AGRONOMIC CHALLENGES FOR ORGANIC CROP HUSBANDRY

DOCTORAL THESIS IN AGROECOLOGY

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ACADEMIC DISSERTATION

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We now need an ecological enlightenment which revolutionizes our world and worldviews ... The change I have in mind is not easy to define, but it certainly would include a broad attachment to qualities of health, harmony, balance, diversity, peace, participation, and justice. Such a commitment does nothing to weaken the objectivity with which scholars handle facts and data. To the contrary, the crisis of sustainability has occurred precisely because of flaws, incompleteness, and biases in our data, facts, and logic. The transition to sustainability will require more complete facts, broader sorts of data, a more thorough integrative logic, greater intellectual creativity, and an even deeper commitment to truth. Environmental education is unavoidably political. At the heart of the issue is the total demand humans make on the biosphere and the way we have organized the flows of energy, water, material, food, and wastes, which in turn affects what political scientists define as the essential issues of politics: "Who gets what, when, and how"?

Orr 1994

ABSTRACT

With respect to resource management and environmental impact, organic farming offers rationales for agricultural sustainability. However, agronomic productivity is usually higher with conventional farming. This work aimed at investigating two factors of major importance for the agronomic productivity of organic crop husbandry, nitrogen (N) supply through symbiotic N fixation (SNF) and weed occurrence. Perennial red clover-grass leys and spring cereal crops subjected to regular agricultural practices were studied on 34 organic farms located in the southern and the north-western coastal regions of Finland. Herbage growth, clover content as a proportion of the ley and extent of SNF in perennial leys, and the occurrence of weed species and weed-crop competition in spring cereal stands were related to climate conditions, soil properties, and management measures.

The herbage accumulated from the first and the second cut of one- and two-year-old leys averaged 7.5 t DM ha^{-1} (SD ±1.7 t DM ha^{-1}); the clover content averaged 43.9% (SD ± 18.8%). Along with the clover content, herbage production decreased with ley age. Radiation use efficiency (RUE) correlated positively with clover proportion but despite low clover contents, three-year-old leys were still productive with regard to RUE. SNF in the accumulated annual growth of one- and two-year-old leys averaged 247.5 kg N ha^{-1} yr^{-1} (SD ± 114.4 kg N ha^{-1} yr^{-1}). It was supposed that if red clover-grass leys constituted 40% of the rotation, then the mean N supply by SNF would be able to sustain two or three succeeding cereal crops (green manure and forage ley, respectively), yielding 3.0 to 4.0 t grain ha^{-1}. Being a function of clover biomass, the SNF increased from the first to the second cut and thereafter declined with ley age. Coefficients of variation of clover contents (and SNF) between and within fields were around 50%, which was about twice as high as those of herbage production. The lower were the clover contents, the higher were the within-field variations of clover as a proportion of the ley. Low clover contents in one-year-old leys and increasing variability with ley age suggested that red clover growth was limited by poor establishment and poor overwintering. The proportions of clover in leys were lower and their variability was higher in the northwest than in the south. Soil properties, primarily texture and structure, had a major impact on clover proportion and herbage production, which largely explained regional differences in ley growth. Within-field variability of soil properties can be amended through site-specific measures, including drainage, liming, and applications of organic manures and mineral fertilizers. Overwintering and the persistence of leys can be improved by the choice of winter-hardy varieties, careful establishment and the appropriate harvest regime.

Mean grain yields of spring cereal crops amounted to 3.2 t ha^{-1} in the south and 3.6 t ha^{-1} in the northwest. At 570 and 565 m^{-2} for the south and northwest respectively, mean weed densities did not differ between the regions, whereas the respective mean weed biomass of 697 and 1594 kg dry weight ha^{-1}, respectively did differ. Weed abundance varied remarkably between single fields. The number of weed species was higher in the south than in the northwest. For example, *Fumaria officinalis* and *Lamium* spp.

were found only in the south. Frequencies and abundances of *Lapsana communis, Myosotis arvensis*, *Polygonum aviculare*, *Tripleurospermum inodorum*, and *Vicia* spp. were higher in the south, whereas those of *Elymus repens, Persicaria* spp. and *Spergula arvensis* were higher in the northwest. The number of years since conversion to organic farming, i.e. long-term management, was one of the variables that explained the abundance of single weed species. *E. repens* was the weed species whose biomass increased most with the duration of organic farming. Another significant variable was crop biomass, which was affected by short-term management. The presence of different weed species was related to the duration of organic farming and to low crop yield. This finding demonstrated that it was not the organic farming regime *per se*, which resulted in high weed infestation and low yielding crops, but failures in the understanding and the management of organic farming systems. Successful weed control relies on farm- and field-specific long- and short-term management approaches.

The agronomic productivity of ley and spring cereal crops managed by full-time farmers with an interest in organic farming was on the same level as of the mean for conventional farming. Given the many options for further improvements of the agronomic performance of organic arable systems, organic farming offers foundations for the development of sustainable agriculture. The main threat to the sustainability of farming in Finland, both conventional and organic, is the spatial separation of crop production and animal husbandry by region, along with the simplification of associated crop rotations.

Keywords: biological nitrogen fixation, BNF, case study, cereals, clover content, clover percentage, clover proportion, coastal regions, farm study, farm survey, Finland, growth model, herbage production, mixed ley, mixed grassland, organic farming, radiation use efficiency, RUE, red clover, spatial heterogeneity, soil properties, symbiotic nitrogen fixation, SNF, *Trifolium pratense*, variability, weed flora, weed occurrence, weed management.

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LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following publications:

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II Riesinger P & Herzon I (2008). Variability of herbage production in mixed leys as related to ley age and environmental conditions: a farm survey. Agricultural and Food Science, 17, 394-412.

III Riesinger P & Herzon I (XXXX). Symbiotic nitrogen fixation in organically managed red clover-grass leys under farming conditions. Accepted article. Acta Agriculturae Scandinavica, Section B, Soil and Plant Science.

IV Riesinger P & Hyvönen T (2006). Weed occurrence in Finnish coastal regions: a survey of organically cropped spring cereals. Agricultural and Food Science, 15, 166-182.

V Riesinger P & Hyvönen T (2006). Impact of management on weed species composition in organically cropped spring cereals. Biological Agriculture and Horticulture, 24, 257-274.

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CONTRIBUTIONS

The following table shows the major contributions of authors to the original articles:

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Logic of reasoning	PR	PR, IH	PR, IH	PR, TH	PR, TH
Material	PR	PR	PR	PR	PR
Analyses	PR, HE, JF, BT	IH, PR	IH, PR	PR, TH	TH, PR
Manuscript	PR, HE, BT	PR, IH	PR, IH	PR, TH	PR, TH

BT = Bengt Torssell, HE = Henrik Eckersten, IH = Irina Herzon, JH = Johannes Forkman, PR = Paul Riesinger, TH = Terho Hyvönen.

GLOSSARY AND ABBREVIATIONS

Accumulated herbage growth	In this work, calculated as accumulated first and second cuts plus (non-cut) aftermath of ley herbage.
Accumulated herbage production	In this work, calculated as accumulated first and second cuts of ley herbage.
Arable farming	Specialization in crop husbandry, no livestock
b_r	Root allocation
C	Carbon
CAP	Common Agricultural Policy
CEC	Cation exchange capacity
Clover proportion	In this work, the clover content expressed as a percentage of the clover-grass ley.
DC	Decimal Code
DCA	Detrended Correspondence Analysis
DM	Dry matter
EU	European Union
FAO	Food and Agricultural Organization
GLM	General Linear Modelling
GHG	Greenhouse gases
IFOAM	International Federation of Organic Agriculture Movements
IP	Integrated Production
IUCN	International Union for the Conservation of Nature and Natural Resources
K	Potassium
Livestock farming	Specialization in animal husbandry
Mixed farming	Integration of crop and animal husbandry on the same farm.
N	Nitrogen
OECD	Organization of Economic Cooperation and Development
OM	Organic matter
P	Phosphorus
PCA	Principal Component Analysis
pNdfa	Proportion of nitrogen derived from the air by symbiosis between bacteria and legumes.
SD	Standard Deviation
SNF	Symbiotic nitrogen fixation
SOM	Soil organic matter
RDA	Redundancy Analysis
RUE	Radiation use efficiency
UN	United Nations
UNPFA	United Nations Population Fund
WCED	World Commission on Environment and Development

1 INTRODUCTION

1.1 Agricultural sustainability through organic farming?

1.1.1 Dimensions of agricultural sustainability

Organic farming aims at sustainable agriculture, as discussed under the theme of the first international scientific conference of the International Federation of Organic Agriculture Movements (IFOAM) in 1977, 'Towards a Sustainable Agriculture' (Gips 1988). Research in organic farming is justified, provided that the particular farming concept in question is synonymous with sustainable farming practice, or that it can be further developed to meet most or all of the criteria for sustainable farming practice. The development of organic farming should also be expected to contribute rationales that improve the sustainability of conventional farming systems (Stockdale et al. 2001, Pimentel et al. 2005). Although some strongly dispute that organic farming might play any important role in the development of sustainable agriculture (Kirchmann & Thorvaldsson 2000, Trewavas 2004), there is general agreement that organic farming complies with a number of parameters of sustainable agriculture to a larger extent than conventional farming, including: (i) resources economy, (ii) environmental stewardship, and (iii) social effects. However, agronomic productivity appears to be a significant challenge for organic farming. Often discussion arises around the question of whether organic agriculture can feed the world, or not (Gewin 2004, Halweil 2006, Connor 2008). Driven by the conclusions resulting from literature reviews on the framework of agricultural sustainability, the paradigms and principles of organic farming, and the sustainability of organic farming, this work focuses on two main factors restricting the productivity of organic crop husbandry in northern conditions, nitrogen (N)-deficiency and weed infestation.

The environmental impact of any population is expressed as a product of three characteristics: population size, affluence, and the damage inflicted by the technologies used to supply each unit of consumption (Ehrlich & Holdren 1971). These factors are influenced by economic interests, cultures and values, and societal organisation (Dunlap 1993). There are limitations to the capacity of the ecosphere to satisfy human resource demands, assimilate wastes generated by human economic activity and regenerate its own viability (Costanza & Daly 1992). The sustainable use of natural resources indicates a consideration of these limitations. Literally, sustainability is the ability to 'keep in existence; keep up; maintain or prolong' (Neufeldt 1988). The idea of sustained yield is rooted in scientific conservation, the use of science to manage nature and natural resources efficiently and in the long term. Scientific conservation is one of the three generic modes of environmentalism documented by Guha (2000). Other strands include the moral and cultural critique of the Industrial Revolution and the idea of wilderness conservation, combining elements of morality, science and aesthetics. Each of these three varieties of environmentalism constituted a distinct response to the emergence and the impact of the industrial society (Guha 2000). Moreover, each of them has influenced the environmental movement (*ibid*.). In 1980 the International Union for the Conservation of Nature and Natural Resources (IUCN) introduced the term Sustainable Development, and suggested that the development of social and economic welfare ought to include considerations of resource limitations and ecosystem carrying capacities, in addition to taking into account the needs of future generations. The World Commission on Environment and Development (WCED) developed this new paradigm, and emphasized that attention ought to be paid not only to the ambiguous relationship between conservation and utilization of natural resources but also to the need for poverty alleviation and social equity (WCED 1987). Problems may arise in the reconciliation of the biophysical, social and economic dimensions of the Sustainable Development paradigm because of different time-scales and objectives (Tisdell 1996, Farrel & Hart 1998).

Food security is one of the universal human rights (UN 1948). In spite of the growth in the human economy during the last 50 years, undernourishment and starvation still prevail (FAO 2006). Agricultural yield increases are offset by rapid population growth (UNFPA 2007). Agronomic options for increasing food production include more cultivated land, improvement of soil fertility, intensified production and more efficient production per unit land area (Cakmak 2002). The fundamental need for food required by the expanding human population is ultimately restricted by the availability of suitable land (Wackernagel et al. 2006). The full scale launch of the Green Revolution in the 1960s was an attempt to shift the emphasis away from the carrying capacity in terms of space to increased agricultural productivity (Borlaug 2007). By increased crop yields the Green Revolution helped food supply to keep pace with the increase of 3.0 to 6.1 billion people of the world population from 1960 to 2000 (UNFPA 2007). High productivity per unit of agricultural land has relieved some of the pressure to increase the area of arable land, and saved erosive lands and areas rich in biological diversity from cultivation. However, on the land under agricultural management, intensification of production contributed to soil degradation, biodiversity loss, environmental pollution and global climate change (Cassman 1999). Agricultural productivity depends on fertile soils, water availability and life supporting services from natural ecosystems (Odum 1983, Bridges & Oldeman 1999). Thus, intensified agricultural practices also threaten the foundations of agricultural productivity. There is also increasing concern over the limitations of the fuel and mineral nutrient inputs necessary for modern agriculture (Pimentel et al. 1973, Smil 2002). Pretty et al. (2006) demonstrated that there are alternative methods to those of the green revolution that boost crop yields in developing countries.

Agricultural sustainability manifests as a desired outcome for agriculture that has been developed in response to concerns about environmental and socioeconomic threats to agriculture, and also as an approach to agricultural practices developed in response to concerns about detrimental impacts of agriculture to the environment and to the society. Lehman et al. (1993) define sustainable agriculture as consisting of agricultural practices that do not undermine our future capacity to engage in the production of food, fibres and certain other products. Crews et al. (1991) argue that long-term sustainability in agriculture is constrained solely by ecological conditions. The definition of sustainable agriculture might even be restricted to the maintenance of soil fertility (Thomas & Kevan 1993, Swift & Woomer 1993). However, others assume that in defining its sustainability, agricultural production cannot be separated from its ecological, social and economic environment. Consequently, a sustainable agricultural system is often defined as one that fulfils a balance of goals through time. These goals generally include the adequate provision for human food needs, environmental stewardship, social welfare and economic viability (Geng et al. 1990, Farshad & Zinck 1993). Emphasis either on biophysical constraints or on human needs and preferences lead to different and competing views of agricultural sustainability (Tait & Morris 2000).

Theoretical definitions of sustainability need to be transformed into practically oriented approaches. A framework of indicators is helpful in identifying and quantifying aspects of sustainability (OECD 2001). For example, indicators of agricultural sustainability proposed by Yli-Viikari (1999) for Finland relate to land use and crop management practices, resource utilization, impacts on the abiotic and biotic environment, human welfare in addition to that of animal production systems, and profitability.

1.1.2 Industrialization of agriculture

Agricultural production is a function of environmental conditions, socioeconomic structures and cultural preferences, and varies by scale, diversity and input intensity (Conway 1987). Subsistence agriculture is characterized by small enterprise scale, diversified plant husbandry and, usually, integration of animal husbandry in the farming system (i.e. mixed farm). The primary goal is security for the family. Having evolved through centuries, subsistence agriculture is structurally and functionally integrated in local environmental and cultural conditions (Lu & Li 2006, Devendra 2007). Where climatic and edaphic disadvantages constrain productivity, agriculture still primarily aims at subsistence (FAO 2006), but elsewhere urbanization, industrialization, and/or export-oriented agricultural policies have resulted in a transition from subsistence to commercial agriculture (Altieri & Rosset 1996). Commercial agriculture is based on plant varieties and livestock bred for output at higher production intensities. External inputs of fuels, fertilizers, pesticides, and feed increase the productivity per unit land and livestock. Costs for mechanization are compensated for by specialization and/or increase of farm hecterage. Mechanization replaces labour, and contributes to increases in scale and a decline in the number of farms (Pimentel et al. 1973).

Intensification, specialization and increase of scale imply an industrialization of agriculture (Pimentel 1984). Specialization in either crop production (i.e. arable farm) or animal husbandry (i.e. livestock farm), along with an external supply of fertilizers and feeds, do not foster crop rotations. The resulting vulnerability is compensated for by an increase of curative interventions with external inputs, including: draught power, machinery, fertilizers and pesticides. Significant amounts of nutrients and pesticides are lost to surrounding areas (Vuorenmaa et al. 2002, Gil & Sinfort 2005, Schriever & Liess 2007), which affect non-target organisms and contribute to deteriorating soil, water and air quality. Plant cropping and animal husbandry become decoupled, both on a farm level and regionally (Oomen et al. 1998). An external supply of feeds, an insufficient land base and a concomitant improper handling and allocation of manures increase the probability of nutrient losses from livestock farms (Thomassen et al. 2008). Increased field and farm size, high fertilizer and pesticide inputs, simplified arable systems, and the loss of non-crop features such as ditches and hedges lead to a decline of farmland and landscape biodiversity (Stoate et al. 2009). Intensification in some regions is accompanied by the abandonment of agricultural production in others; both actions constitute major threats to the ecology of agri-ecosystems (*ibid.*). Industrial agriculture heavily relies on an external supply network. Instead of being embedded in the local economy, industrial agriculture is integrated in the global market (Borgström-Hansson & Wackernagel 1999). There are fewer multiplier effects for local rural development. The integration of industrial agricultural systems with global industries and markets also result in low level of food sovereignty and food security (Kloppenburg et al. 1996). Most of the negative environmental and social consequences of industrial agriculture are externalized to become a cost to society as a whole (Pretty et al. 2000).

Evidence of the drawbacks of industrial agriculture, in addition to progress in agricultural and ecological knowledge provoked the development of Integrated Production (IP). In turn, IP is defined as a farming method that integrates natural resources, natural regulation mechanisms and farming system components to achieve the maximum replacement of off-farm inputs, such as fuels, fertilizers and pesticides (Vereijken 1992). Consequently, IP ordains diverse crop rotations, minimum soil cultivation, disease resistant cultivars, targeted application of nutrients and pesticides, and the promotion of biodiversity (Jordan et al. 1997). Since IP lacks strict regulations, degrees of integration vary between different production systems and between individual farms (Morris & Winter 1999). The 'Agri-Environmental Programmes' implemented in the European Union (EU) since the 1990s can be characterized as a large-scale introduction of certain IP principles. However, so far, these Agri-Environmental Programmes only marginally contributed to the alleviation of the negative environmental impacts of industrialized agriculture (Stoate et al. 2009).

