with high N yields, but rather tended to act like grasses, although no significant decrease in NO_3-N was found (III and Table 4, *J*). Several studies have shown that although legumes fix atmospheric N they do not necessarily increase SMN in late autumn, and can even decrease it. Vyn et al. (2000) reported that undersown red clover lowered soil NO_3-N as effectively as non-legume catch crops sown after harvest in Canada. Lyngstad and Børresen (1996) did not find increased NO_3-N contents in the 0 – 60 cm soil layer in late autumn with undersown white clover in southeast Norway. Moreover, Arlauskiene and Maiksteniene (2008) reported reduced SMN during the post-harvest period as a consequence of legume cover crops in Lithuania. However, Garand et al. (2001) reported that although red clover did not significantly affect NO_3-N content of the 0 – 90 cm soil layer at cereal harvest in Canada, there were some cases of an increase in mid November over three years of trials. Here, during annual clover undersowing, some increase in NO_3-N was found at Laukaa, while at Pälkäne a decrease of NO_3-N was found only when WR was undersown (II).

SMN in spring increased at high seeding rate of white clover and black medic

(III), and varied during the annually repeated undersowing with clovers (I and Table 4, *K*). Similarly, Lyngstad and Børresen (1996) and Arlauskiene and Maiksteniene (2008) found higher contents in the succeeding spring after no increase of SMN followed from legumes in autumn. Garand et al. (2001) found an increase of soil NO_3-N in one year out of three as a result of undersown red clover, but Lyngstad and Børresen (1996) found more regular increase of SMN in spring when white clover was undersown. In contrast, Solberg (1995) reported decreased SMN in the 25 – 60 cm layer both in autumn and spring with undersown white and red clover, although the measurement was only from one year at a single site. It seems that the risk of increased N leaching in the context of undersown legumes is rather low, and release of N occurs in time for its use by the subsequent crop.

The tendency for higher SMN with white clover compared to red clover was obviously not related to increased release of N with increasing N-% or decreasing C/N-ratio of the biomass (Christensen 1986, Marstorp and Kirchmann 1991, Jensen 1992) because the N-% of the two clover species was similar. The initial immobilization of SMN, induced by a high initial C mineralization of red clover material (Dahlin et al. 2005), could have reduced the N release of red clover in this study also. The difference between the two species may be related to lignin and cellulose contents (Müller et al. 1988), which were however not analyzed here. The higher root to shoot ratio of red clover (II, III) can lead to slower N release compared with that for white clover as the release of N has been found to be both lower (Müller et al. 1988) and slower (Sturite et al. 2007b) from roots than from other parts of the plant. However, the possible faster N release from white clover material was confounded here with many other factors, including higher above-ground N yield of white clover than of red (I and III).

Several factors other than fractions of cover crop material, e.g. growth in late autumn and after winter, affect the realized soil N values in field studies as described here. For instance, dying of black medic in autumn possibly led to the higher subsoil NO_3-N content in spring compared with that associated with other legumes (III). On the other hand, according to Kirchmann and Marstorp (1991), the N mineralization from black medic was faster than from clover species. Comparison of species concerning rapidity of N release is summarized in Table 3 (column *F*) according to the results and other reports, but considerable variation is apparent due to differing conditions.

3.2 Competition between main and undersown crop

Significant competitive pressure on the other component of the intercrop by oats, spring barley and spring wheat was reported by Helenius and Jokinen (1994), Andersen et al. (2007) and Ghaley et al. (2005), respectively. Consequently, spring cereals have good prerequisites to grow well with an undersown crop. In the same way as the actual yields of both components of a mixture are lower than that of the highest monocrop yield of a component (Helenius and Jokinen 1994), an undersown crop can decrease the main crop yield. Ohlander et al. (1996) suggested that the negative effect of an undersown crop on grain yield is expected when the yield level of a cereal is otherwise low. On the other hand, undersowing, compared with a pure stand, often reduces DM of cover crops, but yield of the intensively growing main crop can remain unaffected, as when Baributsa et al. (2008) interseeded corn with red clover. Consequently, competition can decrease inputs to the N cycle when legumes are concerned. Talgre et al. (2009) found that N input to soil in the case of undersowing barley with legumes was about 30 % lower than of pure sowings of the same legumes.

3.2.1 Growth before and after cereal harvest

The number of undersown plants decreased in 1996 almost by half, and in 1994 and 1995 by a third between GS 22-23 and GS 60-69 (Zadoks et al. 1974) of barley (IV), suggesting that establishment does not necessarily indicate the degree of subsequent competition. This is in agreement with Decker et al. (1973), who found that cessation of seedling growth was due to competition with companion crops, especially under unfavourable growing conditions.

Legumes did not achieve high DM by the time of cereal harvest. The highest shoot yield, 180 kg ha^{-1}, was reached by black medic at a high seeding rate (III). Thus clovers produced the major part of their above-ground biomass after cereal harvest, as reported by Ohlander et al. (1996). Also timothy produced its biomass mainly during the post-harvest period and even IR doubled its shoot DM, but WR grew to a reduced extent and winter wheat growth was poor after harvest. The above-ground DM of IR and winter wheat at barley harvest was highest, 900 kg ha^{-1} with a high seeding rate, when the shoot yield of WR was small and that of timothy even smaller at 210 kg ha^{-1} (III). Robson et al. (1989) ranked the competitiveness of grasses according to their speed of establishment and rate of tillering, and concerning the species, which were the same as those included here, the ranking was equivalent to the DM at barley harvest in this study. Robson et al. (1989) also noted that clovers in a mixture with ryegrasses were the weaker competitors, as despite good establishment they suffered due to the rapid tillering of ryegrasses.

Clovers grew ideally here, but greater differences between growth rhythms of legumes were found elsewhere. Den Hollander et al. (2007a) found that in spite of a two-day delay in red clover establishment compared with other clovers, it competed more strongly than white clover three months later because of the threefold difference in canopy height. Although the biomass produced by cereal harvest is normally a good indicator of the competition by the undersown crop (Ohlander et al. 1996), initially a fast growing crop can compete more than a crop with slow early growth (Abdin et al. 1997), even if the biomasses end up being the same. Cereals are especially vulnerable to competition at the tillering stage (Bergkvist 2003), emphasizing that an undersown crop should ideally concentrate its growth towards the end of the season, in which respect legumes were superior and perennial grasses better than annuals (Table 3, *C*).