Like elsewhere in the EU member states, the implementation of the Agri-Environmental Programme has not prevented or slowed down further intensification of agriculture in Finland (Valpasvuo-Jaatinen et al. 1997, Stoate et al. 2009). Continuous specialization of production on farm and regional level, and amalgamation of fields and farms into larger units result in more and more homogeneous agricultural landscapes (Hietala-Koivu 2002). Grazing is often confined to a limited area close to the farmsteading whereas forage production is based on arable leys, which either leads to the conversion of semi-natural grassland into arable land, or to the abandonment of land (Pykälä et al. 2005). Both specialization and abandonment contribute to biodiversity loss (Pitkänen & Tiainen 2001). Extensive regulation of watercourses and replacement of open ditches by subsurface drainage also negatively impact on biodiversity (Herzon & Helenius 2008). Moreover, these measures tend to increase nutrient losses (*ibid.*). Marked regional segregation of crop and animal husbandry has negative environmental consequences (Information Centre of the Ministry of Agriculture and Forestry 2008a). In the southern parts of the country, monotonous cultivation of annual cash crops leads to a decrease of soil organic matter (SOM) (Mäkelä-Kurtto & Sippola 2002), increasing the risk for erosion (Alakukku 1999). In central and north-western Finland, high livestock densities and imported feed grain result in nutrient surpluses (Salo et al. 2007). If they occur, soil erosion on arable farms and increased nutrient enrichment of soils on livestock farms both contribute to the loss of nutrients from fields that result in the eutrophication of water courses (Uusitalo et al. 2007).

1.1.3 Paradigms and practices of organic farming

Much of agricultural science and production developed along with the dominating anthropocentric paradigm (as opposed to the environmental paradigm) (Catton & Dunlap 1978). Consequently, this mainstream is characterized as conventional farming. In contrast, alternative world views, principles and attitudes initiated alternative farming practices (Merrill 1983, Vogt 2000). Since the 1970s, alternative agriculture movements united under the umbrella organization of IFOAM. The general term for alternative agriculture now used in the English language is 'organic farming'. During the 1990s the EU within the frames of its Common Agricultural Policy (CAP) encouraged the adoption of organic farming (EC 1991 and 1992). For example, in Finland the area devoted to organic farming increased from 0.3 per cent in 1990 to 6.6 per cent in 2007 (Information Centre of the Ministry of Agriculture and Forestry 2003 and 2008a).

Organic farming is rooted in a social paradigm different to that of conventional farming. Thus this difference is expressed in the following perspectives of organic vs. conventional farming: (i) decentralization vs. centralization, (ii) independence vs. dependence, (iii) community vs. competition, (iv) harmony with nature vs. domination of nature, (v) diversity vs. specialization, and (vi) restraint vs. exploitation (Beus & Dunlap 1990). The foundation of organic agriculture in a paradigm different from that of conventional farming indicates that organic farming often is described by principles, i.e., by a goal-prescribing concept that guides the creation of farming systems. The recent guiding principles of organic agriculture include health, ecology, fairness, and care (IFOAM 2005). These four principles lead further to the definition of organic agriculture:

> *Organic agriculture is a production system that sustains the health of soils, ecosystems and people. It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects. Organic agriculture combines tradition, innovation and science to benefit the shared environment and promote fair relationships and a good quality of life for all involved.*
>
> IFOAM 2008

Hansen (1996) rejects the introduction of sustainable agriculture through goal-prescribing concepts and emphasizes that in order for sustainability to be a useful criterion for guiding change its characterization should be literal, system oriented, quantitative, stochastic and diagnostic. Thus, the term sustainability should be interpreted as a system-describing concept of agriculture, with the goal of using sustainability as a criterion for guiding agriculture. This criterion could be the ability to fulfil a diverse set of goals or as the ability to continue through time (*ibid*.). However, goal-prescribing and system-describing concepts can also be unified. Principles are useful for motivating and guiding changes, whereas practical applications aim to imply the goals proposed by principles. Principles make up the theoretical backbone of organic farming and practical organic farming is specified by detailed regulations both on international and national levels (EC 2007 and 2008).

Organic farms strive for a high degree of self-sufficiency in plant nutrition, plant protection and animal nutrition. Organic agriculture out of principle excludes easily-soluble inorganic fertilizers and synthetic pesticides (EC 2008). Agricultural productivity is achieved by the enhancement of soil fertility, mediated by diverse crop rotations and the application of organic manures (Lampkin 1992). Crop rotation and soil tillage are important tools for preventive weed and pest control (*ibid.*). Crop competitiveness in relation to weeds is also maintained by physical control measures (Bond & Grundy 2001). Some plant diseases and insect pests can be controlled by preventive measures or biological treatments, others by certain pesticides (Altieri 1998, Stopes et al. 2000). Animal husbandry is a fundamental part of many organic farms, as it can be involved in crop production through the recycling of nutrients in animal wastes as organic fertilizer (von Borell & Sørensen 2004). Organic farming is expected to produce high quality food, increase agricultural efficiency in the use of non-renewable resources, sustain soil fertility and biodiversity, and to meet high animal welfare standards (Stockdale et al. 2001).

The actual performance of organic farming on an individual farm is influenced by environmental conditions, economic resources, managerial quality and individual commitment (Schjønning et al. 2002, Bakken et al. 2006). Although the paradigm of organic farming differs from that of conventional farming, mechanization, intensification and specialization also take place on most of the organic farms. In this case, the socioeconomic structure of organic farming is characterized as industrial (Table 1). As a consequence of regional specialization, organic farming is often without livestock in southern Finland, whereas mixed organic crop and animal husbandry is more common in the western, central and eastern parts of the country (Information Centre of the Ministry of Agriculture and Forestry 2008a). Furthermore, fields on organic farms are amalgamated into larger areas, and sub-surface drainage systems are installed. In many cases, specialized conventional livestock farms generate a surplus of manure, which is partly transferred to organic farms. This transfer of animal manure may promote fairly high nutrient levels in organically managed fields. Because of its importance with regard to weed control, soil cultivation is usually more intensive on organic than on conventional farms (Bond & Grundy 2001). High nutrient levels together with the use of modern crop varieties, intensified tillage, and efficient mechanical weed control may result in high yielding and uniform crop stands. In addition, specialization and intensification on organic farms reduce biodiversity (van Elsen 2000). Furthermore, industrialization makes production scale and input intensity of organic farming resemble those of conventional farming (Table 1). Thus, industrialization of agricultural production threatens to contradict principles of organic farming.

Table 1 Socioeconomic structures and features of agricultural production.

Socioeconomic structure		**Subsistence agriculture**	**Commercial agriculture**	**Industrial agriculture**	
Farming concept		**Traditional**	**Organic - IPM - Conventional**		
Economic goal		Subsistence	Profit	Profit	
Economic scale		Local	Regional	Global	
Production scale	Small	=>	=>	=>	Large
Biological diversity	High	=>	=>	=>	Low
Input intensity	Low	=>	=>	=>	High
Productivity in terms of					
- energy and nutrients	High	=>	=>	=>	Low
- labour	Low	=>	=>	=>	High
- acreage	Low	=>	=>	=>	High

1.1.4 The sustainability of organic farming

1.1.4.1 Resource management

Soil, plant nutrients, and energy resources necessary for agricultural production are limited and therefore efficiency in the management of such agricultural production resources is a crucial factor of agricultural sustainability. Leifeld et al. (2009) reported that soil organic carbon (C) contents in organic farming systems did not differ from corresponding conventional farming systems. However, because rotations including perennial crops and the use of organic manures are more frequent in organic than in conventional farming, soil fertility is often higher in organically cropped farms (Pulleman et al. 2000, Stark et al. 2007). Organic crop husbandry practices appear to result in larger microbial biomass and higher microbial activity (Gosling et al. 2006), with positive consequences for nutrient availability (Melero et al. 2008). Higher content of organic matter (OM) and higher activity of soil organisms lead to higher soil aggregate stability (van Diepeningen et al. 2006) and to lower susceptibility to soil erosion in organically managed land compared to conventionally managed land (Siegrist et al. 1998).

Traditional farming depends on soil stocks in satisfying its nutrient demands. Even if all OM is re-cycled on the farm, traditional farming cannot avoid nutrient losses through leaching, erosion and volatilization, and this will gradually restrict yields. Urbanization of human societies additionally causes major disruptions of nutrient cycling, due to net-export of nutrients and OM from rural to urban areas (Tivy 1996). Consequently, conventional and organic farming both depend on external nutrient inputs. In organic farming, N is primarily supplied by symbiotic N fixation (SNF), whereas the supply of other plant nutrients often mainly relies on recirculation of organic wastes and on mobilization from the soil stock (Withers et al. 2001, Öborn et al. 2005). Due to negative balances between inputs and outputs, severe decreases in soil phosphorus (P) and potassium (K) have been observed on organic farms (Løes & Øgaard 2001, Løes & Øgaard 2003). Organic farms are allowed to alleviate nutrient deficiencies if necessary by the application of certain mineral fertilizers, with the general exception of mineral N fertilizers (EC 2008). Nonetheless, inputs of mineral nutrients are usually lower in organic farming than in conventional farming. Although this results in lower yields, it appears that organic agroecosystems may use mineral nutrients in a more efficient manner (Waldon et al. 1998). Due to the ban on industrially fixed N, energy consumption is generally lower in organic farming than in conventional farming systems (Mäder et al. 2002a).

1.1.4.2 Environmental impacts

Detrimental impacts of agriculture on the biotic and abiotic environment pose threats to agriculture itself, and/or to surrounding environments. Organic farming usually has greater diversification of crop and animal husbandry, and therefore maintains genetic resources to a larger extent than does conventional farming. Limitation in pesticide use is the main cause for higher biodiversity in organic farming (Geiger et al. 2010). Weed species diversity is higher in organically managed fields (Hald 1999a, Hyvönen et al. 2003a) and thus provide more extensive sources of nutrition for insects (El Titi 1995). In contrast to conventional cropland, organic fields support greater diversities and abundances of arthropods, spiders, bumblebees, and butterflies (Feber et al. 1997, Pfiffner & Luka 2003, Ekroos et al. 2008). The higher occurrence of bird food, such as weed seeds and insects, have positive impacts on bird populations (Chamberlain et al. 1999), and the nesting needs of certain bird species are accommodated for by higher crop diversity and thinner crop stands (Piha et al. 2007, Kragten et al. 2008). On the other hand, mechanical weed control (typical of organic farming) and early and recurrent cutting of grassland (typical of intensive ley management) can have negative impacts on ground-nesting bird species (Kragten & de Snoo 2007). Landscape features and habitat type are more important for the enhancement of species richness than differences between organic and conventional crop management (Östman et al. 2001, Tscharntke et al. 2005). However, the diversity of landscape and farming system components is usually greater on organic farms (Levin 2007). Field margins and other non-cropped habitats are commonly managed more sensitively in organic sites and therefore these harbour more plant species than those of conventional systems (Petersen et al. 2006).

Emissions of nutrients and pesticides from agricultural fields alter surrounding ecosystems and deteriorate water and air quality (Pretty et al. 2000). Nutrient leaching from organically managed farming systems may be lower than from conventionally cropped agricultural systems, due to a lower input of nutrients and extensive use of catch crops (Hansen et al. 2000). Despite this, the type of production system and the management measures play decisive roles in nutrient emissions (Trydeman Knudsen et al. 2006). In autumn, intensive soil cultivation, application of easily degradable manures, and the termination of clover-rich leys pose considerable risks for nutrient losses, not least on organic farms (Eriksen et al. 1999, Rasmussen et al. 2005). On the other hand, Nykänen (2008) reported low mineral N concentrations after red clover-grass leys, indicating a low N leaching risk. Kramer et al. (2006) found that organic fertilization practices supported more active and efficient communities of denitrifying bacteria, which increased dinitrogen emissions while reducing nitrate losses. The acidification potential and greenhouse gas (GHG) emissions are lower from organic crop production and animal husbandry than from conventional farming systems when calculated per hectare. However, the contribution of organic agriculture to eutrophication, acidification, and GHG emissions may be as high as, or even higher, than that of conventional farming, if the lower yields of organically managed crops are taken into account (Flessa et al. 2002, De Boer 2003, Korsaeth 2008, Thomassen et al. 2008). In contrast to conventional farming, organic farming hardly incurs pesticide emissions (Stockdale et al. 2001, Geiger et al. 2010).

1.1.4.3 Social and health aspects

Sustainable agricultural production entails consideration of social and health factors (WCED 1987). Organic agriculture often requires more labour inputs than conventional farming, in order to replace external inputs such as fertilizers and pesticides (Nguyen & Haynes 1995). Consequently, Loake (2001) concluded that organic farmers experience more physical stress than their conventional farming counterparts. On the other hand, van Calker et al. (2007) concluded that the physical health of conventional and organic farmers was similar. Organic farming standards explicitly demand that farmers and farm workers are offered safe and healthy working conditions (IFOAM 2005). Exposure to pesticides is a risk factor primarily of conventional farming, and there is a large body of evidence on the negative acute and chronic impacts of pesticides on the health of farm workers, their families and children (McCauley et al. 2006, Perry et al. 2007, Colborn & Carroll 2007, Charboneau & Koger 2008).

It is a matter of dispute, whether there are significant differences in food quality and safety between organically and non-organically grown food, or not (Heaton 2001, Magkos et al. 2006). Variable responses in terms of quality and quantity of the harvested product often arise from complex interactions between agronomic and environmental factors (Chassy et al. 2006). With the possible exception of nitrate and protein content, there is no strong evidence that organic and conventional foods principally differ in concentrations of various nutrients (Bourn & Prescott

2002). However, the impact of different farming systems on nutrient bioavailability and non-nutrient components has so far received little attention (Bourn & Prescott 2002). Plant secondary metabolites with antioxidant activities, which are assumed to be important for good health have been found at higher levels in organically produced food plants than in conventionally produced foods (Mitchell et al. 2007). Food safety includes issues such as mycotoxin contents, microbial contamination, and pesticide residues. Weather, site, and storage conditions are the main factors determining the occurrence of mycotoxin producing organisms, and these factors influence all farming systems in the same way (Finamore et al. 2004). Although manure is used more frequently in organic than in conventional farming, there is no evidence that organically produced foods would be more susceptible to microbiological contamination than conventionally produced foods (Bourn & Prescott 2002). Food exposure considerably contributes to the consumers' measurable pesticide burden (Kawahara et al. 2007, Colborn & Carroll 2007). Although it is likely that organically grown foods are lower in pesticide residues, there has been very little documentation of the comparative residue levels (Bourn & Prescott 2002).

1.1.4.4 Agronomic productivity - a challenge

With respect to resources economy, environmental stewardship and social effects, organic farming complies with parameters of agricultural sustainability to a larger extent than conventional farming does. Thus, organic farming provides many rationales for the transition of conventional farming to sustainable agriculture. However, agricultural productivity in terms of yield per unit of land area is higher for conventional farming. Causes for the lower agronomic productivity of organic crop husbandry include lower soil nutrient concentrations, lower intensity in crop protection, and, in the case of arable farms, utilization of a certain proportion of agricultural hecterage for green manure.

Year-to-year variations in the productivity of organic crop husbandry can be large (Taylor et al. 2006). In some horticultural and animal production systems, for which our ecological understanding so far is limited, the performance of organic farming systems is frequently inferior to that of conventional agronomy (MacRae et al. 2007). Yield levels in arable organic farming without livestock inputs are usually lower than in mixed organic farming (Eltun et al. 2002). In European conditions, yields of organic arable crops usually are 50 to 80 per cent of those achieved from comparable conventional systems, depending on crop species and crop management (Mäder et al. 2002a). In contrast, in the low-input systems common to developing countries, organic farming practices often considerably increase crop yields with a minimum of external inputs, while also improving critical environmental services (Pretty et al. 2006).

The lower yields associated with organic farming are, it is suggested leads to both human and ecological disaster (Kirchmann & Thorvaldsson 2000, Goklany 2002, Trewavas 2004). Connor (2008) estimates the carrying capacity of organic agriculture on a global basis to be at 3 to 4 billion people, provided the land area currently being used for agricultural purposes is used. To produce the same amount of yields as those obtained for conventional agriculture organic farming would require more land and/or higher cropping intensity. This would offset some of its advantages, such as higher soil fertility, greater biological diversity, and lower inputs of nutrients and energy. The agronomic productivity of conventional farming is higher than that of organic farming, and therefore it appears to be able to satisfy the needs of an increasing human population without increasing the hecterage of cropland (Goklany 2002). On the other hand, high intensity production has contributed to losses of agricultural land and genetic resources (Mäder et al. 2002b). Options to maintain food security without increasing the intensity of agricultural production, or the hecterage used for agricultural production, include cultural factors such as the choice of food products with high efficiencies in terms of land and energy resources (Carlsson-Kanyama et al. 2003, Cowell & Parkinson 2003), and changes in socioeconomic relationships, including land reforms (Pretty 2003). Still, the improvement of its agronomic productivity remains a challenge for organic farming.

Under organic farming conditions, a number of specific factors may restrict crop yields. In the southern hemisphere, critical factors determining crop yield include SOM, water supply and plant protection measures (Pretty et al. 2003 and 2006). In the northern hemisphere, the primary factors restricting the productivity of organic crop husbandry include N deficiency (Korva & Varis 1990, Fagerberg et al. 1996, Olesen et al. 2002) and weed infestation (Kauppila 1990, Salonen et al. 2001a, Posner et al. 2008). As a matter of fact, N deficiency and weed competition are often referred to in the same context as the main factors limiting crop yields under organic farming conditions (Taylor et al. 2006, Kirchmann et al. 2007, Nykänen et al. 2008).

In northern Europe including Finland, spring cereal crops and perennial leys are the most widely grown crop types (Information Centre of the Ministry of Agriculture and Forestry 2008b). In organic farming the use of mineral N fertilizers is prohibited, thus legume-grass leys along with grain legumes are of paramount importance for the N supply of the non-leguminous crops included in the crop rotations (Crews & Peoples 2005). The persistence of the legume component in perennial leys is of crucial importance for agronomic productivity, especially that of organic farming (Nykänen et al. 2000, Halling et al. 2001, Mela 2003). A dense ley crop is efficient against annual and certain perennial weeds. Weed occurrence therefore primarily may restrict the growth of annual crops, such as spring cereals (Salonen et al. 2001a, Håkansson 2003).

In order to study N deficiency and weed occurrence as the main factors restricting the agronomic productivity of organic farming, this work focused on herbage production of perennial red clover-grass leys, persistence of red clover, SNF in legume-grass leys, and weed occurrence in spring cereal crops.

1.2 Determinants of agronomic productivity under organic farming

1.2.1 Herbage production and persistence of red clover-grass leys

Legume-grass leys are grown as forage (Bertilsson et al. 2001), green manure (Talgre et al. 2009), understorey (Känkänen & Eriksson 2007), and catch crops (Helander 2004). In mixed swards, N fixation by *Rhizobium*-legume symbiosis benefits the N supply to grass (Boller & Nösberger 1988). The resulting over-yielding effect of mixed swards implies that legume-grass mixtures not amended with N fertilizers often reach the same yield levels as fertilized grass swards (Halling et al. 2001). Legumes reduce inputs of fertilizers because of SNF. Moreover, legumes reduce inputs in animal production systems of concentrate feeds because of their high nutritional value. Consequently, crop rotations based on legume-grass leys have lower requirements for fossil energy than those based on pure grass leys (Alföldi et al. 1995). The life cycles and plant communities of perennial legume-grass leys differ from those of cereal monocultures. Therefore, they help counteract the emergence of specialized weed communities and pests (Karlen et al. 1994). Deep-rooting ley species improve the structure of the subsoil, extending the nutrient and water supply accessible for the roots of succeeding crops (Lövkvist 2005). Enriching SOM through biomass residues, perennial leys sustain the aggregate stability and increase the nutrient- and water-exchange capacity of soils (Könekamp 1957). Higher contents of SOM also are associated with an increase of soil microbial biomass and enhanced mobilization of nutrients from soil stocks (Anderson & Domsch 1989). In addition to their agronomic value, perennial grasslands may constitute important habitats for certain plant and animal species (Hopkins & Holz 2005). However, high fertilization rates, frequent mowing and/or intensive grazing, and incorporation in the arable crop rotation result in a decline of grassland biodiversity (Stoate et al. 2001).

The growing season in northern Europe is characterized by a prolonged day light, high light intensity and relatively low temperatures, i.e., those climate conditions that are favourable for ley growth, the nodulation of red clover, and SNF (Bowley et al. 1984, Carlsson & Huss-Danell 2003). However, spring and summer drought may seriously limit grass and legume growth, and adverse overwintering conditions often jeopardize the persistence of overwintering crops (Mukula & Rantanen 1987). In Finland, perennial leys for cutting are grown on approximately 30 per cent of the conventionally cropped arable land. The share of perennial leys in the southern coastal districts varies between 10 to 20 per cent of the arable land, whereas it exceeds 30 per cent in the north-western coastal districts (Information Centre of the Ministry of Agriculture and Forestry 2003 and 2008a). This reflects the disparate specialization of different branches of agricultural production systems. Of the arable land managed according to organic farming practices, ley crops grown for harvest make up around 40 per cent. In addition, around 15 per cent of the organic arable hecterage is managed either as green or black fallow (Information Centre of the Ministry of Agriculture and Forestry 2003 and 2008a). In southern Finland and in the central parts of the country, red clover (*Trifolium pratense* L.)-grass mixtures grown without N application perform well, even though pure grass leys with intensive N fertilization give the highest yields (Halling et al. 2001, Mela 2003). In northern Finland, where clover persistence is restricted by more adverse overwintering conditions, grass mixtures amended with N fertilizer perform markedly better than red clover-grass mixtures (Nissinen & Hakkola 1995).

Spatial and temporal heterogeneity of crop yields is not only high between but also high within single fields (Geypens et al. 1999, Shi et al. 2002). Causes for within-field yield variability have been related to soil properties and management factors (Delin & Lindén 2002, Taylor et al. 2003). In mixed leys, the physiological differences between legumes and grasses contribute to the variability in herbage production and to its botanical composition. As a function of all these factors, the growth of legume-grass leys fluctuates markedly on spatial, annual and intra-annual scales (Mela 2003). This variability is a focal issue where the productivity of ley crops is concerned. Within-field variability of soil properties require site-specific approaches to crop management namely: drainage, liming, tillage, fertilization, seed rate, and crop protection (Verhagen et al. 1995, Frogbrook et al. 2002).

Due to SNF, legumes compete successfully with grasses in conditions of limited N supply. On the other hand, high N supply achieved by the mineralization of SOM and/or fertilization generally increases the competitiveness of grasses in relation to legumes. Grasses have a lower temperature optimum than legumes and usually dominate in the first growth. The second ley growth may be hampered by drought and reduced concentrations of soil N. In these cases, red clover´s deeper reaching root system and SNF provide it with a competitive advantage (Raininko 1968). Consequently, red clover contents usually increase from the first to the second cut (Mela 2003). Differences in the growth patterns of companion grass species also add to the variability of herbage production and composition during the annual growth cycle of red clover-grass leys. Timothy (*Phleum pratense* L.) produces large yields at the first harvest. However, in the second growth, timothy is hampered by its poor regrowth capacity whereas meadow fescue (*Festuca pratensis* Huds.) readily establishes new shoots, and produces a higher yield (Virkajärvi 2003). The competitiveness of meadow fescue limits the clover content in the second growth and provides more balanced forage (Raininko 1968).

The overwintering of ley crops is jeopardized by a number of abiotic and biotic factors. A lack of snow cover may result in freezing and consequent winter kill. Flooding, ice encasement and desiccation are more frequent in the maritime climate of the coastal regions than in the interior of Finland. Under these conditions, timothy is more persistent than meadow fescue. Therefore in certain cases timothy is the only companion grass in red clover-grass mixtures, although this leads to a domination of red clover in the second growth (see above). However, due to its ample regrowth capacity, meadow fescue is usually included in the ley mixtures used in the coastal regions. In central, eastern and northern Finland, snow on unfrozen ground benefits the spreading of low-temperature fungi, and therefore meadow fescue is the preferable grass species (Lindén et al. 1999). The overwintering survival of red clover is better in mixed swards than in pure stands (Raininko 1968, Belzile 1987). Despite this, overwintering damage generally affects ley legumes more than it does the grasses. Due to poor winter survival, the duration of red clover in mixed leys is usually restricted to two or three years (Mela 2003).

In addition to plant species and climate, soil properties markedly influence grassland growth. Soil texture and SOM determine soil structure and thus gas exchange between soil and atmosphere, and retention of soil water. Prevention of anaerobiosis improves the resistance of plants to soil-borne pathogens (Lager 2002). In the case of legumes, good soil structure enhances nodulation by bacteria and transfer of N to grasses, and thereby SNF overall (Nadian et al. 2005). In acid soils, liming contributes to increased grassland productivity (Sumner & Yamada 2002). Since legumes are more sensitive than grasses to soil acidity, their content in a mixed sward increases as the pH-level rises from 5.5 to 6.0 (Hojito 1998). Low soil pH is more detrimental to rhizobial populations than to clover growth itself. The consequent impaired competitiveness of legumes in relation to grasses primarily results from a decline in N fixation effectiveness (Watkin et al. 2000).

Although the effect of N fertilization is greater for pure grass leys than for clover-grass leys, it also causes a considerable increase in the latters´ yields (Raininko 1968). Nevertheless, uptake from other sources decreases the proportion of N derived from the air (pNdfa), thereby impairing the competitiveness of clovers relative to grasses (Streeter 1988). Consequently, extensive N mineralization from soil stocks and ample N supply from animal manure or from mineral fertilizers are causes for a high variability and poor persistence of clover (Fagerberg & Ekbohm 1995, Hatch et al. 2007). Due to more efficient uptake (Mengel & Steffens 1985), grasses have lower requirements for soil nutrient concentrations than clovers (Wheeler 1996). The addition of P and K to mixed leys therefore favours the growth of grasses more than that of clovers (Høgh-Jensen et al. 2001, Schils & Snijders 2004). Only in those soils deficient of N does SNF provide legumes with a competitive advantage in relation to grasses. Under such conditions, added P and K may increase the competitiveness of clovers in relation to grasses (Simpson et al. 1988, Acuña & Wilman 1993). Limitations in the supply particularly of P, calcium (Ca), iron (Fe) and molybdenum (Mo) may affect legume nodule development and function (O´Hara 2001). However, Høgh-Jensen et al. (2002) and Høgh-Jensen (2003) reported that P or K deficiency in clover is primarily expressed by a decline in relative plant growth; although N fixation is down-regulated it is not the decisive factor that limits plant development. Thus, the biomass growth of legumes provides a reliable estimate as to whether SNF is limited by nutrient deficiencies or not.

Ley regrowth largely depends on post-defoliation carbohydrate stores, leaf area and the number of active meristems, and thus on defoliation timing and height (Virkajärvi 2003). An increased cutting frequency lowers the total dry matter yield of grasses that have a high proportion of generative tillers (e.g. timothy) more than that of grasses with a high proportion of vegetative tillers such as meadow fescue (Nissinen & Hakkola 1995). The competitiveness of white clover (*Trifolium repens* L.) increases under recurrent defoliation, due to its stoloniferous growth habit and its capacity for vigorous regrowth. In contrast, red clover regrowth and persistence are inversely related to defoliation frequency (Frame et al. 1998). Generally, lower cutting frequency results in higher total herbage yield and improved ley persistence, but with lower herbage digestability and protein content (Raininko 1968, Pulli 1980). In perennial plants the amount of carbohydrates and nutrients partitioned to storage organs is essential for winter persistence and spring regrowth (Dhont et al. 2002). Factors decisive for the amount of energy and nutrient reserves accumulated in plant storage tissues include plant species and variety (Cunningham et al. 2001), environmental conditions (Junttila et al. 1990), sowing time (Kilpatrick et al. 1966), fertilization (Pulli 1980) and cutting regime (Dhont et al. 2002).

1.2.2 Nitrogen supply through symbiotic fixation

The build-up of C and N pools in perennial swards reaches a certain plateau at which these stocks remain relatively constant (Tyson et al. 1990). Subsequent arable management to a certain degree implies a consumption of these and other nutrient stocks (*ibid*.). The N pools accumulated under pure legume and legume-grass swards have a considerable capacity to supply subsequent crops with N due to the fixation of N from the air through the symbiosis between *Rhizobium*-bacteria and legumes. Management of these N-pools requires knowledge of their quantity and quality (Hauggaard-Nielsen et al. 1998). Organic farming regulations prohibit the application of N fertilizers produced through industrial N fixation. Consequently, SNF is crucial for the N supply of organic farming. If primary N supply is to be based solely on SNF, then the accumulation of soil N for the benefit of subsequent annual arable crops under Nordic climate conditions requires that about 30 to 40 per cent of the arable hecterage is devoted to legume crops, preferably to perennial legume-grass mixtures (Granstedt 1992). The red clover content of mixed leys should exceed 40 to 50 per cent in order to achieve a surplus of N that provides N for succeeding crops (Nykänen 2008).

Variations in plant species and variety, *Rhizobium* strain, stand age, soil type, weather, and management cause large differences in legume biomass and SNF (Carlsson & Huss-Danell 2003). If effective indigenous strains of *Rhizobia* are insufficient or absent, then inoculation is essential to ensure an adequate nodulation and N fixation. This is especially the case in acid soils (Watkin et al. 2000). Averaged over the life of the stand and the season, 75 to 85 per cent of the N contained in red clover in mixed leys was reported to be derived from the air (Huss-Danell et al. 2007). The addition of N to the crop decreases pNdfa, especially in pure legume stands (Carlsson et al. 2009). In swards consisting of legumes and grasses, below-ground transfer of N from legumes has been found to constitute 40 to 50 per cent of the N in the non-legume. N is transferred from living in addition to decaying roots and nodules, either directly from the legume plant or after its transformation by soil microbial biomass. Another pathway for N transfer is through the mycorrhizal fungi linking two plants (Rasmussen et al. 2007). Due to the competition from associated grasses for soil N and transfer of N from legumes to grasses, intercropping of legumes and grasses increases pNdfa (Boller & Nösberger 1988). On the other hand, cultivation in mixtures with grasses limits clover biomass production and may thereby imply a lower total amount of SNF compared to that derived by pure legume stands (Jørgensen et al. 1999). Shading and leaf aging with resultant loss of photosynthetic efficiency are significant constraints to root and root nodule activity (Cralle & Heichel 1981). The acquisition of N from the air generally reaches a maximum at early flowering (Andrén et al. 1990), and repeated harvesting therefore implies both higher total biomass production and higher N yields (Bruuselma & Christie 1987).

Legume-grass leys have a markedly higher preceding crop value than pure grass crops due to SNF. Agronomic and environmental considerations require correct assessment of the fertilizer replacement value of legume ploughdown. Such an assessment particularly for organic farming constitutes the basis for crop rotation planning that aims for high and stable yields from non-legume crops. The preceding crop value of a mixed ley depends on its legume content and on the proportion of biomass returned to the soil (Badaruddin & Meyer 1990). Bruuselma & Christie (1987) estimated that if the contribution of red clover to the yield of the succeeding crop was solely due to N, then about 65 per cent of legume N would have been released following termination. Granstedt & Baeckström (2000) calculated that the preceding crop effect of one- and two-year-old leys equalled about 30 to 40 per cent of the N contained in soil-incorporated ley residues, whereas that of three-year-old leys equalled 10 to 15 per cent of the soil-incorporated N. However, the contribution of plant biomass ploughdown to the yield of the following crop is not solely due to plant-derived N but not least a result of improved soil structure, and factors related to this. For example, higher rates of turnover of SOM including soil organic N, improved water and nutrient retention, promoted root growth, and higher amounts of soil nutrients taken up as a result of promoted root growth (Bruuselma & Christie 1987).

In Fennoscandia, leys are most often established in spring by undersowing cereal crops. If only used as a catch crop, the ley is ploughed down in late autumn (Känkänen & Eriksson 2007), whereas for its use as green manure, the crop usually is terminated first at the end of the following growing season (Lahti & Kuikman 2003). Mixed leys grown for harvesting forage are usually maintained for three production years (Halling et al. 2001). Utilization of herbage production either for forage, or for green manure, or both, is decisive for the amount of N returned to the soil. Incorporation of the whole biomass of a ley results in the greatest return of N to a subsequent crop. Seasonal variations in N concentrations for perennial legume-grass leys appear to be minor, and consequently total N contents follow the same trends as DM (Huss-Danell et al. 2007). Approximately 50 to 60 per cent of the total N content is located in the herbage, 10 to 20 per cent is in stubble and harvest residues, and 20 to 30 per cent is allocated in root biomass (Andrén et al. 1990, Høgh-Jensen & Schjoerring 2001). In addition, rhizodeposits of red clover may total one-third to two-thirds of its total N content (Høgh-Jensen & Schjoerring 2001, Talgre et al. 2009). Huss-Danell et al. (2007) reported considerable differences in N allocation between harvests. The proportion of N remaining in clover stubble and roots after the first and second harvests was about 60 and 25 per cent, respectively, whereas about 60 per cent of the N in grasses remained in the stubble and the roots after both harvests.

In northern European conditions, approximately 30 per cent of the N contained in crop residues is mineralized during the following cropping period (Wivstad 1997, Gunnarsson & Marstorp 2002). Even so, the actual legume-N recovery by a subsequent crop appears to be lower than the amounts of N released from biomass incorporated to the soil. Cereals grown after legume incorporation take up between 5 and 30 per cent (usually around 20 per cent) of legume N (Müller & Sundman 1988, Janzen et al. 1990, Crews & Peoples 2005). Recoveries of legume N in the subsequent crop are even lower, ranging from between a few up to 15 per cent (Heichel 1988, Janzen et al. 1990, Giller & Cadisch 1995). Moreover, about two thirds of legume N may be plant-available over a period of seven years (Ladd et al. 1986). Thus, the main contribution of legumes appears to be the maintenance or improvement of soil-organic N (Seo et al. 2006). However, the impacts of N derived from leguminous organic materials on microbial pool substitution and subsequent soil N dynamics is such that total N availability for crop uptake is often much greater than would appear solely from measurements of the direct crop recovery of legume N (Crews & Peoples 2005). On the other hand, Nykänen et al. (2008) reported the residual N effects of red clover-grass leys on successive grain crops to be negligible, and independent of ley age. This might have been caused by low or even negative N balances of the leys, or weed competition. Alternatively, by mineralization of N from SOM, though this is less probable in the case of the soils where these trials were carried out.