3.2.2 Cereal straw and grain yield

Winter wheat greatly decreased straw yield of spring barley, 600 – 1050 kg ha^{-1} (III), indicating the competitive nature typical of cereals, although winter wheat grows slowly compared with spring cereals (Huusela-Veistola and Känkänen 2000). When Robson et al. (1989) reported IR to be the most competitive species among several grasses, their arguments concerning rapid early growth and tillering apply to winter wheat. Obviously the fast initial growth of wheat compared with other undersown species caused the increased competition with barley, such that the straw yield decrease was almost twofold that associated with IR despite similar DM values at harvest. Furthermore, WR had similar effects as IR on barley straw yield, although the shoot yield at harvest was smaller, which also can arise from faster early growth of WR than IR. Effects of ryegrasses on barley growth in our field trials were much greater than those reported for the lysimeter study of Bergström and Jokela (2001), for which no significant above-ground biomass decrease of barley was established due to perennial ryegrass (*Lolium perenne* L.), which may originate from the more limited growth factors here. Timothy and legumes did not significantly affect the straw yield (III).

IR decreased grain yield by almost 500 and 1000 kg ha^{-1} using a standard and a high seeding rate, respectively (III), in accordance with the results of Kunelius et al. (1992), Andersen and Olsen (1993) and Lyngstad and Børresen (1996). The stronger competition of winter wheat resulted in an even higher yield decrease. The relatively small grain yield decrease due to WR, from 170 to 480 kg ha^{-1} with increasing seeding rate (I, III), compared with barley straw yield may have resulted from early cessation of growth. This was often evident as WR started to ripen only slightly later than barley, in accordance with Karlsson-Stresse et al. (1996), who found WR to be the only one of a wide selection of species that flowered during the year of undersowing. Because of the small competitive effect of timothy, corresponding with the findings of Spaner and Todd (2003), no negative effect on grain yield was established at low and standard seeding rates. Even at a high seeding rate for timothy the grain yield decrease was moderate and similar to that corresponding to a low seeding rate for IR and WR, about 200 kg ha^{-1}. Consequently, high grain yields in the year of undersowing are likely with perennial grasses, and achievable also with the less competitive legume species (Table 4, *G*).

Although no significant effect of legumes on grain yield in the year of undersowing was found, there was a tendency for yield decrease, which reached 230 kg ha^{-1} (I, III). Also Ohlander et al. (1996) reported moderate grain yield decrease associated with undersowing red clover. In contrast, Talgre et al. (2009) found that red clover did not induce any yield loss in the main barley crop, and according to Garand et al. (2001), spring wheat tolerates the competition by red clover because of its higher early growth rate, height advantage and more extensive root system.

Greater yield decrease with increasing seeding rate of white clover was detected, but this was not the case with other legumes (III). Otherwise no differences between clovers were found, contrary to the report of den Hollander et al. (2007b), where white clover was the weakest competitor among several clover species. However, the negative effect of red clover in their study was associated with a much longer growing time for the main crop than for the cereals used here. Furthermore, Solberg (1995) established a grain yield decrease with undersown red clover but not with white clover, although he used higher seeding rates than were used here. It is clear that realized biomass plays a major role in the differences among results. Arlauskiene and Maiksteniene (2008) reported considerable yield decrease of winter wheat, and the aboveground biomass of undersown red clover was about four times that reported here using the same N (II) or seeding rate (III).

Legumes did not increase the grain N in the year of undersowing (III), although mineralized N from legume roots can contribute to the N nutrition of an associated plant in an intercrop (Burity et al. 1989, Jensen 1996a, Jensen 1996b). Possibly the competition between species counteracted this positive effect. Although Garand et al. (2001) assumed, after a non-significant effect on grain yield, that no significant N transfer occurred from undersown red clover to spring wheat, the conclusion was obviously affected by the simultaneous competition of clover, as reported also in this study.

The effect of grasses on grain N was linked with effects on grain yield, and was emphasized at a high seeding rate (III). Winter wheat decreased grain N-% at all seeding rates, but mostly at the highest one, and IR decreased it mainly at the highest rate (unpublished data), although results from the lysimeter study of Lemola et al. (2000) suggest a decrease also at the standard rate. Possibly the competition for fertilizer and soil N increased more than other growth factors in such cases of high DM, reducing the available N at grain filling. Furthermore, the grain N yield of barley decreased more than that of shoot N yield of winter wheat at harvest at standard and high seeding rates, suggesting substantial competition throughout the main crop growth period.

3.3 Effects of annual undersowing

To reap their full benefits, undersown crops should be suitable for regular use, and for continuous cereal farming annual undersowing could be considered. This makes the evaluation of overall effects more difficult than in the case of individual single years of undersowing, although even a catch crop grown in one year can both increase and reduce N supply to the succeeding crop. This was pointed out by Thorup-Kristensen (1993), who termed the latter pre-emptive competition, and moreover showed that finally the rooting depth of the succeeding crop confirms the whole effect in terms of N leaching in the complex system of catch crops and main crops. Furthermore, when grown annually, the competitive effect of an undersown crop and the residual effects of previous crops are confounded. Optimally the competition with the main crop is low and previously absorbed N is released at the most opportune time for cereal use. Usually an early start in spring in release of residual N is desired, which Hauggaard-Nielsen et al. (1998) suggested as a probable key determinant for DM production of a subsequent cereal crop, as it benefits from freely available N at bushing and at the beginning of stem elongation.

3.3.1 Varying conditions between years and sites

During seven years a post-harvest air temperature sum (>0°C) of 500 was reached at Laukaa only twice, and at Pälkäne not at all (I), whereas at Vihti it occurred once during four years (IV). It indicates that establishing a cover crop by undersowing was justifiable, as according Schröder (2001) such a sum is necessary for sufficient cover crop growth if it is sown after a main crop. Varying weather conditions and differing duration of post-harvest growth resulted in large differences between years in biomass and N yields, similarly as reported by Lyngstad and Børresen (1996), Abdin et al. (1997) and Sturite et al. (2007a). The above-ground DM ranged in long-term trials from 100 to 3600 kg ha^{-1} (II) and the N yield in shoots and roots from 3 to 160 kg ha^{-1} (I). The low yields were related to low precipitation in early summer or early autumn, or with low temperatures between harvest and ploughing. Results over an extended period obviously reduced the risk of drawing false conclusions due to a narrow range of conditions, but also showed the impossibility of gauging expected impacts of undersowing precisely.

N-% in clovers in late autumn was higher than at harvest, 3.6-3.8% and 2.5-2.9%, respectively (III). However, this is contrary to the report of Wivstad (1997), who recorded a decrease in above-ground N-% of red clover between corresponding dates in a greenhouse experiment. One possible reason for the difference was the strong growth of leaves after cutting at harvest, as according to Wivstad (1997) the main reason for the decrease of N-% during ageing was the decreasing proportion of leaves, whose N-% was about double that of stems. Differing N-% in the same undersown species has been reported from elsewhere also (e.g. Marstorp and Kirchmann 1991), and for which differing growing times and growth stages are obvious underlying reasons.

A large difference was recorded in N yield of WR at Pälkäne and Laukaa, (at 90 N); on average 53 and 14 kg ha^{-1}, respectively (I). A significant influence of experimental site was reported also by Andersen and Olsen (1993), Lyngstad and Børresen (1996) and Abdin et al. (1997). In addition, release of N during the winter varies considerably from year to year, depending on the climatic conditions. Variation in weather conditions was recorded (I: Table 1) in four periods, between the end of soil frost in spring and the first soil frost in autumn, assuming that a cold winter period has only minor effects on N losses. However, according to the simulations of Blombäck et al. (2003), increase in mineralization rate in late winter and early spring was correlated with the freezing periods during winter. Koenig and Cochran (1994) suggested that physical rather than biological processes caused the substantial biomass loss from crop residues during the subarctic winter. Sturite et al. (2007a) mentioned severe freeze-thaw episodes in early autumn followed by early snowfall, a prolonged period with snow coverage and relatively high winter temperatures as particular reasons for nutrient losses from plant tissue. Thus it is presumed that different winters also played a role in differing soil N levels in spring (II).

3.3.2 Differing effects of species on grain yield

The positive effect of undersown clovers on cereal grain yield was evident even when sown annually, and was on average 280 kg ha^{-1} (I). A difference between red and white clover was not established (Table 4, *H*), although the above-ground N yield of the latter was higher, as in paper III. Contrary to us, Marstorp and Kirchmann (1991) and Solberg (1995) reported higher N and grain yield of the crop succeeding white clover than when following red clover. Here, the effect on the succeeding cereal yield was not studied after a separate undersowing year, which partly explains the smaller effect compared with that of Talgre et al. (2009), for example, who reported that the grain yield of a successive oat crop increased by 1400 kg ha^{-1} after red clover.

We found no improved N availability from WR residues over time (I), contrary to findings of Schröder et al. (1996) and Berntsen et al. (2006) with repeatedly undersown ryegrass. WR decreased the grain yield by 230 kg ha^{-1} on average, which is not much less than the effect of the competition in the year of undersowing (III) and actually similar to the effect for the first undersowing year (I). This is in accordance with Lyngstad and Børresen (1996), who reported grain yield decrease with repeated undersowing of IR, ranging from 2 to 12% in experiments similar in duration to ours. The relatively low N yields in their experiments and those reported here (I) probably interfered with the increased N availability over the rather short term. Although IR was an interesting species for inclusion in the long-term trials because of its substantial N catching capacity, it probably would have had little effect on increasing the N availability as its N-% was lower compared with that of WR (III). In contrast, the higher N-% and lower competitive effect of timothy might lead to increased N availability sooner, although this is debatable.

According to grain yield results over the two years after the undersowing period (I), no significant soil improvement occurred. However, we did not measure soil fertility factors as Schröder et al. (1996), who found more stable aggregates but no significant effect of IR undersown in maize on SOM content after six years. Marked effects were anyhow not expected as biological transformations in soil take place over a long time, as reported by Olson et al. (1986), who found no consistent benefit to corn after four years of interseeding with alfalfa and rye. It seems that a six year period was too short for substantial improvement in soil fertility at the experimental sites, or that the circumstances for benefits to come about as higher yields were not otherwise favourable. Effects can depend on initial conditions. Hansen et al. (2000b) found that introduction of ryegrass as a catch crop after 25 years of removal of all harvest residues caused a rapid yield increase in spring wheat. As the N yields of legumes were moderate (I: Table 2) and also small in the last year of undersowing, and as the effect of undecomposed residues decreases sharply after the first year (Fox and Piekielek 1988), the lack of a residual effect in the second year after undersowing was understandable. No long-term effect, even after red clover, was evident, although Müller and Sundman (1988) recommended using it instead of white clover, if N recovery for the subsequent crops over a longer period is aimed at.

3.3.3 Soil mineral N in long-term undersowing

The soil NO_3-N before winter was increased by annual undersowing of clovers at Laukaa during periods 2 to 4 (II), but the increase was so small that it did not provide clear evidence of increased N leaching risk. Moreover, although annually undersown white clover increased SMN at sowing in spring in period 2 at all fertilization rates and in period 3 at 0 N (I), but not at the same seeding rate when undersown once (III), this at most implies a possible cumulative effect of annually undersown white clover. Such a cumulative effect might have been expected, however, as decomposition and N release from legume material is reported, e.g. by Fox and Piekielek (1988), to continue over several years. The release is however emphasized during the first year, and it is obvious that although in the long-term experiments biomass decomposition of more than one year's cover crop occurred simultaneously, the N released in each year was mainly from the preceding year's biomass. Furthermore, except for modest N yields, a high retention rate in the soil possibly induced relatively small loss of released clover N, as in the study of Müller and Sundman (1988).