Ley grown for harvest of forage is an indispensable part of the crop rotation on farms with ruminant livestock, whereas organic farms devoid of livestock depend on green manure crops as a means to add OM to the soil, and to accumulate N for succeeding crops (Stopes et al. 1996, Schmidt et al. 1999). Harvest implies the transfer of nutrients to animal feed, and, to a minor extent, further to the human food chain. Most of the nutrients contained in the forage are transferred to animal manure, a redistributable nutrient source, which can be applied according to expected crop requirements. Regular circulation of mineral nutrients and OM between fields and animal pens contributes to a gradual decrease of between- and within-field heterogeneity in soil properties. In contrast to harvest, the utilization of leys for green manure implies mulching and, when the crop is terminated, the incorporation of herbage into the soil. Mulched herbage may interfere with ley regrowth and reduce pNdfa. However, Hatch et al. (2007) concluded that total N yields did not differ between forage and green manure treatments. Incorporation of herbage together with root biomass and above-ground plant litter increases soil nutrient concentrations and thereby also the risk for nutrient losses (Torstensson 1998). A management regime that combined the harvest of the first growth and left the regrowth mulched as green manure resulted in yield levels of the succeeding crop as high as that of the utilization of the ley by green manure alone, but decreased leaching and provided animal manure for use in other fields (Dreymann et al. 2003).

When leys are grown for forage, around 50 per cent of the N contained in the crop is removed from the field with the harvest (Høgh-Jensen & Schjoerring 2001, Huss-Danell et al. 2007). Supposed that animal manure is handled as slurry, approximately 30 and 70 per cent of the total N will be in the form of organic and ammoniacal N, respectively (Mattila 2006, Olesen et al. 2009). Assuming a loss of 40 per cent of the ammoniacal N content during storage and after soil application of animal manure (Schröder 2005), a total of 86 per cent of the N accumulated in the ley crop can be returned to the soil (Table 2). On the other hand, improper and untimely applications of animal manure cause nutrient losses widely exceeding the above value (Turtola & Kemppainen 1998, Turtola & Yli-Halla 1999). When herbage is cut and left on the soil surface around 10 per cent of its N content is lost in the form of volatile ammonia (Whitehead & Lockyer 1989). With 50 per cent of the total crop N contained in the herbage, this corresponds to a loss of 5 per cent of total crop N, implying that 95 per cent of the total N contained in the ley crop is left in the field (Table 2). Thus, N losses are somewhat lower with green manuring than with the forage-animal manure-chain approach (Table 2).

Table 2 Volatilization of nitrogen (N) from red clover-grass leys managed for forage and green manure (% of total N content).

	Forage harvest[a]	**Green manure**[b]
Volatilization from animal manure	40	-
Volatilization from herbage	-	10
Recirculated to the field	86	95

[a] Assuming 50 per cent of total crop N in herbage, and ammoniacal N making up 70 per cent of total N in animal manure.
[b] Assuming 50 per cent of total crop N in herbage.

Ammonia volatilization correlates positively with N concentration, temperature and time, and negatively with lignin content (Glasener & Palm 1995). Decomposition under moist and windy conditions may lead to losses of up to 50 per cent of herbage N, whereas losses of ammonia are negligible during rapid drying of fresh herbage (Whitehead et al. 1988). Incorporation of fresh herbage into soil almost eliminates ammonia losses (Janzen & McGinn 1991). Incorporation also results in more rapid and more extensive short-term supply of plant-available N, compared with residues retained on the soil surface (Mohr et al. 1998). The appropriate depth of incorporation depends on soil texture and soil structure. Ploughing down of fresh OM to an anaerobic environment results in the depletion of soil oxygen, denitrification, accumulation of phytotoxic substances and increased growth of damping off-fungi (Lynch 1980, Breland 1994).

The synchronization between the N demand of the next crop and the N mineralization from the residues of the present crop is a challenge for farm management. Factors to be considered include the amount of nutrients returned to the soil, the biochemical properties of the biomass left in the field, environmental factors such as soil type, moisture and temperature, and management factors such as crop rotation, timing of termination and desintegration of crop residues (Wivstad 1997, Eriksen & Jensen

2001, Gunnarsson & Marstorp 2002). When tillage is carried out in late autumn instead of early autumn, lower temperatures limit microbial activity and a larger proportion of the nutrients contained in crop biomass residues and humus is first mineralized during the subsequent growing season. Late autumn or spring termination also allows the crop to grow further and take up N during the autumn, which reduces N leaching risks (Lindén & Wallgren 1993). Concentrations of N in the soil and in plant biomass are usually lower after grass-dominated than after clover-rich leys. Grass dominated leys therefore can be terminated as early as late summer, which thus provides an option for autumn-sown crops (Loges 1998). In contrast, clover-rich leys should be terminated in late autumn or spring (Känkänen et al. 1998).

Spring tillage might improve the synchronization between OM mineralization and uptake by a spring-sown crop (Breland 1994). However, spring tillage may have adverse effects on soil structure and water economy. Even on sandy soil, incorporation of green manure crops by ploughing in spring resulted in lower grain yield than autumn ploughing, owing to soil compaction (Känkänen et al. 1999). Decomposition of plant residues with high C:N ratios initially results in immobilization of N (Mary et al. 1996). Therefore the incorporation of leys in spring may cause a lack of available N at the beginning of the growing period. As decomposition proceeds during summer, soil mineral-N content will increase, which will lead to losses during autumn and winter (Torstensson 1998). Therefore, plant residues especially those with a high C:N ratio should be incorporated as early as late autumn (Känkänen et al. 1998). In conditions of the Nordic winter, considerable amounts of N are lost through leaching and surface run-off from aboveground biomass (Sturite et al. 2006). This is another reason why incorporation of herbage in late autumn generally is preferable (Lahti & Kuikman 2003).

1.2.3 Weed occurrence and weed management in spring cereals

All plants occurring in an agricultural field without the farmer´s intention, including volunteer crop plants, are termed weeds (Håkansson 2003). As a result of competitive (Patterson 1995, Blackshaw et al. 2003) and allelopathic (Burgos et al. 2000, Reddy et al. 2003) interactions, weeds interfere with crops. Weeds may also transfer pathogens, increase the risk for fungal diseases and lodging, decrease crop yield and quality, render the harvest more difficult, and increase the costs for drying and cleaning (Milberg & Hallgren 2004). If weeds are not kept under control, weed infestation may increase exponentially, markedly restricting the establishment and growth of agricultural crops. However, weeds also have a number of positive agronomic and environmental effects. Subsequent to harvest, crop volunteer and/or weed growth decreases soil erodibility and nutrient leaching (MacDonald et al. 2005). Interspecific competition of weeds prohibits a single species from becoming a dominant problem weed (Cussans 1995). Weeds may interfere visually or chemically with host plant colonization by specialist herbivores, and/or dilute attacks by polyphageous herbivores (Schellhorn & Sork 1997). Being food resources, weeds support population densities of a number of insect species, many of which are predators of agronomically noxious insect species (El Titi 1995). Weed seeds, in addition to many insects feeding on the weeds, supply farmland birds and their young with a food source (Holland et al. 2006). Finally, weeds constitute genetic resources necessary for crop breeding (Brush 1989). Thus, weed management aims at control but not at extinction of weeds.

Composition and abundance of weed communities are influenced by climatic and edaphic factors, and agricultural practices (Dale et al. 1992, Hyvönen et al. 2005). Annual weather conditions may, or may not affect weed occurrence (Milberg et al. 2000 and Lundkvist et al. 2008, Leeson 2000 and Milberg & Hallgren 2004). Variability of weed occurrence has been found to be higher between fields within the same farm and within fields, than between regions and farms (Walter et al. 2002, Hyvönen et al. 2003b). The type of soil and physical soil properties, such as water holding capacity and aeration, often influence weed diversity and abundance more than chemical soil properties (Ellenberg 1991, Andreasen et al. 1991). Certain weed species are characteristic of coarse-grained and organic soils, whereas others typically grow in fine-textured soils (Salonen 1993a, Hallgren 1996). Weed density is usually higher in sand than in clay soils (Mukula et al. 1969, Albrecht & Sommer 1998), whereas weed biomass often increases with SOM content (Salonen 1993a, Milberg & Hallgren 2004).

Field amelioration, such as drainage and liming may improve the competitiveness of the crop relative to weeds (Andreasen et al. 1991, Erviö et al. 1994). In many cases, weeds can be sufficiently controlled by preventive management measures (Lundkvist et al. 2008). The main components of preventive weed management include crop rotation, soil tillage, the handling of animal manure, crop species, and the establishment and management of single crops. There are interaction effects among agricultural system components, carrying-over from one growing season to the next. Thus, successful weed management includes the integration of cultural practices and an extended time span (Bàrberi 2002). In some studies, crop rotation appeared to have a stronger effect on weed community composition and abundance than tillage and direct weed control measures (Leeson et al. 2000, Cardina et al. 2002). In contrast, the largest differences in weed abundance found in other studies were due to soil tillage, or mechanical, or chemical weed control (Bàrberi et al. 1997, Doucet et al. 1999). The effects of fertilization on weed species composition and abundance are often outweighed by the above factors (Andersson & Milberg 1998, Swanton et al. 1999). Provided the appropriate management measures are used, the conversion to organic farming need neither encourage the dominance of noxious weeds (Albrecht 2005), nor increase weed abundance (Lundkvist et al. 2008).

Annual spring-sown, annual autumn-sown and perennial crops have different life cycles, and the rotation of these crop types benefits the diversity of weed species. Simultaneously, the variation of management operations associated with each crop type prevents the domination of a specialized weed flora (Hald 1999b, Leeson et al. 2000). Leys are more competitive in relation to weed seedlings than winter cereals and spring-sown crops (Sjursen 2001), and legume-grass leys have a stronger effect against weeds than pure grass leys (Andersson & Milberg 1996). *Cirsium* *arvense* and *Sonchus arvensis* are difficult to control in grain crops, but their abundance can be reduced in perennial leys, provided a relatively early first cut is taken (Dock Gustavsson 1997). Weed abundance is lower in crop rotational systems than in monocultures (Liebman & Dyck 1993). However, this difference may emerge only with the use of less intensive direct weed control practices (Bàrberi et al. 1997).

The longevity of weed seeds in the soil varies according to the species (Ball 1992) but generally increases with decreasing concentrations of oxygen, and thus with their depth of incorporation (Roberts & Feast 1972). Irrespective of placement, all seeds loose viability at an exponential rate over time (Omami et al. 1999). If the input of weed seeds is prevented or minimized, most viable seeds will be lost from the seed bank within five years (Roberts & Dawkins 1967). Few weed seeds germinate at depths below 50 mm (Cavers 1995). Tillage reduces the mechanical strength of soil, increases gas exchange and exposes buried seeds to light, thus inducing germination (Hartmann & Nezadal 1990). Consequently, intensive soil cultivation accelerates seed demise (Roberts & Dawkins 1967). Reducing tillage depth increases the amount of weed seeds on or near the soil surface (Roberts & Stokes 1965). Cardina et al. (2002) found that weed density was higher in reduced tillage than in mouldboard depth ploughing and highest in fields with zero-tillage. However, if the accumulation of weed seeds in the upper soil layer is counteracted by successful weed control measures, zero-tillage in the longer perspective may lead to fewer seeds in the weed seedbank, and less weed emergence, than from mouldboard ploughing (Tørresen 1998). Instead, reduced and zero-tillage strategies favour biennial and perennial weeds spreading through vegetative propagules, especially in conditions of monocropping (Clements et al. 1996).

Weed seeds are brought from the fields to the animal pens in the forage, feed cereals and straw, and also by dairy cows grazed on pasture but milked in the cowhouse. If not cleaned thoroughly, or treated with conserving agents that destroy germinability, feed cereals will contain viable weed seeds. Weed seeds are destroyed when feed cereals are milled into small particles, but if feed cereals are only rolled, the smaller weed seeds may survive (Zimdahl 1993). Seed survival during passage through the digestive tract of animals is a function of the intensity of digestion and the rate of passage of digesta, and varies depending on the animal species and the type of diet (Blackshaw & Rode 1991). Weed seeds contained in animal manure are destroyed by moisture combined with either high temperatures or with high concentrations of gases, typically ammonia. In order to achieve a significant reduction in seed viability by windrow composting of manure, a base temperature above 45ºC is required (Nishida et al. 1998), whereas the duration of the process seems less important (Ozores-Hampton et al. 1999). The storage of slurry for a minimum period of three months can significantly reduce weed seed viability (Rieder 1966). The incorporation of slurry directly into the soil compared to spreading it onto the surface decreases weed abundance, and also increases crop yields (Rasmussen & Petersen 1997).

Cultural weed management aims at improving the competitive advantage of a specific crop in relation to weeds (Lazauskas 1994). Before sowing the crop, the rate of weed seeds induced to germination by tillage should be as low as possible and the preparation of the seedbed in spring should therefore be carried out as shallow as possible. A stale seedbed is a suitable environment to allow the destruction of early germinating weeds by non-selective harrowing before or shortly after the crop is sown (Väisänen et al. 2003). Tillage and sowing operations in darkness reduces germination and the subsequent emergence of weed seedlings, compared with the same operations undertaken during daylight (Hartmann & Nezadal 1990). Increased seeding rate together with a more uniform distribution of seed density results in lower weed biomass and weed seed production (Roberts et al. 2001). Adequate soil moisture, shallow placement of the seeds and sowing at relatively high soil temperatures enhance crop establishment and increase crop competitiveness (Håkansson 2003).

Plant growth is nutrient limited in low-productive habitats and light limited in high-productive habitats (Goldberg & Miller 1990, Wilson & Tilman 1991). Nitrogen has a strong impact on weed/crop competition and weed community composition, whereas other nutrients, such as P and K, play a minor role (Andreasen et al. 1991, Walter et al. 2002). At low cereal seed rates, the addition of N increases weed biomass, whereas the number of weeds declines. In contrast, N fertilizer application at higher seed rates increases the competitiveness of the crop in relation to weeds (Erviö 1972). Different levels of applied N also have differential effects upon weed communities (Mahn 1988, Andersson & Milberg 1996). Many weed species have low N requirements and/or similar or greater biomass responses to increasing amounts of soil N as the crop, and these species are therefore likely to be serious competitors (Jørnsgard et al. 1996, Blackshaw et al. 2003). A high rate of N fertilization also benefits shade-tolerant and/or tall and erect weed species, and generally leads to a decrease of weed species abundance and diversity (Ellenberg et al. 1991, Pyšek & Lepš 1991). Fertilizer placement limits the access of weeds to N, which entails a disadvantage especially for nitrophilous weed species (Rasmussen et al. 1996).

Direct weed control measures are necessary when weed infestation exceeds certain thresholds. A definition of the need for direct weed control implies a prediction, based on the competitiveness of single weed species in relation to the competitiveness of the individual crop stand (Salonen 1993b). Weed control thresholds include a prediction of crop yield and product value, and of performance and cost of treatment. Long-term aspects of weed control to be considered include the biological attributes of the weed (fecundity, persistence, vegetative propagules, etc.), land management system, and the potential for control in the various crops of the system (Cussans 1995). A number of direct physical weed control measures are available for organic farming including: stubble cultivation, fallowing, weed harrowing and interrow cultivation (Bond & Grundy 2001). If weed abundance has radically increased in one year, then the weed seed rain and the increase of seeds in the soil seedbank can be avoided by an early harvest. In this case, grain crops can be harvested either as green forage or as whole-grain silage (Pilipavicius & Lazauskas 2000).

2 OBJECTIVES

Organic farming performs well with respect to all dimensions of sustainable agriculture, except for agronomic productivity. In the northern climate and soil conditions, N deficiency and weed competition are known to be the major obstacles restricting the agronomic productivity of organic farming. The focus of this work is on N deficiency and weed occurrence as major obstacles to the agronomic productivity of organic farming under northern climate and soil conditions. Perennial clover-grass leys are the primary contributors of N to organic farming systems in northern Europe. Spring cereals are the most frequently grown agricultural crops in Fennoscandia. Consequently, the objectives of this study involve assessments of the herbage production of perennial red clover-grass leys, of the persistence of red clover, of the level of SNF in legume-grass leys, and of weed occurrence in spring cereal crops. The following research questions are also relevant for the productivity of conventional agriculture.

The general objectives of this work were to

- (i) document the agronomic productivity of organically managed ley and spring cereal crops in the southern and the north-western coastal regions of Finland through the investigations of fields subjected to regular agricultural practices
- (ii) explain agronomic productivity, clover persistence, SNF, and weed occurrence by relating these dependent variables to environmental conditions and agricultural management measures
- (iii) suggest management measures suited to the improvement in agronomic productivity of organic (and conventional) farming.

Specific objectives were to

- (i) quantify herbage production and content of clover, model radiation use efficiency (RUE), and calculate SNF in organically cropped perennial red clover-grass leys (**I**, **II**, **III**)
- (ii) explore the between- and within-field variations of these variables, since they indicate an unrealized potential for higher yields (**I**, **II**, **III**)
- (iii) study the vigour of mixed leys expressed by RUE as a function of the growth period (first and second growth, ley age), of the clover content, and of some site properties (location, soil type, humus content) (**I**)
- (iv) examine the role of geographical location, ley age, and soil properties (the latter being within the scope of improvement on the farm level), in determining herbage production, clover content, and amount of SNF (**II**, **III**)
- (v) suggest management measures suited to improve ley establishment and persistence, especially with regard to the clover component (**I**, **II**)
- (vi) propose the appropriate management measures to optimize the preceding crop value of perennial legume-grass leys (**III**)

(vii) calculate the possible potential of the studied red clover-grass leys in supporting subsequent non-legume crops with N and, *vice verse*, relate measured cereal yields to the potential supply of N from red clover-grass leys (**synopsis**)

(viii) investigate weed communities in the southern and the north-western coastal regions of Finland, thus supplementing the latest national weed survey (**IV**)

(ix) assess levels and variability of weed occurrence between regions and fields (**IV**)

(x) identify the weed species that are most competitive under organic farming conditions (**synopsis**)

(xi) explore interactions between the occurrence of certain weed species and specific agricultural management measures (**V**)

(xii) suggest appropriate weed control measures (**V**).

3 MATERIALS AND METHODS

3.1 Regions, farms and fields

Effects of environment and management on crop growth are usually studied as single causative factors in laboratory or field experiments. In addition, on-farm research plays an important role in the development of agricultural systems (Taylor 1990, Schiere et al. 1999). On-farm research explores agricultural production in the complex reality of farm conditions, yielding information on the relationships between single components of the agricultural system. Observed relationships between dependent and explanatory variables can then be related to knowledge gained by experimental studies. On-farm surveys may identify agronomic potentials contemporaneously unrealized under practical farm conditions, and identify constraints and obstacles to crop and animal performance typical of practical farming. Thus, on-farm research results in guidance for farm management and highlights issues unresolved at farm level for further experimental research. The study of challenges to the agronomic productivity of organic farming by on-farm research was part of the objectives of this work.

This study was carried out in two regions, the southern and the northwestern coastal regions of Finland (hereafter referred to as south and northwest), to assess possible impacts of different environmental conditions on herbage and grain yields, the level of SNF, and the occurrence of weeds. South and northwest regions differ from each other and also from inland regions, in their climate and soil conditions (Kurki 1982, Mukula & Rantanen 1987). Consequently, they also differ with respect to crop productivity and weed occurrence (Mukula et al. 1969). Another reason for the choice of these regions was that ley production, SNF, and weed occurrence in these regions previously had not been monitored as frequently as those of inland regions (Mela 1988, Erviö & Salonen 1987, Nykänen et al. 2000, Halling et al. 2001, Salonen et al. 2001a and b, Mela 2003). The ley and cereal crops studied here were located in the coastal regions of Finland from about 60º to 65º North, along the Gulf of Finland and in the archipelago in the south (the districts of Uusimaa, Varsinais-Suomi, and on the Ahvenanmaa Islands), and along the Gulf of Bothnia in the northwest (the district of Pohjanmaa) (Figure 1).

Herbage samples from leys were collected during the growing seasons of 2001 and 2002, whereas crop and weed samples from spring cereal fields were taken only in 2002. Climate data were obtained from the official meteorological station closest to each farm (FMI 2002 and 2003). The weather conditions during the two seasons differed but the growing periods were consistently longer, warmer and drier in the south than in the northwest. Fields in the south and the northwest differed from each other with regard to their soil texture, humus content and concentrations of plant nutrients (**II** and **IV**).

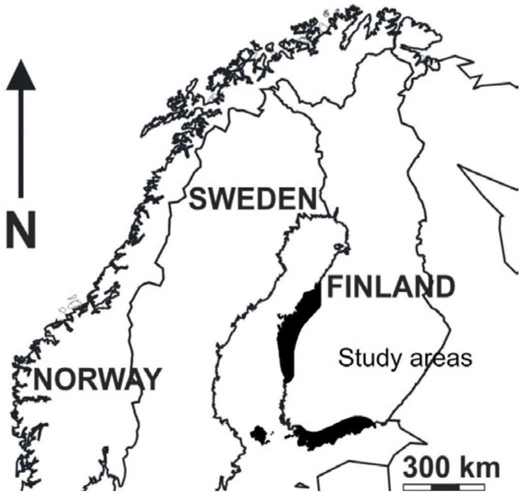

Figure 1 Study areas (highlighted).

The farms included in this study were selected with help from the regional extension services. Criteria for the selection of the farms included certified organic farming, crop rotations including grain and ley cropping, and full-time farmers with an interest in organic farming. Selection aspired to attain an even spatial distribution of farms over the two regions to make use of the data provided by the FMI climate-stations. The study included both arable and mixed farms to avoid a restriction in the number of farms available for the sample. Variations between farms with regard to the duration of organic farming were expected to allow certain dependent variables to be related to this explanatory variable. Finally, the inclusion of an individual farm into the sample depended on the agreement of its farmer to participate in the study.

The sample was restricted to full-time farmers with an interest of organic farming because (i) agronomic productivity was intended to be representative of productive as opposed to extensive farming (in terms of commitment, and labour and input intensity) and because (ii) agronomic productivity, N supply and weed occurrence were intended to be related to proper organic management practices. Restriction to full-time farmers with an interest in organic farming did not intend any preference for farms characterized by excellent conditions for organic farming and/or farms with excellent management. Nonetheless, it is recognized that this restriction did involve a bias towards higher crop productivity. Thus, the level of agronomic performance reported here is not truly representative of the statistical average of organic farming in the coastal regions of Finland, and even less of the statistical average of organic farms in Finland in general.

The focus on full-time farming also resulted in a bias on farms with relatively large areas of arable land. The average size of arable land per farm was 64.2 ha (median = 51.8 ha), about twice that of the average of organic (and conventional) farms in Finland (**II** and **IV**; Information Centre of the Ministry of Agriculture and Forestry 2003). On large farms, farmers have the opportunity to concentrate on the farm business and they are likely to be educated for this profession. Due to the advantages of scale, large farms usually are technically better equipped than their smaller counterparts. Furthermore, a large hecterage may indicate that cereals were preferably grown on soils particularly suitable for these crops. These socioeconomic circumstances additionally influenced the yield levels recorded in this study of organic farming.

Ideally, organic farming in the northern locations combines crop and animal husbandry (Lampkin 1992, von Borell & Sørensen 2004). However, agricultural policy in Finland has encouraged regional specialization, with arable farms being concentrated in the south and mixed farms with an increasing specialization in animal husbandry in the other parts of the country, including the northwest (Information Centre of the Ministry of Agriculture and Forestry 2008a). Organic farms reflect these regional differences in the distribution of enterprises. However, out of practical reasons and/or due to the regulations specific for organic farming, organic arable and organic mixed farms apply similar soil tillage, fertilization, and plant protection measures. Arable organic farms frequently apply animal manure transferred from conventional mixed farms. With only three exceptions, the farms participating in this study applied animal manure obtained either from the farm´s own livestock production enterprise or from other farms (**II** and **IV**). The management of leys constitutes a more general difference between organic arable and organic ruminant livestock farms. On the latter, all cuts are usually harvested, whereas on the former the second, or even both cuts, are usually mulched. However, this difference in management was not expected to influence subsequent ley growth in a decisive way (Hatch et al. 2007, **II**). Dependent variables were related to soil properties, whether these were influenced by type of production, or not. Accordingly, both arable and mixed farms were included in the sample.

The 34 farms that participated in this study were managed according to the regulations defining organic farming in the member states of the EU (EC 1991 and 1992). The crop rotations of all farms included ley and grain crops. The proportion of ley in relation to other crops included in the crop rotation ranged between 25 to 34.9 per cent on nine, between 35 to 44.9 per cent on eight and between 45 to 54.9 per cent on 13 of the farms, and exceeded 55 per cent on four farms. Low proportions of ley were compensated for by the importation of manure from other farms. Twenty of the farms were located in the south and 14 in the northwest. Eighteen farms kept cattle or pigs, whereas 16 farms had no livestock. Mixed farms and arable farms were not distributed evenly along the coastal regions. In the south and in the southernmost part of the northwest, the farms mainly had no livestock. In contrast, all farms in the northern part of the north-western region specialized in milk production. Five of the surveyed farms had been managed according to organic farming principles since as early as the 1980s, 18 farms had converted during the 1990 to 1994 period, and 11 farms had switched over to organic farming 1995 to 1999. The pioneer farms were situated on Ahvenanmaa and in southern Pohjanmaa, the newcomers were evenly distributed across the coastal regions (**II** and **IV**).

Red clover-grass leys were studied on 19 farms in the south and on 14 farms in the northwest. The rotations of the investigated farms included red clover-grass leys with a duration of one, two, or three years. Leys on mixed farms most often lasted for three years whereas leys on arable farms usually were terminated after one or two production years. The leys were cut twice per season, as generally recommended for red clover-grass leys in Finland (Mela 2003). On dairy and cattle farms both first and second cuts were harvested (17 farms). On half of the arable farms the first cut was harvested as a cash crop or in exchange for manure, whereas the second cut was left in the field as green manure. On the remaining 50 per cent of the arable farms both first and second cuts were exclusively mulched for green manure. Three of the non-livestock farms used a part of the leys for seed production, and one farm produced clover and grass seed from the whole ley area. Of the farms producing clover and grass seeds, two were situated in the south and two in the northwest. Further details on ley management are given in studies **I** and **II**.

Weed occurrence in spring cereal crops was surveyed on 30 farms, of which 18 were located in the south and 12 in the northwest. On half of the farms the proportion of spring cereals was between 15 to 44.9 per cent, on the other half between 45 to 75 per cent. Preceding crops were ley (17 fields), cereals (nine fields), potato (one field), and fallow (three fields). The fields were ploughed, with one exception where a spring-tine cultivator was used. The seedbeds were prepared by harrowing 2 to 4 times. Subsequent to the sowing of seed, the seedbed was in many cases re-compacted by rolling (22 out of 30 fields). Numbers of viable crop seeds per square meter were highest for summer wheat and markedly lower for oats and barley (means 700, 550, and 450 seeds m^{-2}, respectively). The first crops were established at the beginning of April (southwest), and the last ones at the end of May (northwest). Further details on weed management in spring cereal crops are found in studies **IV** and **V**.

3.2 Sampling

Ley samples were taken on 34 farms from one-, two-, and three-year-old leys, i.e., leys in the first, second, and third production year, whenever these were available. Samples were taken prior to the first and to the second cuts and, of the aftermath, after the growing season had ended. Samples obtained from 114 leys (33 farms) were used for the calibration of RUE (**I**). Samples from the first and the second cut of 79 crops (27 farms) were collected within the cut-off value of 20 days between sampling and harvest by the farmer. These samples were used for the determinations of herbage production and SNF (**II**, **III**). Samples from the aftermath were obtained from 52 of these 79 leys (20 farms), which made it possible to calculate SNF over the whole growth period (**III**). Samples were also taken from five leys grown for harvest of seed (four farms).

At each sampling, four plots were chosen by dividing the longest diagonal across the field into five equal distances. The herbage was cut with shears at 20 to 30 mm above the soil surface, separated by hand into two fractions, clover and grass (also including all dicotyledons other than clovers), and dried using air-flow dryers at between 25 to 30°C to a constant weight of around 5 per cent moisture content. The samples were weighed to the nearest 0.01 g. All herbage weights were corrected to dry-matter (DM) weights. The samples taken from each plot were treated separately but pooled for the analyses of herbage production, clover contents and SNF on a field level (**I**, **II**, **III**).

For the study of weed occurrence, one spring cereal crop each was selected on 30 farms. Samples from spring cereal crops were obtained from four 0.25 m^2 plots per field. In each field, weed density and biomass weight were determined at species level. The competitive capacity of the crop was assessed by the determinations of shoot density, biomass weight and the average height of the crop stand. At crop development stage decimal code (DC) 14-16 according to the Zadoks scale for cereals (Zadoks et al. 1974), the plots were placed along a diagonal line across the field at even distances. Weed and crop samples were collected at crop DC 70-79. Crop and weed species were cut at soil surface, sorted by species or taxa, counted, and dried in paper bags. The samples were dried with an air-flow dryer at 30 to 40ºC. All biomass weights are given as air-dry above-ground biomass (dry weight), referring to 5 per cent moisture content. Moisture contents were equalled before weighting. The samples were weighed to the nearest 0.01 g. For all assessments, the samples were pooled at the field level (**IV**, **V**).

3.3 Analyses of data

The actual ley yields obtained by the farmers at the time of harvest were simulated using a grassland growth model (Torssell et al. 2007), which was calibrated to fit the dry matter weight of the sample at the date when the sample had been taken (**I**). The clover content is expressed as a percentage of the clover-grass ley and also referred in this text as the clover proportion. SNF was calculated from clover herbage dry-matter yield with the empirical model proposed by Høgh-Jensen et al. (2004). In 89 samples, N concentration in clover herbage was analysed by the Kjeldahl method (Nousiainen et al. 2003). Seasonal variation in N concentrations was assumed to be minor (Huss-Danell et al. 2007). The model was applied with the parameter values proposed for cut one- and two-year-old red clover-grass leys grown on clay type soils (**III**).

RUE, root allocation (b_r), and clover proportion in perennial red clover-grass leys were related to the explanatory variables ley age, annual growth cycle, region, soil type, humus content, and the interaction between ley age and annual growth cycle, in a linear mixed model in SPSS 12.0.1 (SPSS Inc. 2002). Pairwise comparisons between the three variables RUE, b_r and proportion of clover were made using *t*-tests (**I**). Herbage production, clover proportion, and SNF were related to ley age, annual growth cycle, geographical location, and soil properties by general linear modelling (GLM) in SPSS 15.0 (SPSS Inc. 2003 and 2006). Principal Component Analysis (PCA; in SPSS 15.0) was used to summarize soil properties prior to the analysis of variance. Herbage production was also expressed as a function of clover content. Differences in herbage production, clover contents, and SNF between the first and the second cuts, between the regions, and between the two sampling years were determined by *t*-tests with Duncan-Šidak corrections for multiple testing. Within-field variation was expressed as the coefficient of variation of the four sub-samples from each field (**II**, **III**).

In the analyses of weed occurrence in spring cereal crops, the following parameters were determined and compared between south and northwest regions using the Wilcoxon two-sample test: mean numbers of weed species, crop densities, weed densities, dry weights of crops, dry weights of weeds, densities and dry weights of single weed species. Since the number of fields varied between south and northwest, the total species numbers between regions could not be compared. Instead, the expected number of species was calculated by rarefaction (Heck et al. 1975, Krebs 1999; **IV**). Relationships between weed occurrence and agricultural management were analyzed by using Redundancy Analysis (RDA) and CANOCO 4 software (ter Braak & Šmilauer 1998; **V**).

4 RESULTS AND DISCUSSION

4.1 Perennial red clover-grass leys

4.1.1 Herbage production and symbiotic nitrogen fixation

The organically cropped red clover-grass leys studied here under regular farming conditions were productive and SNF added considerable amounts of N to the fields. As pointed out under Materials and methods (heading 3.1), the objective of this study was to present yield levels representative of full-time and professional organic farmers, and most of all to identify challenges to the productivity of organic farming.

During the autumn following the harvest of the nurse crop, the undersown leys in many cases built up considerable amounts of herbage with high proportions of clover that resulted in relatively high levels of SNF. Mean ley growth subsequent to the harvest of the nurse crop was 1.4 t ha^{-1} (SD ± 0.6 t ha^{-1}), with a clover proportion of 56.2 per cent (SD ± 24.9%). In the establishment year, the autumn growth of the leys on average fixed 38.6 kg N ha^{-1} (SD ± 25.2 kg N ha^{-1}). Herbage growth of undersown crops was assessed at the end of the growing season. Losses of herbage at the harvest of the nurse crop were not considered, and therefore the values presented here are an underestimation especially of herbage production and SNF values. The amount of herbage removed from an undersown crop at the harvest of the nurse crop depends on the competitiveness of the undersown crop in relation to the nurse crop and on the stubble height of the cutterbar. The taller and well-developed the undersown crop and the lower the stubble height, the more herbage is cut down. Another factor that influences the development of an undersown crop is the time of harvest. The earlier the harvest of the nurse crop, the longer is the time that the ley crop has at its disposal for further incremental growth (Table 3, **II**, **III**).

Table 3 Herbage biomass, clover proportion and symbiotic nitrogen fixation (SNF) in organically cropped leys established in cereal nurse crops at the end of the first growing period (n = 36; means averaged over two years; standard deviations in parenthesis).

Herbage biomass (t DM ha^{-1})		Clover proportion (%)		SNF (kg N ha^{-1})	
South[a]	Northwest[a]	South[a]	Northwest[a]	South[a]	Northwest[a]
1.2	1.5	69.6	42.9	45.3	31.1
(0.7)	(0.5)	(24.1)	(25.7)	(32.5)	(17.9)

[a] South = southern coastal region, northwest = north-western coastal region.

The herbage production accumulated from the first and the second cut of one- and two-year-old leys averaged 7.5 t DM ha^{-1} (SD ± 1.7 t DM ha^{-1}; n = 79). In addition to herbage production (i.e., first and second cut), accumulated herbage growth includes the (non-cut) aftermath (Table 4). The herbage was cut 20-30 mm above the soil surface, which is about half of the normal defoliation height. On the other hand, the values of herbage production reported in this study are based on herbage DM weight at the time of sampling. When the farmers cut the leys, the crops on average yielded 13.0 per cent more. Thus, the red clover-grass leys studied here produced herbage yields comparable with the levels reported from Nordic field experiments with mixed legume-grass leys not treated with easily soluble N fertilizers (**II**; Granstedt & Baeckström 2000, Halling et al. 2001). In field experiments carried out in Finland, one- and two-year-old grass leys treated with 200 kg ha^{-1} mineral N fertilizer yielded about 30 per cent more herbage (Halling et al. 2001). On the other hand, the 10-year average ley yield obtained in practical conventional farming in the coastal region is around 25 per cent lower than the values recorded in this study (Information Centre of the Ministry of Agriculture and Forestry 2008c).

Table 4 Herbage growth in organically cropped leys (n = 52; means averaged over two years; standard deviations in parenthesis).