The effect of six years of undersowing with WR had no effect on soil NO_3-N in periods 3 and 4 (II). Conditions during long-term experiments, together with N inputs and realized crop growth, apparently did not favour increased N release, contrary to the report of Kumar et al. (2001), who found that the initially immobilized soil N was released during the third year as a result of low N residues. Also the results of Jenkinson (1977), Jensen (1992), and Thomsen and Jensen (1994), indicated that decomposition and release of N from ryegrass material continued for several years, supporting the case for cumulative N effects.

In addition to the fact that that a six year period was possibly too short for establishing cumulative effects, observation was confounded by substantial variation in SMN over years. Such variation is a normal phenomenon, as are the various effects of different crops on soil N over years (Andersen and Olsen 1993, Thorup-Kristensen 2006). Tendencies can often be detected during a long-term experiment however. Sturite et al. (2007a) found that the N content in seepage water was significantly higher for white clover than for IR one year in four. Consequently in the results reported here, N leaching risk was considered to be somewhat higher because of annual undersowing of white clover rather than red clover, whereas the increased risk associated with IR over the course of time was considered possible according to the results from the published literature (Table 4, *L*).

The NO_3-N content varied greatly among sampling times, being highest in May before sowing, and when measured in 1996 at Pälkäne, also clearly higher than in March before soil thawing (II), which is a critical time for N losses related to spring flow peaks (Gustafson 1987). The results were similar to those of Müller and Sundman (1988) who reported that the phase of highest N release from plant material occurred prior to the growing time of the subsequent crop, although they did not specify the timing of the release between autumn and spring. Soil was normally frozen during the winter when these studies were conducted, which is typical for Finland, and SMN during late autumn is expected to describe the situation before soil melts in spring. This assumption however conflicts with the results of Koenig and Cochran (1994) who found significant N loss from different plant residues during a cold winter in a sub-arctic soil. Although the data reported here were only from the three last years and were incomplete (II), they emphasise the consequences of weather conditions on potential N leaching losses similarly to Dahlin et al. (2005) in Sweden. Moreover, challenges caused by mild and rainy winters are set to increase because of climate change (Peltonen-Sainio et al. 2009).

The risk of N leaching according to the NO_3-N content was considerable on sandy soil at Pälkäne compared with the silt loam at Laukaa, in agreement with the results of Nieder et al. (1995), Lemola et al. (2000), Beaudoin et al. (2005) and Knudsen et al. (2006). The NO_3-N content also varied between years, being high at Pälkäne in May 1996 and 1997, and rather similar in the deepest than the two upper soil layers. The NO_3-N content deeper in the soil was not measured, and this is a valid criticism as Thorup-Kristensen (2006) found increased inorganic N deeper than 2 m and much lower values were associated with a catch crop grown over two seasons than were associated with the absence of a catch crop. Consequently, although the soil NO_3-N decreased to a low level by the following sampling time, it is not known if the SMN present during spring was used by the subsequent crop or was leached into the deeper soil layers during the summer. It seems however, that N was released at a suitable time for use by the following crop. Moreover, high evapotranspiration compared with precipitation during early summer further decreases the risk of leaching at that time.

It is noteworthy that high N mineralization in spring also occurred in plots of pure cereal, and thus undersown crops had minimal effect compared with total N release in the soil. However, at Laukaa white clover seemed to increase soil NO_3-N in spring, especially when it was otherwise high (II), in accordance with Dahlin et al. (2005). It is also notable that after a high yield in 1995, WR decreased soil NO_3-N clearly in autumn and the following winter (II), although it was otherwise rather ineffective (III).

It should be remembered that the long-term experiment here was actually of relatively short duration as far as issues of soil fertility are concerned. Hansen et al. (2000a) warned that if the higher mineralization due to long-term use of a cover crop is not taken into consideration by adjusting the cropping system, the reduction in nitrate leaching caused by the cover crop may not be as significant in the long-term. As several studies have indicated [Blombäck et al. (2003), Beaudoin et al. (2005), Berntsen et al. (2006)] regarding reports of a reduction in N leaching associated with long-term use of catch crops, it is presumed that annual use of cover crops reflects N mineralization in the longer term under Finnish conditions, although soil NO_3-N results presented in papers I and II only provide some evidence of this.

3.4 Solutions in cultivation technique

3.4.1 Choice of species

As IR was superior in decreasing soil NO_3-N in late autumn (III), its suitability for annual use might have been investigated rather than WR. Because of the higher N yields of IR, its residual effect could compensate for the increased competition compared with WR, although the slightly lower N-% might lead to a contrary effect. Similarly, as timothy grew better than meadow fescue (III), it would have been interesting to follow its performance in the sowing technique experiments. Moreover, as the inherent N-% of grass species varies greatly according Garnier et al. (1997), it would be possible to focus further on the N catching and release features of grass cover crops.

Red and white clover proved to be suitable species for undersowing, as reported by Kauppila (1983). This is also in accordance with Abdin et al. (1997), who found that red and white clover grew successfully under corn, and were not among the most competitive clover species. Talgre et al. (2009) found that lucerne (*Medicago sativa* and *Medicago media*) served as well as red clover for undersowing.

Winter wheat failed to decrease N leaching risk, and the grain yield decrease is in accordance with relay intercropping studies (Känkänen et al. 2004). Thus, winter wheat is not suited to catching N as an undersown crop, although, because of its other benefits, further studies in relay intercropping are worthwhile according to Roslon (2003).

Some species were rejected after poor growth in 1995 (III). It was, however, an extreme year because of exceptionally high precipitation during early summer, and did not represent normal conditions. It might have been interesting to study chicory (*Cichorium intybus* L.) further, for example, as Thorup-Kristensen (2006) reported that its roots extended deeper than 2.5 meters. Karlsson-Stresse at al. (1996) also thought chicory to be a promising species. Caraway (*Carum carvi* L.), which was also rejected for further studies after 1995, has since been sown on an increased area and adapting it for undersowing would be an interesting subject for further studies. There exist many additional species that might be suitable for undersowing. Here however, a wide assortment of grasses was studied together with the more obvious legumes, allowing a general comparison among species and evaluation of their features in an undersowing system, (Tables 3 and 4).