	First cut (t DM ha^{-1})		**Second cut (t DM ha^{-1})**		**Aftermath (t DM ha^{-1})**	
	South[a]	**Northwest[a]**	**South[a]**	**Northwest[a]**	**South[a]**	**Northwest[a]**
One-year-old leys	3.8 (1.5)	4.0 (1.1)	4.1 (0.8)	3.5 (1.0)	2.1 (1.5)	2.2 (0.9)
Two-year-old leys	3.4 (1.3)	4.5 (1.0)	3.6 (0.8)	3.2 (1.1)	2.7 (1.3)	1.8 (0.7)
Three-year-old leys	-	3.8 (0.8)	-	2.5 (0.7)	-	1.5 (1.1)

[a] South = southern coastal region, northwest = north-western coastal region.

When the proportion of clover was averaged over the first and the second cut of one- and two-year-old leys, 43.9 per cent (SD ± 18.8%; n = 79) was obtained. Proportions of clover were considerably higher in the south than in the northwest (Table 5, **II**). In both regions, the proportions of red clover were lower than the levels reported by Halling et al. (2001) from southern and northern locations in Finland. In a considerable number of leys, clover contents were already low in the first production year. The lower the proportions of clover, the higher were within-field variations of clover proportions and SNF (**II**, **III**). Moreover RUE differed considerably between single sites (**I**).

Table 5 Clover proportions in organically cropped leys (n = 52; means averaged over two years; standard deviations in parenthesis).

	First cut (%)		**Second cut (%)**		**Aftermath (%)**	
	South[a]	**Northwest[a]**	**South[a]**	**Northwest[a]**	**South[a]**	**Northwest[a]**
One-year-old leys	61.3 (23.4)	24.2 (14.6)	77.7 (13.2)	51.2 (19.4)	67.5 (22.0)	49.4 (19.9)
Two-year-old leys	40.9 (34.8)	20.4 (17.6)	68.4 (17.3)	38.9 (23.8)	57.8 (22.4)	29.0 (18.4)
Three-year-old leys	-	18.1 (30.5)	-	18.4 (7.7)	-	16.6 (8.3)

[a] South = southern coastal region, northwest = north-western coastal region.

Mean SNF in the accumulated annual growth of one- and two-year-old leys amounted to 247.5 kg N ha^{-1} yr^{-1} (SD ± 114.4 kg N ha^{-1} yr^{-1}; n = 52); of that, the contribution of the aftermath was 62.1 kg N ha^{-1} yr^{-1} (SD ± 49.8 kg N ha^{-1} yr^{-1}) (Table 6, **III**). Pure red clover seed leys produced 8.2 t DM ha^{-1} yr^{-1} (SD ± 0.8 t DM ha^{-1} yr^{-1}), containing 422.1 kg symbiotically fixed N ha^{-1} (SD ± 40.7 kg N ha^{-1}). The DM of clover herbage was obtained by cutting it 20-30 mm above the soil surface instead of using shoot biomass cut at normal defoliation height. The clover thus obtained was subsequently used as input-data for the model described by Høgh-Jensen et al. (2004) and the determination of which resulted in an over-estimation of SNF. On the other hand, the values of SNF reported in the present study are based on clover herbage DM weight at the point of time of sampling (see above). In addition, the average N-concentration in a number of analyzed red clover samples appeared to be 7 per cent higher than the standard value proposed by Høgh-Jensen et al. (2004). The values reported for the present study exceed or are comparable to levels of SNF reported from other parts of Finland (Känkänen et al. 1999, Väisänen 2000, Halling et al. 2001, Nykänen 2008). However, the use of different methods for determining or estimating SNF complicates comparisons. For example, the model developed by Høgh-Jensen et al. (2004) used in this present study gave an estimate of SNF that is about one third higher compared with the values derived from the model proposed by Carlsson & Huss-Danell (2003).

Table 6 Symbiotic nitrogen fixation (SNF) in organically cropped leys (n = 52; means averaged over two years; standard deviations in parenthesis).

	First cut (kg N ha^{-1})		Second cut (kg N ha^{-1})		Aftermath (kg N ha^{-1})	
	South[a]	**Northwest[a]**	**South[a]**	**Northwest[a]**	**South[a]**	**Northwest[a]**
One-year-old leys	123.6 (83.3)	52.7 (44.2)	163.7 (51.2)	92.9 (48.6)	78.6 (70.1)	61.9 (47.2)
Two-year-old leys	63.6 (47.7)	46.2 (40.6)	131.3 (49.9)	67.6 (54.0)	77.4 (54.4)	30.6 (27.6)
Three-year-old leys	-	41.8 (71.0)	-	26.0 (14.6)	-	18.2 (20.2)

[a] South = southern coastal region, northwest = north-western coastal region.

From the first to the second cut, herbage production decreased whereas clover proportion increased. With increasing ley age, herbage production and clover proportion decreased (**II**). These patterns of red clover-grass growth are corroborated by a number of previous studies (Granstedt 1992, Fagerberg & Ekbohm 1995, Mela 2003). On the other hand, Nykänen et al. (2000), Halling et al. (2001), and Huss-Danell et al. (2007) reported that herbage production reached its highest level in two- and three-year-old red clover-grass leys, along with stable or increasing clover contents. Being a direct function of clover biomass, SNF increased from the first to the second cut and thereafter decreased in the aftermath. Over the production years, SNF declined with ley age (**III**). The proportion of clover positively affected the RUE value (**I**). Herbage production appeared to be dependent on the proportion of clover (**II**). This concurs with the findings by Mallarino & Wedin (1990), Newton (1995) and Ritchey et al. (2004). On the other hand, Nykänen (2008) did not find any consistently positive correlation between herbage production and clover proportions.

The proportion of clover dropped with increasing ley age, particularly from the second to the third production year, resulting in a decline of herbage production. On the other hand, RUE declined from one- to two-, but not further to three-year-old leys, indicating a relatively high potential of productivity in three-year-old leys. However, a decline in clover biomass was associated with sparser crop stands. In addition, lower cold tolerance and increased incidence of diseases in older plants represent greater risks of winter damage in aging stands (Bélanger et al. 2006). If N cycling solely depends on green manuring, red clover grass leys ought to be terminated after the first, or possibly second, production year. Three production years are valid only if N is circulated both through harvest residues and in a forage-feed-manure chain (for further exploration of this topic see 4.1.3). This reasoning at least applies to mineral soils in which the amount of N available from SOM is relatively low. On mull and peat soils, crop N supply can be based on mineralization of N from soil stocks. In this case, forage leys can be maintained as long as the swards are productive, irrespective of their clover contents.

4.1.2 Variability of ley growth

The variability of clover content as a proportion of the sward between different fields and within single fields markedly exceeded that of herbage production. Whereas the variability of herbage production did not differ between the regions, the between- and within-field variability of clover proportions was considerably higher in the northwest than in the south (Tables 4, 5, 7, 8). For a mean of one- and two-year-old leys, the coefficients of between-field variation of accumulated herbage production amounted to 23.3 per cent in the south and 21.3 per cent in the northwest, whereas their respective proportions of clover were 38.3 per cent and 54.9 per cent (n = 79). Similarly, coefficients of within-field variation of herbage production averaged 20.0 per cent in the south and 17.7 per cent in the northwest, whereas those of clover proportions were 34.7 per cent and 61.4 per cent (n = 79). Being a function of clover biomass, between- and within-field coefficients of variation of SNF for the accumulated growth of one- and two-year-old leys were markedly higher in the northwest than in the south (65.6 vs. 36.7% and 67.4 vs. 36.2%, respectively; n = 52).

The between- and within-field variability of clover contents and of SNF markedly decreased from the first to the second cut but increased in the aftermath. With increasing ley age the variability of clover contents and of SNF quantities increased. In contrast, between- and within-field coefficients of variation of herbage growth only slightly changed during the production cycle of the leys. Between- and within-field coefficients of variation for herbage growth had a tendency to increase over the three annual growth cycles. In the northwest region, between- and within-field coefficients of variation for herbage growth appeared to decline from the first to the third production year (Tables 4, 5, 6, 7, 8; **II**, **III**). Owing to the positive correlation between the proportions of clover in a ley and RUE, the variability of RUE mirrored that of clover, increasing from the first to the second cut, and from the first to the second production year. However, this association did not occur during the third production year (**I**).

Table 7 Coefficients of within-field variation of herbage growth in organically managed red clover-grass leys in the coastal regions of Finland, averaged over two growing seasons (n = 52).

	First cut (%)		Second cut (%)		Aftermath (%)	
	South[a]	**Northwest[a]**	**South[a]**	**Northwest[a]**	**South[a]**	**Northwest[a]**
One-year-old leys	15.2	20.5	18.0	22.5	23.6	25.2
Two-year-old leys	18.3	11.9	17.9	15.9	23.3	25.3
Three-year-old leys	-	13.9	-	16.8	-	25.9

[a] South = southern coastal region, northwest = north-western coastal region.

Table 8 Coefficients of within-field variation of clover proportions in organically managed red clover-grass leys in the coastal regions of Finland, averaged over two growing seasons (n = 52).

	First cut (%)		Second cut (%)		Aftermath (%)	
	South[a]	**Northwest[a]**	**South[a]**	**Northwest[a]**	**South[a]**	**Northwest[a]**
One-year-old leys	22.5	82.6	10.7	41.0	18.6	53.3
Two-year-old leys	46.6	70.6	19.6	51.5	31.4	73.8
Three-year-old leys	-	85.2	-	73.4	-	112.1

[a] South = southern coastal region, northwest = north-western coastal region.

High variability of clover growth between and within fields is known (Fagerberg & Ekbohm 1995, Nykänen et al. 2000, Hansen & Vinther 2001), but its magnitude under practical farming conditions has so far not been quantified. Leys established by undersowing in cereal nurse crops obviously have a potential as catch and green manure crops, but due to their large variations in herbage production and clover contents, and therefore also in SNF, their benefits appeared to be hard to predict. During the production years, between- and within-field variations of clover contents were high, indicating that herbage production and forage quality varied more in clover-rich than in grass-dominated leys. In addition, high between-field variability of clover growth and SNF complicates calculations of the preceding crop value of leys.

Low proportions of clover and low SNF on field level were strongly related to high within-field variation of clover contents and of SNF. High within-field variation of SNF affects the growth of the succeeding crop, if N is the limiting factor. Alternatively, the yield of the succeeding crop may be limited by other factors that also constrain legume growth. In both cases, restricted crop growth contributes to a gradual deterioration of soil fertility in certain parts of the field, and to an increase in within-field patchiness of plant growth (Frogbrook et al. 2002). Within-field variability of soil fertility can be amended through targeted measures including: drainage, liming, and applications of organic and mineral fertilizers (Palojärvi & Nuutinen 2002).

In arable organic farming, the herbage of green manure leys is usually cut and left on the ground, to be incorporated into the soil when the ley has been terminated (Stopes et al. 1996). Since green manuring involves the cycling of plant nutrients within a rather narrow area, within-field variability of SNF will lead to increasing patchiness of crop growth. In contrast, a harvest of forage entails that around half of the total crop biomass is removed from the field, with most of its plant nutrient content being transferred to animal manure. High SNF in certain field patches promotes herbage growth in these patches and, if the resulting herbage is harvested for forage, then it leads to a stronger depletion of nutrients from these patches. If animal manure is allocated evenly over a single field, relatively high amounts of nutrients are returned to low-, and low amounts to high-yielding patches. Thus, animal husbandry provides an option to redistribute plant nutrients not only between fields but also within fields. Animal manure also enriches SOM, thus alleviating other obstacles to plant growth, such as a low cation exchange capacity (CEC), poor water-holding capacity, and soil compaction (Schjønning et al. 1994). In the long run, the redistribution of OM and nutrients through animal husbandry will bring about a decrease of between- and within-field differences. Therefore, integration of crop and animal husbandry is an important mechanism to improve soil fertility between and within fields.

4.1.3 Establishment and persistence of leys

Herbage production and SNF of mixed perennial leys depend on legume growth. Consequently, management measures ought to aim at optimizing establishment and persistence of the legume component. The clover contents in the seed mixtures used for the establishment of the leys investigated in this study potentially entail a domination of clover in the herbage growth of one-year-old leys. However, in a considerable number of leys, clover proportions were low already in the first production year, which suggests a poor establishment and/or poor persistence during the first winter (**II**). Poor establishment was also expressed by poor predictability of herbage production in the spring growth. In the northwest, the variability of clover in the leys was higher at one year than at two years (**II**; Jørgensen et al. 1994). A lower between- and within-field variability in the red clover content and RUE in the second than in the first cut indicated a certain degree of stabilization during the summer, whereas an increase in the variability with ley age expressed a decline in vigour and persistence especially of red clover (**I**, **II**; Lindén et al. 1999). The risk for damage to overwintering crops is higher in the northwest than in the south. The water-holding and capillary humus-rich silt and organic soils frequent in the northwest are more prone to frost-heaving than the clay soils dominating in the south. Furthermore, the topography of fields in the northwest is often more even, leading to a higher incidence of flooding and ice-encasement (Mukula & Rantanen 1987, Lindén et al. 1999).

On about half of the surveyed farms, solid animal manure (farm yard manure, i.e. faeces and urine mixed with bedding) was spread on the fields prior to ley establishment. A considerable proportion of the N contained in solid manure is mineralized first in late summer and autumn, especially when there is a soil moisture deficit in spring and early summer (Schröder 2005). Excessive N uptake has a detrimental impact on the overwintering of ley crops (Pulli 1980). In mixed leys, N available from the soil stock or fertilizers also impairs the competitiveness of legumes relative to grasses (Streeter 1988). Therefore, amounts of N added prior to the establishment of perennial leys should be moderate. Fertilizers containing large proportions of readily plant-available N, such as urine and slurry are appropriate rather for top-dressing older leys with lower clover contents than for store fertilization prior to ley establishment. Whereas excessive N uptake jeopardizes overwintering, the supply of P and K improves winter hardiness and spring regrowth of grasses and clovers (Pulli 1980, Bélanger et al. 2006). Clover establishes slowly and therefore sowing no later than in the middle of July benefits overwintering (Kilpatrick et al. 1966). In order to prevent shading, the straw of harvested nurse crops should be removed as soon as possible after combining (Fergus & Hollowell 1960). Straw stubble, on the other hand, increases snow entrapment, which in turn facilitates the development of an insulating snow cover and thus decreases the risk of ice encasement (Bélanger et al. 2006).

A harvest regime with intervals long enough for the replenishment of energy and nutrient reserves is critical for the persistence of perennial ley crops (Bélanger et al. 2006). The timing of the last cut should allow for at least six weeks of post-harvest growth preceding the expected date of the first killing frost (Bélanger et al. 2006). Late cutting will have a less severe impact, if little or no regrowth occurs before the first killing frost (Dhont et al. 2002). However, removal of leaves may interfere with the reallocation of nutrients from shoots to roots (Dhont et al. 2003). On the other hand, too lush an aftermath may increase the incidence of fungal diseases (Bowley et al. 1984). Generally, a limitation of the harvest regime to two cuts fits in well with Finnish conditions under which swards harvested two times per season produce more herbage than those harvested three times (Pulli 1980, Mela 2003).

4.1.4 Influences of soil properties on ley growth

Soil properties influenced herbage production, clover content, and therefore also SNF. In certain cases these properties turned out to have such a strong influence, that effects of region and ley age were not apparent (**II**, **III**). Compared to the south, lower clover content, lower SNF, and the greater between- and within-field variabilities of these variables in the northwest suggested that clover growth was affected by factors related to geographical location. Consequently, that clover growth was influenced by climate and soil conditions specific to the northwest. Since the inclusion of soil properties into the analyses partly invalidated the effects of region as an explanatory variable for the clover contents and SNF, adverse soil-related factors characteristic of the northwest were more likely to be decisive than a harsh climate *per se* (**II**, **III**). Soil properties that influenced herbage production, clover proportions and SNF included CEC, humus content, pH and soil nutrient concentration (**II**, **III**).

Herbage production, clover content, and SNF were positively related to a soil gradient determined by CEC, i.e., to increasing nutrient and water exchange capacity. The CEC is positively related to the soil´s clay and humus contents, i.e., to factors that also define soil texture and structure (Munkholm et al. 2002). In fine-textured soils, nutrient availability is usually higher and nutrient stocks are larger (Withers et al. 2001, Öborn et al. 2005). Soil texture and soil structure both determine soil porosity, and therefore water transport and gas exchange. These are the preconditions for the microbial activity and the chemical reactions decisive for nutrient mobilization (Thomsen et al. 2003). Good soil structure also is important for facilitating the ease of penetration of the soil by roots (Lynch 1980, Dexter 1988). Red clover thrives best on soil types characterized by friable surface soils and permeable subsoils (Fergus & Hollowell 1960, Rufelt 1986). This is the probable cause for the finding by Mela (2003) that well-aerated sandy soils in north-western Finland were more favourable for the growth of red clover than the clay soils dominating in the south. Soil compaction by machinery is a serious threat to the productivity of arable production, causing reduced plant growth, poorer soil workability and erosion (Alakukku 1999, Munkholm & Schjønning 2004). Reintam et al. (2009) showed that even a low-weight tractor induced compaction and considerably decreased plant productivity. To avoid soil compaction, load of machinery, the number of passes, and tillage intensity should be reduced (Munkholm & Schjønning 2004, Reintam et al. 2009). The commencement of field operations is suitable when soil moisture content is 70 to 90 per cent of field capacity, depending on soil texture (Nugis et al. 2004).

Although a soil´s humus level is indicative of the amounts of nutrients contained in the SOM and available for plant growth through the mineralization process, a soil gradient related to humus content correlated negatively with herbage production. Had there also been a negative correlation between humus content and clover proportion, the negative consequences of high humus contents on herbage production might have been explained by a decreased competitiveness of clover in relation to grasses caused by ample supply of N from SOM (Ledgard & Steele 1992, Griffin et al. 2002). However, this was not the case in the present study. Instead, the positive effect of N mineralization from SOM on herbage production may have been counteracted by the detrimental impact that an extensive uptake of N has on the hardening and overwintering of leys (Pulli 1980, Bélanger et al. 2006). The abundance of nitrophilous weeds in the spring cereal fields studied on the same farms suggests that N was not a limiting factor for ley growth (**IV**). Humus-rich soils are also prone to frost heaving and, since they often are located in low-lying grounds, to flooding. Damage during winter is thus another probable factor explaining the negative correlation between a high humus content and herbage production. Ley establishment and growth on humus-rich mineral and organic soils may also have especially suffered from competition by *Elymus repens*. This perennial monocotyledonous weed species prefers humus-rich soils and is also highly competitive in grassland but produces lower yields than specially bred ley grasses (Håkansson 2003). *E. repens* constituted 1.8 and 10.8 per cent of the average total crop and weed dry weight in the investigated spring cereal fields (for south and northwest, respectively) (**IV**). It is likely that the occurrence of *E. repens* was also prominent in the ley fields of the farms participating in this study.

In contrast to herbage production, clover content and SNF were not related to the gradient of high pH values in the summarized soils. This was surprising since red clover requires a higher pH than do grasses and since legumes generally respond better than grasses to liming (Pires et al. 1992, Hojito 1998). However, most of the surveyed fields had neutral pH values and rather high humus contents. With very few exceptions, all crops including legumes cease to respond to lime above pH 5.5-5.8 (Sumner & Yamada 2002). Higher pH-values also promote the mineralization of N from SOM and thus an increase in the proportion of grasses at the expense of legumes (Ledgard & Steele 1992, Schechtner 1993). Herbage growth, clover content and SNF appeared to be positively related to soil nutrient concentrations. Ley growth requires a supply of P and K (Acuña & Wilman 1993, Pant et al. 2004). The importance of K for cold resistance may have contributed to the positive correlation between soil-K and clover proportions (Bélanger et al. 2006).

Differences in growth between leys of the same age grown in the same region may be caused by local climate conditions, specific soil properties, and individual management factors. Within each field, weather conditions and management measures were consistent. Therefore, within-field variation was related to spatial differences in soil properties, to field topography, and also possibly to minor variations in sowing. In some fields, spatial variability of herbage growth may have been caused by weed occurrence, primarily by *E. repens* (**IV**). The levels of variability in herbage production, clover content and SNF within fields were similar to those between fields. This suggests that soil properties were also mainly responsible for the variability of these dependent variables between fields. Management, through crop rotation, fertilization and harvest regimes, did not considerably increase the variability of these response variables between fields. This finding might partly be due to the fact that the organically cropped leys included in this study were largely subjected to the same patterns of management, and that easily soluble mineral fertilizers and herbicides were omitted. In the longer perspective, management not only directly affects crop growth but also determines it indirectly through changes in soil fertility.

4.1.5 Nitrogen supply of mixed leys to succeeding crops

With respect to N supply, the cropping of legumes is a generator of soil fertility. It enriches the N soil stock, which is then depleted by succeeding cereal crops (Tyson et al. 1990, Hauggaard-Nielsen et al. 1998). Management of legume-grass leys for forage or green manure has a differentiating impact on the supply of N to succeeding crops, and on the total amount of N available within a whole crop rotation cycle. Thus, different crop rotations have to be used on mixed and on arable farms.

On arable farms, leys were usually terminated after the first production year. One-year-old leys in the south fixed a mean of 366 kg N ha^{-1}. Assuming that 80 per cent of the N in red clover is derived from the air, the ley crop contained 457.5 kg N ha^{-1}; of this, 5 per cent is lost by ammonia-volatilization (Table 2). Of the 435 kg N ha^{-1} remaining, around 20 per cent (87 kg N ha^{-1}), is available for a succeeding cereal crop. Together with 50 kg N ha^{-1} derived from the mineralization of SOM, this may suffice for a grain yield of 4 t ha^{-1} (15 per cent moisture content). In the following year 10 per cent of ley-N, 43.5 kg N ha^{-1}, should be available for crop growth, and together with the N mobilized from the soil stock, this is enough to produce 3 t grain ha^{-1} (Table 9). This suggests that if a cereal nurse crop was to be used for ley establishment, in the third year, the second crop after ley termination should be neutral, or positive with respect to N requirement. Otherwise, soil-N levels in the third year after ley termination would be too low to allow for a reasonable grain yield. Consequently, a four-year-crop rotation on an arable organic farm may consist of (i) one ley year, followed by (ii) cereals, (iii) pulses, and (iv) cereals with undersown ley (see further down on the phytopathological drawbacks of such a short rotation).

Table 9 Red clover-grass leys managed for green manure: estimated preceding crop value, total nitrogen (N) supply to succeeding crops, and transformation of N into yield.

	Preceding crop value (kg N ha^{-1})	
SNF[a]	366	
Total N content in the ley crop[b]	457.5	
Left after volatilization[c]	435	
	N supply to succeeding crops (kg N ha^{-1})	
Crop order	I	II
+ Preceding crop value[d]	87	43.5
+ Mineralization of SOM[e]	50	50
= N available for subsequent crops	137	93.5
	Transformation of N into yield (t ha^{-1})	
Grain yield[f]	4	2.7

[a] Mean value of SNF measured in the south (one-year-old ley, green manure).
[b] pNdfa making up 80 per cent of total N content (Carlsson & Huss-Danell 2003).
[c] Ammonia volatilization making up 10 per cent of the N contained in mulched herbage (Whitehead & Lockyer 1989).
[d] 20 and 10 per cent of the N contained in ley biomass being available to the first and the second succeeding crop, respectively (Crews & Peoples 2005).
[e] Assuming mineral soil with 5 per cent humus content (arable farm), and a mineralization rate of 1 per cent of total soil N during the growth period (Kummer & Dawson 2008).
[f] Assuming a crop need of 35 kg N per 1 t grain (Aufhammer 1998), 15 per cent moisture.

In the case of ruminant livestock farms, leys were usually terminated after three production years. SNF in three-year-old leys in the northwest averaged 86 kg N ha^{-1}, i.e. the crop contained 107.5 kg N ha^{-1}. Of this, around 20 and 10 per cent (21.5 and 10.75 kg N ha^{-1}), respectively, should be available during the two years subsequent to ley termination. In the case of a mixed farm where leys are kept for three production years, and manure is applied regularly, N mineralization is supposed to be twice as high as that obtained under conditions of arable farming and ley termination after one production year (100 instead of 50 kg N ha^{-1}). Additional N is re-circulated in manure. One-, two- and three-year-old ley crops contained a mean of 175.9 kg symbiotically fixed N ha^{-1}, i.e. a total of 220 kg N ha^{-1}, of which 110 kg N ha^{-1} were removed with the forage. Assuming that animal manure is handled as slurry with 70 per cent of total N as ammoniacal N (Mattila 2006, Olesen et al. 2009), and 40 per cent losses of ammoniacal N during manure handling (Schröder 2005), 46.2 kg ammoniacal N ha^{-1} can be applied annually to three one-hectare units, corresponding to the amounts of N in the herbage removed from one hectare each of one-, two-, and three-year-old leys. Only ammoniacal N is immediately crop-available, and of that, only around 40 per cent are taken up (Mattila 2006, Olesen et al. 2009). Thus, the total amounts of N calculated to be available can support two succeeding cereal crops, plus a cereal nurse crop with undersown ley, which should result in grain yields of between 3.4 to 4 t ha^{-1}. This calculation is based on the assumption that leys are not amended by using animal manure, which is possible, provided clover proportions of 30 to 50 per cent (Granstedt 1992, Nykänen 2008), or sufficient amounts of N mineralized from SOM (Table 10).

Table 10 Red clover-grass leys managed for forage: estimated preceding crop value, total nitrogen (N) supply to succeeding crops, and transformation of N into yield.

	Preceding crop value (kg N ha^{-1})[a]		
SNF[b]	86		
Total N content in the ley crop[c]	107.5		
	N supply to succeeding crops (kg N ha^{-1})		
Crop order	I	II	III
+ Preceding crop value[d]	21.5	10.75	-
+ Mineralization of SOM[e]	100	100	100
+ Animal manure[f]	18.5	18.5	18.5
= N available for subsequent crops	= 140	= 129.25	= 118.5
	Transformation of N into yield (t ha^{-1})		
Grain yield[g]	4	3.7	3.4

[a] Assuming that 50 per cent of the N contained in the crop is removed from the field with the harvest (Høgh-Jensen & Schjoerring 2001).
[b] Mean value of SNF measured in the northwest (three-year-old ley, forage).
[c] pNdfa making up 80 per cent of total N content (Carlsson & Huss-Danell 2003).
[d] 20 and 10 per cent of the N contained in ley biomass being available to the first and the second succeeding crop, respectively (Crews & Peoples 2005).
[e] Assuming mineral soil with 10 per cent humus content (mixed farm), and a mineralization rate of 1 per cent of total soil N during the growth period (Kummer & Dawson 2008).
[f] Corresponding to the N export in forage from one-, two-, and three-year-old leys; application of slurry containing 70 per cent of N as ammoniacal N (Mattila 2006); 40 per cent losses of ammoniacal N (Schröder 2005); crop uptake of 40 per cent of ammoniacal N (Mattila 2006).
[g] Assuming a crop need of 35 kg N per 1 t grain (Aufhammer 1998), 15 per cent moisture.

With regard to the N supply, organic farming in the coastal regions of Finland can be expected to achieve grain yields of between 3 to 4 t ha^{-1}. Circulation of herbage N through animal manure sustains higher grain yields than green manuring. On the other hand, this requires ruminant livestock, and a larger share of land devoted to ley and feed cereal production. Irrespective of utilization for forage or green manure, adequate N supply requires relatively high and stable ley yields, and clover contents in one- and two-year-old leys of at least 50 per cent and 30 per cent, respectively. Leys with low clover proportions do not supply a succeeding crop with N and should be terminated. This applies to soils with humus contents lower than 10 per cent. On those soils that have higher contents of SOM, the soil stock can be exploited. Proportions of clover are usually low in such soils because the mineralization of large amounts of N promotes grass growth and proliferation relatively more than it does for legumes. Yet, a certain proportion of clover is beneficial for soil structure, and improves the palatability of the herbage.

Certain soil-borne fungi are serious obstacles to frequent cropping of clovers and pulses. Root rot fungi (mainly *Fusarium* spp.) are not host-specific, and various legume crops should be regarded as one crop in the crop rotation (Lager 2002). Factors rendering legumes susceptible to root rot include lack of vigour, mechanical damage, poor drainage, and poor crop rotations (Rufelt 1986). On the other hand, clover rot (*Sclerotinia trifoliorum*) is a rather host-specific pathogen of clovers that spreads through poor crop rotations and susceptible varieties (Ylimäki 1969). In addition to these phytopathological challenges, there are other research questions worth further consideration. Suppose that the ley is terminated in the third year: What is the fate of the N fixed by the leys during the first and second production years? What is the fate of animal manure N not immediately available to plant growth? How do these N fractions impact on crop production on a longer time scale?

4.2 Weed occurrence in spring cereal crops

4.2.1 Weed communities in Finnish coastal regions

Analysis of weed abundance in the coastal regions revealed a clear difference in weed species composition of arable fields between the south and the northwest (Fig. 2). Total and mean numbers of species were higher in the south (33 and 15.6) than in the northwest (26 and 10), respectively. There was a larger number of dominating weed species in the south than in the northwest. In the south, eight species/taxa accounted for around 70 per cent of total weed density and seven species/taxa constituted around 70 per cent of total weed biomass. The equivalent 70 per cent values in the northwest region were obtained with only three species/taxa for weed density and two weed species/taxa for total weed biomass (**IV**). Weed occurrence was therefore studied separately for these two regions.

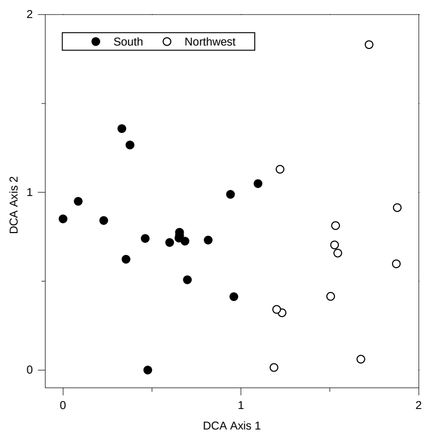

Figure 2 Detrended Correspondence Analysis (DCA) ordination plot for individual weed species densities. Each dot in the plot represents one field in the south and the northwest, respectively. Eigenvalues for axis 1 and 2 are 0.222 and 0.119, respectively.

Frequencies and abundances of weed species and weed taxa are given in Table 11 and **IV**. The most frequent species were generally the most abundant with respect to density and also to dry weight. The exception to this was *Viola arvensis*. *Brassica* spp. (in the south) and *Sonchus arvensis* (in the northwest) were more prominent with respect to dry weight than could be deduced from their frequencies and densities. *Chenopodium* spp., *E. repens*, *Erysimum cheiranthoides*, *Galeopsis* spp., *Spergula arvensis*, *Stellaria media* and *V. arvensis* occurred at high frequencies and abundances in both study regions. *Fumaria officinalis*, *Lamium* spp. and *Plantago major* were found only in the south, where they are favoured by a

Table 11 Frequencies and abundances of weed species and weed taxa in organically cropped spring cereal stands located in the southern and the north-western coastal regions.

	Both coastal regions			South			Northwest		
Weed species and taxa	**Frequency**	**Density (shoots m^{-2})**	**Dry weight (kg ha^{-1})**	**Frequency**	**Density (shoots m^{-2})**	**Dry weight (kg ha^{-1})**	**Frequency**	**Density (shoots m^{-2})**	**Dry weight (kg ha^{-1})**
Achillea millefolium L.	3	0.1	1	0	0	0	8.3	0.2	1.6
Achillea ptarmica L.	3	1.7	3	0	0	0	8.3	4.2	8.5
Anchusa arvensis (L.) MB	3	0.3	1	5.6	0.6	1.5	0	0	0
Brassica L. ssp.	20	3.4	37	27.8	5.6	61.6	8.3	0.1	0.2
Capsella bursa-pastoris (L.) MEDIK.	23	6.8	3	38.9	11.3	4.6	0	0	0
Centaurea cyanus L.	3	0.3	1	5.6	0.5	1.4	0	0	0
Chenopodium L. spp.	97	133.7	223	100.0	156.3	171.8	91.7	99.7	299.7
Cirsium arvense (L.) SCOP.	17	0.4	2	22.2	0.6	3.2	8.3	0.2	0.1
Elymus repens (L.) GOULD	83	118.5	414	77.8	56.1	101.6	91.7	212.1	882.2
Equisetum arvense L.	27	2.3	7	33.3	2.9	11.6	16.7	1.5	0.8
Erodium cicutarium (L.) L HÈR.	3	0.05	0.01	5.6	0.06	0.01	0	0	0
Erysimum cheiranthoides L.	73	21.1	16	72.2	23.5	13.1	75.0	17.4	20.5
Fallopia convolvulus (L.) Á. LÖVE	60	17.6	30	66.7	27.7	45.1	50.0	2.5	7.0
Fumaria officinalis L.	43	3.2	7	72.2	5.3	11.6	0	0	0
Galeopsis L. spp.	77	25.3	55	66.7	20.4	29.1	91.7	32.7	93.3
Galium L. spp.	57 [a]	7.8	17	66.7	10.0	23.7	41.7	4.4	6.4
Gnaphalium uliginosum L.	3	0.4	0.04	0	0	0	8.3	0.9	0.1
Lamium L. spp.	43	14.5	19	72.2	24.1	31.6	0	0	0
Lapsana communis L.	57	19.9	10	88.9	33.0	15.9	8.3	0.2	0.04
Leontodon autumnalis L.	3	0.7	1	0	0	0	8.3	1.8	2.1
Myosotis arvensis (L.) HILL	50	8.3	2	72.2	13.6	3.9	16.7	0.2	0.4
Papaver dubium L.	3	0.05	0.02	5.6	0.06	0.04	0	0	0
Persicaria L. spp.	63	11.6	16	44.4	6.2	5.4	91.7	19.7	32.9
Plantago major L.	7	0.6	0.1	11.1	0.9	0.1	0	0	0
Polygonum aviculare L.	57	3.1	3	72.2	4.5	4.05	33.3	0.9	1.3
Ranunculus repens L.	20	0.5	2	11.1	0.1	0.03	33.3	1.2	5.0
Rumex L. spp.	7	0.3	0.1	0	0	0	16.7	0.7	0.2
Sonchus arvensis L.	57	13.3	37	77.8	19.7	35.6	25.0	3.7	38.2
Spergula arvensis L.	67	59.6	52	61.1	19.7	5.7	75.0	119.5	122.1
Stachys palustris L.	3	0.1	2	5.6	0.2	3.6	0	0	0
Stellaria media (L.) VILL.	97	41.4	36	100.0	50.2	43.2	91.7	28.2	24.1
Taraxacum L. spp.	23	0.7	0.05	33.3	1.1	0.07	8.3	0.2	0.01
Thlaspi arvense L.	17	2.2	2	27.8	3.7	3.8	0	0	0
Tripleurospermum inodorum SCH. BIP.[a]	53	10.1	6	72.2	16.6	10.5	25.0	0.3	0.03
Tussilago farfara L.	3	0.4	2	5.6	0.6	2.6	0	0	0
Veronica L. spp.	3	0.05	0.2	5.6	0.06	0.4	0	0	0
Vicia L. spp.	30	4.2	14	44.4	6.8	22.9	8.3	0.2	0.3
Viola arvensis MURRAY[b]	77	32.7	9	88.9	43.2	10.4	58.3	16.9	6.9

[a] incl. *Matricaria matricarioides* (LESS.) PORTER and *M. recutita* L.
[b] incl. *Viola tricolor*

warmer climate and dry clay soils (Mukula et al. 1969, Salonen 1993a). *Lapsana communis*, *Myosotis arvensis*, *Polygonum aviculare*, *Tripleurospermum inodorum* and the legume species *Vicia* spp. thrive on dry mineral soils with high pH, and this is the probable cause for their higher frequencies and abundancies in the south (Ellenberg et al. 1991, Erviö et al. 1994). *Galium* spp. occurred more frequently in the south, where it is known to thrive (Salonen 1993a), but was also abundant in the northwest. The higher occurrences of *E. repens*, *Galeopsis* spp., *Persicaria* spp. and *Spergula arvensis* in the northwest are related to the moist coarse mineral and organic soils, and to the relatively low pH levels typical of this region (Salonen 1993a, Erviö et al. 1994) (**IV**).