The results suggest good possibilities for being able to combine the useful features of various species in seed mixtures to achieve specific aims such as catching N in autumn and spring with a mixture of IR and timothy. On average the N-% in a mixture of red clover and meadow fescue was 0.2 – 0.6% lower than in pure red clover (I), corresponding with the findings of Hauggaard-Nielsen et al. (1998), who reported the C/N-ratio for both shoots and roots to be intermediate in a mixture of ryegrass and white clover compared with individual pure stands. The targeted proportion of species was however reached only once in four years (IV), indicating that it is not possible to predict accurately the outcome of legume-derived positive N-effects (Nykänen 2008) and grass-derived immobilization (Hauggaard-Nielsen et al. 1998). In an optimal instance, a mixture can be self-regulating, where a non-legume can grow more and utilize N when there is a surplus of it in the soil (Øyen 1991), whereas under poor soil N conditions legumes can produce N that can be used by the main crops in rotation. Moreover, timothy as a perennial grass in a mixture with an undersown legume could also use the N released in the following spring, as Goodman (1991) reported for N transfer from white clover to ryegrass following winter.

3.4.2 Seeding rate

Doubling the seeding rate nearly doubled the plant number, although the relationship between seeding rate and plant number was not always strict. On average, IR, WR, timothy and black medic exceeded 100 plants m^{-2} even at a low seeding rate, whereas white and red clover reached 100 and 75 plants m^{-2}, respectively (unpublished data). Establishment was good on average compared with the findings of Stenberg (1998), for example, who by using a similar seeding rate for perennial ryegrass, as was standard here, frequently failed to reach the target of 100 plants m^{-2}. According to the literature referred to in this dissertation, a wide range of seeding rates can be used, although the values normally range between the high and low rates reported in paper III.

Increasing the seeding rate increased the biomass of undersown crops at cereal harvest (III), as reported by Kvist (1992). This ensured establishment at a higher seeding rate also often increased competition with the main crop, similarly as found by Helenius and Jokinen (1994), who reported that one component in an intercrop responded to the presence of the other particularly at high densities. In spite of increased competition, increasing number of grass plants had only a small or negligible influence on soil NO_3-N, which diminished in late autumn (III). Consequently, less seed than the standard recommended rate should be used for a strong competitor such as IR, which catches N well even at a low seeding rate. As timothy did not significantly decrease grain yields, even at high seeding rates, a relatively high rate is advisable to increase N take-up. However, when grown in a mixture, the required plant number for timothy decreases and IR absorbs N effectively in autumn so that the lowest seeding rates for the two grass species should suffice.

As seeding rate of legumes had a negligible effect on soil NO_3-N in late autumn (III), and their moderate competition was in accordance with Kauppila (1983), a large number of legumes seems safe. Karpenstein-Machan and Stuelpnagel (2000) also recommended high seeding rates for crimson clover (*Trifolium incarnatum* L.) when intercropped with highly competitive rye in order to reach high BNF. However, realized plant number varies greatly, and Arlauskiene and Maiksteniene (2008), for example, only doubled the plant number by using five times the seeding rate for red clover than was used here (IV). Hollander et al. (2007a) suggested that small-seeded species are especially sensitive to conditions that might result in poor establishment, when in two subsequent years the ratio between seedlings and sown seeds of white clover was 0.07 and 0.31, respectively. Consequently, as growth of clovers largely depends on ambient conditions, the standard seeding rate or an even higher one seems justifiable.

3.4.3 N fertilization rate

The above ground and root yields of clovers were often more than double at 0 N than at 90 N (II). The decrease in legume DM with increasing N fertilization evidently stems from better growth and competition of the main crop. Correspondingly Ghaley et al. (2005) reported that fertilizer N enhanced the competitive ability of wheat and decreased the proportion of pea (*Pisum sativum* L.), and Helenius and Jokinen (1994) concluded that the differential demand for soil N modifies the competitive relationships between the components in intercropping legume and non-legumes.

N fertilization had a positive effect on shoot and root yield of undersown WR (II), but this influence was smaller than the contrary effect for clovers. Kauppila and Kiltilä (1992) found effects analogous to those reported here with clovers and ryegrass shoots, but the root yield of IR decreased with increasing N fertilization. Lyngstad and Børresen (1996) reported that the increase of IR biomass with increasing N was substantial, whereas the decrease of white clover biomass was relatively small. Ohlander et al. (1996) reported that the shoot yield of undersown ryegrass was similar at 80 and 40 kg ha^{-1} N, but that of red clover was about double the latter. All in all, N fertilization obviously has a negative effect on undersown legumes, whereas its effect on grasses is less predictable because of the influence on the competitive relationship between two non-legumes.

N fertilization was moderate or even low for cereals, which obviously reduced residual N in the soil, decreased the amounts of absorbed N, and possibly decreased the residual N effect in the case of WR (I and II). Correspondingly Lyngstad and Børresen (1996) and Schröder et al. (1997) reported that the N effect of grass cover crops on the successive crop could be negative at low N application rates and positive at high rates. Thorup-Kristensen (1993) found that an increase in SMN after an IR cover crop increased with increasing N fertilization of the successive crop, suggesting that N fertilization should be reduced after cover crops. It seems that N fertilization should be fitted with the N content of incorporated cover crop biomass, and thus determining its N-% would be valuable. Also in that case however, N release could increase later. Berntsen et al. (2006) suggested that in continuous use of ryegrass catch crops N leaching increases after approximately ten years if fertilizer N application is not reduced. Consequently, with a pre-history of cover crop use, N fertilization could be reduced without causing yield reductions (Hansen et al. 2000b). Thus, in the long run, the increased N mineralization should be taken into account in an adaptive undersowing system.

Grain yield increased in the presence of undersown clovers at Laukaa by an average of 710, 460, 330 and 250 kg ha^{-1} at 0 N, 30 N, 60 N and 90 N, respectively (I), and the reduction in the positive effect with increasing N application was analogous to that reported by Badaruddin and Meyer (1990), Lindén and Wallgren (1993) and Vyn et al. (2000). The grain yield increase with clovers at low N was much lower however at Pälkäne, where grain yield at 0 N was otherwise higher and the effect of N fertilization smaller than at Laukaa. Correspondingly, Lyngstad and Børresen (1996) found that during four years of undersowing white clover without N fertilization, there was an increase in the cereal grain yield at an experimental site supporting a low yield level, but not at a site associated with high yields.

N-fertilization replacement value (NRV) for clovers at Laukaa was 29, 19, 14 and 10 kg ha^{-1} at 0 N, 30 N, 60 N and 90 N, respectively. NRV relative to measured amounts of N in legume biomass at ploughing was about half and one third at 0 N and 90 N, respectively. According to the data in paper I, the average NRV at both sites and for all N fertilization rates was 15 kg ha^{-1} for red and white clover, and 13 kg ha^{-1} for the mixture of red clover and meadow fescue. NRV for WR was negative, at -12 kg ha^{-1}. Thus, results from Pälkäne clearly decreased the average NRV for clovers, although their N yields were, with few exceptions, similar or higher than those at Laukaa (I: Table 2). However, at Laukaa the effect was slight compared with the results of Garand et al. (2001), who concluded that N fertilizer application to spring wheat could be reduced by 90 % of the recommended 90 kg ha^{-1} from the second year of annual undersowing with red clover. Consequently, the need of the main crop and use of the current undersown crop should take into account the fertility of the field when of the rate of N fertilizer application is determined based on N yield and supposed release of N from preceding legumes. It is apparent that further research into N fertilization in the context of undersowing would be valuable.

3.4.4 Sowing technique

Red clover and meadow fescue established faster and had higher plant number under dry conditions if seeded through coulters, but with a high precipitation sum after sowing, broadcasting resulted in higher numbers of red clover plants (IV), as noted by Øyen (1991). Thus, although Andersen et al. (2007) suggested that sowing practices represent opportunities for manipulating intercrop competition, it is a highly condition-dependent measure. Seeding through coulters increased the proportion of meadow fescue, which is in accordance with Laidlaw and McBride (1992), but only when its share was otherwise low. However, broadcasting with seed-covering equipment behind the drill leads to the smallest variation in DM among years, which is desired as the estimation of the cover crop effects becomes easier. Press-wheels or a long-tined harrow attached behind the drill were recommended in paper IV instead of the cage-roller, which increased weed biomass. As the grain yields associated with these techniques, without rolling after undersowing, were 300-450 kg ha^{-1} greater than those following conventional seeding through coulters, they seem justifiable for use. In contrast, separate rolling with a continental Cambridge roller after undersowing seemed not to be profitable (IV).

The undersown species were seeded simultaneously or immediately after the cereal in this study, as delayed undersowing has not been shown to be beneficial for yield formation of the main cereal crop in the field, and has been found to substantially decrease biomass production of the cover crop (Kvist 1992, Ohlander et al. 1996). Establishing a cereal crop in a living perennial legume crop is an interesting option, which however can easily result in a large decrease in cereal yields (Williams and Hayes 1991) and thus needs improving (Bergkvist 2003) and merits more research.

3.4.5 Timing and method of cover crop termination

Autumn ploughing was done as late as possible (I, II), not only to ensure sufficient growing time for cover crops, but also to decrease the risk of N leaching (Breland 1994, Känkänen et al. 1998, Magid et al. 2001, Korsaeth et al. 2002, Lahti and Kuikman 2003). Late autumn ploughing can even decrease the N losses compared with spring incorporation, as when a crop overwinters a great deal of N in the above-ground biomass present in autumn is not recovered in the biomass in the spring (Sturite et al. 2007a, Känkänen et al. 1998). Furthermore, tillage in mid-October under Finnish conditions was supported by Lemola et al. (2000), who suggested that spring tillage reduced N leaching only on peat soil when spring barley was undersown with IR.

Late autumn incorporation of green manure has been reported to be more reliable for Finnish conditions than ploughing or reduced tillage in spring to secure good spring cereal yields (Känkänen et al. 1999, Lahti and Kuikman 2003). On the other hand, Talgre et al. (2009) reported that spring ploughing of green manure in Estonia, compared with autumn ploughing, gave 4-15% extra yield. Also Korsaeth et al. (2002 in southeast Norway) concluded that synchronization between net N mineralization and plant N uptake would be better through spring rather than autumn incorporation, although large winter losses due to freeze-thaw damage and surface runoff counteract the spring incorporation. The timing of incorporation is obviously site dependent, as Ball et al. (2007) suggested ploughing in March in UK, when the cold restricts N mineralization initially, but N becomes available for early crop growth as the temperature increases.

Reduction in N leaching associated with growing perennial grasses is, according to Kyllingsbæk (1989), improved if incorporation is delayed in autumn or postponed until the next spring. As IR did not survive the winter, and the effect of winter wheat on SMN was negligible, a capacity to absorb mineral N in spring can be expected only for perennial species like timothy. According to results in the spring after undersowing (III), timothy decreased NO_3-N to a similar extent in different soil layers. However, the effect in the deepest layer was pronounced in spring compared to the preceding autumn and in taking account of the low actual NO_3-N content. In that respect timothy showed a similar tendency to empty deeper soil layers in spring, as did overwintering grasses in the study of Thorup-Kristensen (1993), although there spring incorporation increased SMN in the topsoil. Magid et al. (2001) did caution, however, that substantial immobilization of N can be detrimental for the following crop if tissues with a high C/N-ratio are ploughed-under shortly before sowing. Thus, although spring incorporation allows timothy to absorb N in spring, examining the effects further during the subsequent summer would require studying cultivation methods and after-effects in this context.

Although late autumn incorporation seems to be applicable for incorporation of N-rich material in Finland, spring ploughing is not a suitable option for heavy clay soils, which are common. Instead, minimum tillage and no-till techniques allow the growth of cover crops until spring sowing on clay soils. However, according to Kristensen et al. (2000), mineralization of N in no-till soil is low. Furthermore, contact with the soil affects the decomposition process differently with different crop residues (Henriksen and Breland 2002). Consequently, integrating direct drilling and cover crops needs dedicated research.

Removing straw after cereal harvest, which was done to enhance cover crop growth, can affect N mineralization and leaching. According to Thomsen and Jensen (1994), recovery of ryegrass N in the succeeding barley crop was higher when the undersown IR was incorporated without rather than with chopped barley straw. When Korsaeth et al. (2002) incorporated a mixture of white clover material and barley straw, microbial N demand during C utilization of straw resulted in net N immobilization after transient accumulation of clover-derived inorganic N. Arlauskiene and Maiksteniene (2008) found that both the content of NO_3-N in filtration water and SMN in the following spring were reduced if straw was incorporated with clover cover crops, compared to the case without straw. This is expected as cereal straw mixed with legumes markedly reduces the C/N-ratio of the biomass compared with pure legumes (Talgre et al. 2009).

Chopping straw in the field is normal practice, which may lower still the risk of N leaching with undersown clovers compared with what the results here suggest (II, III). Furthermore, if undersown plants at cereal harvest are higher than the cutting height, part of their biomass is either removed with the straw or chopped in the field. Cutting height is one factor that affects the portion of old and new plant parts in a crop following post-harvest growth that may influence the N release, and which decreases with increasing plant age (Müller et al. 1988). Thus, the effect of removing or leaving the straw depends on species involved, cutting height, C/N-ratio and even particle size of residues, which has been shown to affect decomposition and mineralization-immobilization turnover of N in the soil (Jensen 1994). However, it is presumed that the undersown cover crop itself plays a major role in the system.

3.4.6 General border conditions

Undersowing represents a cost to the farmer, which is partly compensated for by BNF, but improvement of the overall productivity of cultivated soil can only be expected over the long term. This study demonstrated the feasibility of simultaneous sowing (IV) and specified seeding rates (III), although undersowing inevitably requires financing, especially when to reduce N leaching by undersowing grasses. Seed costs of IR or mixtures of IR and timothy, according to current commercial prices, would be approximately €20 – 30 ha^{-1} and the yield decrease (III) associated with rather low cereal prices in 2010 double the costs even when a moderate seeding rate of about 10 kg ha^{-1} is used. Corresponding seed cost for clovers is approximately €40 – 70 ha^{-1} and the average benefit in yield increase from annual undersowing (I) is 30 €, which suggests that they are unlikely to be sown if no positive effects on soil fertility can be expected by farmers. However, the profitability of undersown legumes also depends on the farming system, N fertilization rates, and current soil fertility of individual fields. All in all, the future of undersowing systems depends on how valuable its environmental contributions are in addition to other factors.

Similarly as with all actions taken to reduce agricultural loading, it might be better to focus on the areas that contribute most to the current loading (Ekholm et al. 2007). Undersowing of highly competitive grasses that absorb N efficiently could be a focus for areas where there is a high leaching risk. Elsewhere undersowing can be used to substitute for mineral fertilizer N via BNF. Furthermore, if successful coexistence between an undersown and a main crop can be achieved, undersowing could ensure optimal N fertilization for good quality yields and reduced leaching as an alternative to decreased mineral N fertilizing (Granlund et al. 2007) as a separate action. Moreover, as undersown crops cover the soil and use water during the post-harvest period, there is an obvious role for them in reducing the annual variation in N losses, which according to Granlund et al. (2007) is strongly affected by hydrological processes. Furthermore, in addition to the N related aims, undersowing represents a means for improving agricultural biodiversity.

3.4.7 An adaptive undersowing system

A model of an adaptive undersowing system (Figure 1) was outlined in order to explain the benefits of undersowing by indicating the measures that could be introduced according to needs. The model starts from border conditions, showing that when the risk of N leaching is the main concern, cover crops could be used for catching N. Biological N fixation by legumes can substitute for fertilizer N, whereas both legumes and non-legumes can be used for diversifying cereal cropping. The greater the need for catching N, the higher the seeding rate for intensively growing grass species. However, the considerable competition with the main crop has to be borne in mind. When replacing expensive N fertilizer, high seeding rates for legumes increase N yields, but the competition with the main crop also increases. At the same time, decreasing the application of fertilizer N creates better conditions for legume growth. The primary timing of incorporation depends on species-specific traits, although it is limited by soil type. Continuous observation of growth, yields and conditions, and re-evaluation of the measures undertaken are all central to the model.

Using the model for an adaptive undersowing system in practice is undoubtedly challenging. The field experiments did not furnish complete answers that would contribute to the whole system and some components of the system are very difficult to control. Although the model is based on consistent understanding according to original publications and articles cited in this dissertation, further research is undoubtedly necessary to make it more comprehensive and realistic. Increased accuracy of the system would require analyses to be made on farm, which could transpire in the future but until then are substituted for by careful observation. However, as climatic conditions greatly influence crop growth and release and leaching of N, perfection cannot ultimately be reached.

It must be remembered that this system, which is based on cereal monoculture, is not ideal, and many of the aims of undersowing can also be achieved by diversifying crop rotations and improving cultivation techniques. On the other hand, the basic principles of undersowing introduced here are adaptable to commercial crops other than spring cereals as long as the competi-

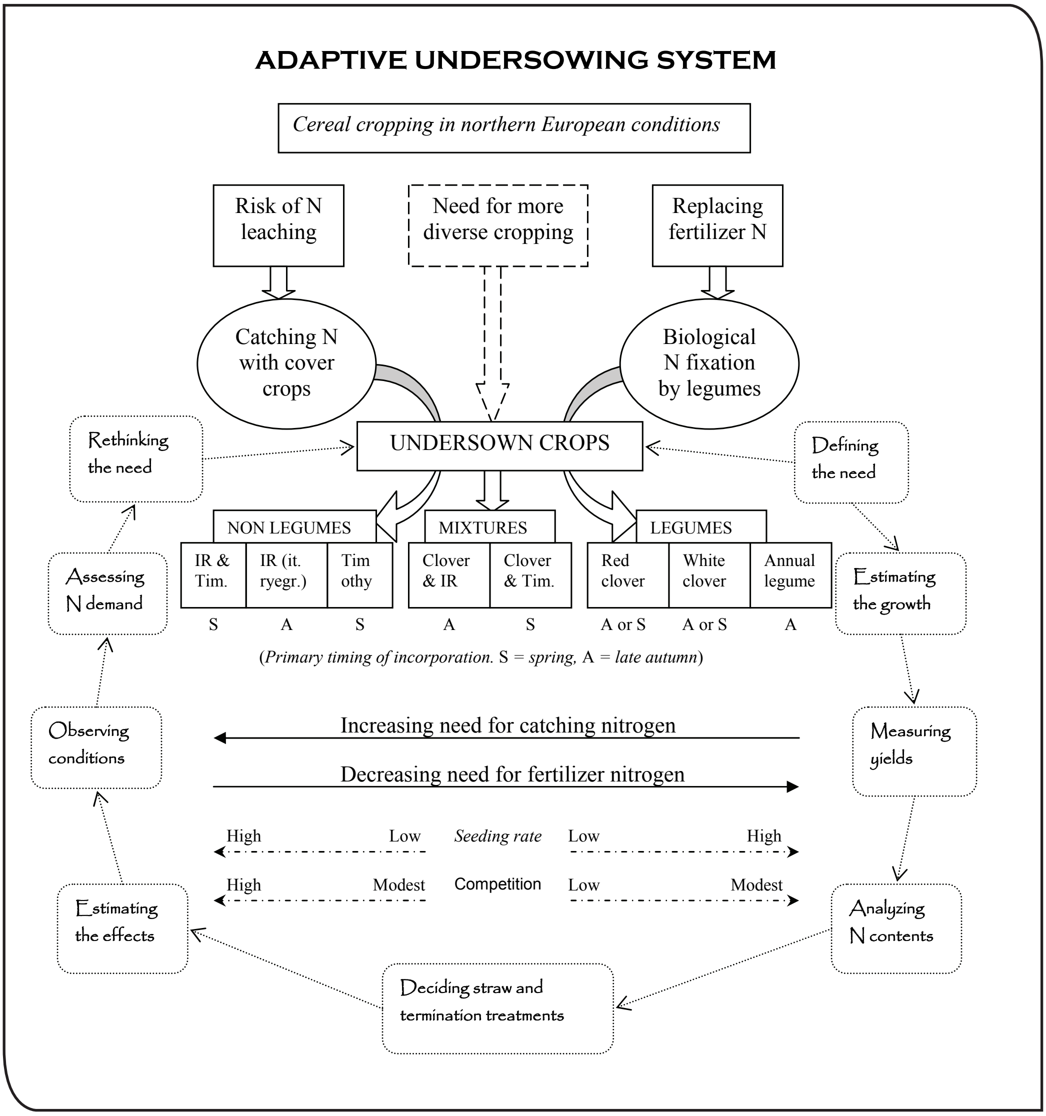

Figure 1. Schematic representation of decision making in an adaptive undersowing system. Uppermost are the strategic guidelines according to border conditions and in the middle the main decisions concerning cultivation, surrounded by continuous observation, estimation and re-evaluation.

tiveness and growing time of the main crop, and its capacity to take up residual N, are taken into account. The basis for the adaptive undersowing system however remains firm: choosing measures according to conditions and needs. It starts by defining the goal, proceeds with decisions concerning choice of species, seeding rates, termination of the cover crop and N fertilization, and includes continuous monitoring.

4 Conclusions

Quantified accumulation of N in above- and below-ground biomass of undersown crops in Finland demonstrated the capacity of legumes to fix N for use by subsequent spring cereals and the ability of grasses to take up soil mineral N during seasons where there is a risk of increased N leaching. Thus, the first objective of the study was fulfilled.

The effects of undersowing were very species dependent. WR and winter wheat decreased main crop yields greatly and were unsatisfactory regarding take-up of soil N in autumn. Consequently IR, which effectively reduced soil NO_3-N, is recommended when there is a high risk of leaching during autumn. Reduced competition with the main crop was registered for perennial grasses, among which timothy was the most reliable in terms of growth and effectiveness at catching N in the subsequent spring. The second objective was realized, although differences among legumes were greater than among grasses. It seems, however, that white clover slightly increased N leaching risk in the following spring, as did annual black medic, but the risk was lowered through use of red clover.

Concerning the third objective, the net effects of annually repeated undersowing of legumes on cereal grain yield were positive, and that of WR negative. WR seemed not to release significant amounts of N for use by a cereal crop during annual undersowing, which may result from low N-% and that a six-year period was possibly too short for establishing cumulative effects. However, as N-% of grasses varied among species and according to conditions, increased N release recorded for long-term use elsewhere, according to the references provided, has to be taken into account in annually repeated undersowing of grasses.

Crop husbandry practices affected the outcome of the undersowing system in many ways, indicating the importance of the fourth objective. Broadcasting with seed-covering equipment was a reliable method to establish an undersown crop. Only moderate seeding rates were needed for grasses to avoid substantial yield decrease of the main crop, but fairly high seeding rates could be used to ensure high N yield of a clover cover crop. Biomass production of undersown legumes decreased with increasing N fertilizer application, thus decreasing the residual N effect. Late autumn incorporation, which according to the literature reviewed, has earlier been reported to be associated with N-rich residues, worked well in the context of undersowing. Moreover, overwintering of timothy enhanced absorption of residual N in the soil, although the effects during the subsequent summer would require other studies.

It was surmised that various factors influence the implementation of undersowing. At first a strategic decision has to be taken if the target is to fix atmospheric N or catch it from the soil, or if a more diversified cropping and increased soil fertility are the main goals. When substantial negative effects of N leaching are expected, a mixture of IR and overwintering timothy is best as an undersown crop, but fertilizer N costs can be reduced by undersowing clovers. The benefits from mixtures of legumes and non-legumes lie in between, and red clover with timothy, for example, can be recommended because it results in relatively reduced competition and can replace N fertilizer to some extent without increasing the risk of N leaching substantially.

The model for an adaptive undersowing system highlighted the principles involved in using the system based on the base situation and goals, indicating the possibilities to realize the aims of the fifth objective. However, implementation of the system in practice requires considerable thought about conditions, realized cover crop growth and improved soil fertility over the long term. As for the undersowing system itself, the model needs continuous adjustment as more experience of undersowing systems is gained and more data are generated.

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