Galeopsis spp., *Persicaria* spp. and *Spergula arvensis* are summer annuals, and therefore occurred more commonly in the northwest, where spring-sown cereal crops dominate, whereas *Anchusa arvensis*, *Centaurea cyanus*, *Erodium cicutarium*, *M. arvensis* and *Papaver dubium* are favoured by the cultivation of autumn-sown annual crops, which are more common in the south (**IV**). *Brassica* spp. was more common in the south, probably because of a higher frequency of oilseed rape cropped in this region (**IV**; Information Centre of the Ministry of Agriculture and Forestry 2003). *Brassica* spp. are disseminated as volunteer crops, also through poorly cleaned seed, and through seeds contained in feed cereals that are transferred to manure fertilizer.

The frequency of *C. arvense* was higher in the south but the differences in its abundances between south and northwest were not statistically significant (**IV**). *Sonchus arvensis* occurred at higher density in the south, whereas its biomass weight was higher in the northwest (**IV**; Mukula et al. 1969, Salonen et al. 2001b). *C. arvense* has a deep reaching root system and therefore competes successfully with agricultural crops, especially in dry clay soils, whereas *Sonchus arvensis* with its rather shallow root system thrives in the coarse mineral and moist soils typical of the northwest (Mukula et al. 1969, Salonen 1993a). Both species are favoured by rotations involving high proportions of annual crops (Donald 1990).

E. repens previously was more common in the south (Mukula et al. 1969, Mela 1988), but now it is more frequent and abundant in the northwest, at least under organic farming practices (**IV**; Erviö & Salonen 1987, Salonen et al. 2001a and b). The moist silt and humus-rich mineral soils characteristic of central and western Finland benefit the growth and the spread of *E. repens* (Mukula et al. 1969, Salonen et al. 2001b). Increasing proportions of perennial ley required by intensified cattle husbandry and concomitant decrease in tillage intensity incite the spreading of *E. repens*. This is the case in the northern part of the north-western coastal region. In contrast, increased proportion of arable land devoted to annual crops resulted in more intensive soil tillage in the south, and a concomitant decline of *E. repens* (Håkansson 2003).

4.2.2 Weed occurrence and grain yield

Mean weed densities did not differ between the north-western (570 plants m^{-2}) and the southern regions (565 plants m^{-2}) whereas average weed biomass production was markedly higher in the northwest (1594 kg dry weight ha^{-1}) than in the south (697 kg dry weight ha^{-1}). Weed abundance differed remarkably between single spring cereal crops. In one third of the crop stands, weed densities were below 300 plants m^{-2}, whereas in another third it exceeded 600 plants m^{-2}. The distribution of the fields was about the same in both regions with regard to weed density, but differed largely with regard to biomass weight. In the south, weed dry weights exceeded 1000 kg ha^{-1} in one third of the fields surveyed, whereas in the northwest, this was the case in two thirds of the fields. The mean proportion of weed biomass in relation to total weed and crop biomass was 11.4 vs. 20.6 per cent in the south and the northwest, respectively. The high weed dry weight in the northwest was largely due to the occurrence of *E. repens*; the mean of this weed species was 10.8 per cent of the total crop and weed dry weight in the northwest (**IV**).

Compared to the clay soils dominating in the south, the high weed biomass production in the northwest is generally favoured by its predominant humus-rich mineral and organic soils (Salonen 1993a). In addition to the supply of N from the soil stock, humus-rich mineral and organic soils have a high water holding capacity (Andreasen et al. 1991). In contrast to the findings of this study, Mukula et al. (1969) recorded higher weed biomass production in the south, and explained this with a longer growing period and a higher temperature sum. In the 1960s, mixed farming was still common in southern Finland. However, since the 1970s, mixed farming in the south was replaced by pure crop husbandry, consisting mainly of monotonous spring cereal cropping, whereas animal husbandry in the northwest was intensified. High livestock densities based on the importation of cereal and concentrate feed from southern Finland and from abroad, which gave rise to positive nutrient balances, are another probable reason for the increase of weed biomass in the northwest (Salonen 1993a, Salo et al. 2007).

When grain yield was assessed as 50 per cent of total above-ground crop biomass, mean yields (85 per cent DM) amounted to 3.4 and 3.7 t ha^{-1} in the south and in the northwest, respectively (**IV**). These yield levels correspond to the yields feasible with respect to the values of SNF for perennial red clover-grass leys recorded on the same farms (4.1.5 and Tables 9 and 10). One weight-unit of weed biomass corresponds to a yield loss of one weight-unit of crop biomass (Lazauskas 1994). Assuming that grain biomass makes up half of the above-ground biomass of a cereal crop, one t ha^{-1} of weed biomass at harvest causes a grain yield loss of 0.5 t ha^{-1}. According to the measurements of weed biomass weights (95% DM) mentioned above, the mean yield loss caused by weed infestation in the south and the northwest amounted to about 0.4 and 0.9 t grain (85% DM) ha^{-1}, respectively. This additional yield potential may be sustained by a higher mineralization rate of the SOM than that calculated above (4.1.5), and/or by imports of N to the farm in the form of concentrate feed, feed cereals, forage and/or organic manures.

Together with the central part of southern Finland, the coastal regions belong to the locations most favourable for grain cropping in Finland. In 2002, yields of conventionally managed spring cereal crops in the south and in the northwest averaged 3.2 and 3.6 t ha^{-1}, respectively (Information Centre of the Ministry of Agriculture and Forestry 2003). Thus, the average grain yields recorded in organically managed spring cereal stands exceeded those of conventional farming. On the other hand, in a recent trial carried out under identical environmental conditions in the southern coastal region, organic spring cereal crops reached only 65 to 85 per cent of the yield level obtained with more or less intensive conventional crop management methods (Heinonen 2009). The choice of full-time farmers with an interest in organic farming in this study protocol determines that the yield levels reported here cannot be related to those obtained from a population comprising all full-time and part-time conventional farmers in the respective regions. Yet, the yield levels reported here point out a yield level achievable under practical organic farming conditions (3.1). In any case, the intensity of long- and short-time cereal crop management differed considerably between the farms participating in this study (**IV**, **V**).

Between 30 to 40 per cent of a hecterage has to be grown with legumes in order to supply an organic cropping system with N fixed from the air. Under Nordic conditions, perennial legumes have a higher capacity for SNF than annual legumes (Granstedt 1992). In Finland, around 30 per cent of the conventionally managed arable land is cropped with perennial forage leys, but the differences are large between single regions and between farms (Information Centre of the Ministry of Agriculture and Forestry 2008a). On most of the arable organic farms participating in this study, N was also supplied by the importation of animal manures from conventional farms, namely, by an appropriated indirect support area ('shadow hecterage'). In order to introduce organic farming in a larger scale, and to primarily make use of ley cropping by harvesting the herbage for forage, mixed farming ought to be re-introduced over the whole country.

4.2.3 Development of weed occurrence over time

In the south, weed density was significantly related to the duration of organic farming, and there was a tendency for the weed dry weight to be related to the duration of organic farming. In the northwest, no such relationships were detected (**IV**). In both coastal regions the mean weed densities in organically cropped spring cereal fields were at a similar level as that reported for conventional crops in the first national survey conducted in the 1960s, and also for the surveys on organic farming which were carried out in the 1980s and 1990s. Compared with the mean values for present conventional farming in Finland, weed density in organically farmed spring cereal crops in the coastal regions was more than twice as high in this study (Table 12).

Mean weed biomass weight resembled that recorded in the 1960s, and was markedly higher than in previous surveys of organically managed spring cereal stands, and more than twice as high as that of conventionally farmed cereal crops at the present (Table 12). Although soil tillage had

Table 12 Average weed abundances found in surveys of spring cereal stands in Finland over 1962-2002.

	Present survey[a]	**Salonen et al. (2001a)**[b]	**Mela (1988)**[b]	**Mukula et al. (1969)**[c] **and Mukula (1974)**[c]	**Erviö & Salonen (1987)**[b]	**Salonen et al. (2001b)**[b]
Years of investigation	<= <= <= <= <= 2002	<= <= <= <= <= 1997-1999	<= <= <= <= <= 1984-1986	1962-1965	=> => => => => => 1982-1984	=> => => => => => => 1997-1999
Socioeconomic structure		Industrial[d]		Commercial[e]	Industrial[d]	
Farming concept		Organic, no herbicides		Conventional, no herbicides	Conventional, herbicides	
Weed density (plants m^{-2})	567	469	505	550	173	220
Weed biomass (kg dry weight ha^{-1})	1056	678	575	1000	320	351
Proportion of weed in relation to crop biomass (%)	16.0	17.1	12.0	16.3	Not assessed	3.0[f]

[a] Southern and north-western coastal regions of Finland.
[b] Southern and central Finland.
[c] Southern and central Finland, including the eastern and western parts of the country.
[d] Specialization on either crop or animal husbandry; high inputs of fuels, fertilizers and purchased feeds.
[e] Mixed crop and animal husbandry; low inputs of fuels, fertilizers and purchased feeds.
[f] In crop stands not treated with herbicides, the proportion of weed in relation to crop biomass was 12.6 per cent.

been intensified, weed abundance in organically cropped spring cereals in the coastal regions of Finland was on a level comparable to that of conventional farming in the 1960s. In the south, the average proportion of weed dry weight in relation to total weed and crop dry weight was 11.4 per cent, and in the northwest it constituted 20.6 per cent (**IV**). If a level of weed biomass of 5 per cent of total above-ground biomass is regarded as tolerable (Salonen 1993b), then the level of weed biomass found here in organically cropped cereal stands appeared to be a yield-limiting factor.

When related to the abundance of single weed species, the number of years since the conversion to organic farming appeared to be one of the few statistically significant explanatory variables. Species occurring in high densities in fields with a long history of organic cropping included *E. repens*, *Capsella bursa-pastoris*, *T. inodorum*, *Thlaspi arvense*, *Chenopodium* spp., *C. arvense*, *V. arvensis*, *P. aviculare* and *M. arvensis* (in descending order). Moreover, *E. repens* was the weed species whose biomass increased most as a result of long-term organic farming. It was followed by *C. bursa-pastoris, E. cheiranthoides, T. arvense, P. aviculare, T. inodorum, C. arvense* and *Galeopsis* spp. (**V**).

The annual weed species that dominated in organically cropped fields were largely the same as those reported to be most common in contemporary conventional farming (Erviö & Salonen 1987, Salonen et al. 2001b). Conversion from conventional to organic crop production primarily seemed to increase the frequencies and abundances of these dominating weed species to and, in some cases, even above the levels recorded in the 1960s by Mukula et al. (1969). In both coastal regions, *Chenopodium* spp. reached higher densities and dry weights than in previous surveys of conventional and organic farming in Finland. In the south, the abundances of *Brassica* spp., *Fallopia convolvulus, Galium* spp. and *Lamium* spp. were much higher compared with the meaned data reported from previous national surveys (**IV**). In this present study, there were considerable changes in the frequencies and abundances of perennial weed species compared with previous national surveys. In the northwest, *E. repens* exceeded previously recorded average levels of occurrence (**IV**; Mukula 1974, Mela 1988, Salonen et al. 2001a and b). On the other hand, the frequencies of perennial ruderal and grassland weed species, such as *Achillea millefolium*, *Achillea ptarmica*, *Equisetum arvense*, *E. cicutarium*, *Leontodon autumnalis*, *P. major*, *Ranunculus repens*, *Rumex* spp. and *Tussilago farfara*, in both coastal regions were markedly lower than previously recorded (**IV**; Mukula et al. 1974, Mela 1988).

The annual and perennial weed species that became increasingly abundant under organic farming conditions were either nitrophilous or, owing to their tall or climbing growth habit, competitive in tall and dense crop stands (Mahn 1988, Ellenberg et al. 1991, Jørnsgård et al. 1996, Blackshaw et al. 2003). In this study, multivariate analysis showed that the abundances of the nitrophilous weed species *Chenopodium* spp., *C. arvense*, *E. repens*, *E. cheiranthoides* and *Galeopsis* spp. (Ellenberg et al. 1991) were positively related to the number of years since the conversion to organic farming (**V**). The frequency and abundance of nitrophilous weed species in organically cropped spring cereal fields suggest high soil N levels and contradicts the prediction by Rydberg & Milberg (2000) that conversion to organic farming practices would lead to an increase especially of non-nitrophilous weed species. High N supply in organically cropped fields may be due to high levels of SOM, to application of animal manure, and/or to high levels of SNF (**III**). High soil N levels offer a potential for high crop yields provided that weed occurrence is kept under control.

Non-nitrophilous weed species also became more abundant with the duration of organic farming. However, there was no consistent pattern between the duration of organic farming and increased abundance of non-nitrophilous weeds compared to nitrophilous weed species (**V**). A probable cause for this is the ban on herbicides, which is a consequence of conversion to organic farming. Out of all agricultural management practices, the application of herbicides has been found to exert the largest influence on weed species diversity and abundance (Bàrberi et al. 1997, Doucet et al. 1999). As a consequence of the conversion to organic farming, the selective pressure of herbicides was removed and weed species especially sensitive to the previously used herbicides were allowed to spread (Hald 1999a, Hyvönen et al. 2003a). The omission of herbicides is the cause for the increased occurrence of any non-nitrophilous or nitrophilous weed species sensitive to herbicides.

Compared with the south, leys in the northwest took up a larger share of the arable land, were more often grown for forage than for green manure, and usually terminated after three production years had elapsed (**II**). These may be the main causes for the higher occurrence of perennial ruderal and grassland weeds in the northwest (Raatikainen et al. 1985, Mela 1988). However, in both regions, land amelioration by sub-surface drainage and liming, reduced area under pasture, and intensified soil tillage detered the spreading of ruderal and perennial grassland weeds under organic or conventional farming management (Erviö & Salonen 1987, Rydberg & Milberg 2000). In contrast, the arable perennial weeds *C. arvense*, *E. repens* and *Sonchus arvensis* are well adapted to soil cultivation (Håkansson 2003).

Levels of weed infestation may be fairly low during the first years after conversion, given that weed control has previously been carried out as a routine during the years of conventional farming. Low weed infestation during the first years after conversion may lead to the neglect of precautionary measures. Thus, farmers may aim at maximizing the share of cash crops instead of applying crop rotations beneficial for soil fertility and weed control. In such a case, levels of weed infestation will increase with the duration of organic cropping (Rantzau et al. 1990, Freyer 1991). In Finland, Salonen et al. (2001a) warned that the perennial weed species *E. repens*, *Sonchus arvensis*, and *C. arvense* may threaten the future of organic cereal production, if their control is not given due attention. In a survey of weeds on organic farms in Sweden carried out by Rydberg & Milberg (2000) neither *E. repens* nor *C. arvense* were particularly frequent, which suggests that appropriate soil cultivation technology can lower the occurrence of perennial weed species. Large differences in weed abundance between single fields highlight the crucial role of individual farm management practices, such as preventive husbandry practices and mechanical weed control measures (Bond & Grundy 2001).

4.2.4 Competitive weed species

Weed communities in the south and the northwest differed from each other (**IV**), and successful weed control therefore relies on the identification of the most competitive weed species and the choice of appropriate management strategies. Therefore, the competitiveness of single weed species under the conditions of organic farming in Finnish coastal regions was assessed. The competitiveness of a single weed species was defined by its mean dry weight and its respective percentage of the total above-ground phytomass. The mean biomass of a weed species in a certain crop indicates its potential competitiveness in relation to its associated crop, whereas its mean percentage of total phytomass expresses its actual abundance in that crop (Table 13).

Table 13 Plant weight and competitiveness of weed species in organically cropped spring cereal fields, assessed at cereal crop DC 70-79 (Zadoks et al. 1974)[a].

Weed species, respectively taxa	Mean plant dry weight (g)	Percentage of total above-ground phytomass (%)[b]
Brassica ssp.	1.10	2.18
Cirsium arvense	0.50	0.30
Capsella bursa-pastoris	0.04	0.19
Chenopodium spp.	0.17	2.86
Elymus repens	0.35	6.46
Equisetum arvense	0.31	0.42
Erysimum cheiranthoides	0.08	0.30
Fallopia convolvulus	0.16	0.65
Fumaria officinalis	0.22	0.35
Galeopsis spp.	0.22	1.14
Galium spp.	0.22	0.34
Lamium spp.	0.13	0.73
Lapsana communis	0.05	0.50
Myosotis arvensis	0.03	0.07
Persicaria spp.	0.14	0.34
Polygonum aviculare	0.10	0.08
Ranunculus repens	0.38	0.15
Sonchus arvensis	0.27	1.15
Spergula arvensis	0.09	1.61
Stellaria media	0.09	0.63
Taraxacum spp.	0.01	0.01
Thlaspi arvense	0.10	0.24
Tripleurospermum inodorum	0.06	0.19
Vicia spp.	0.33	0.98
Viola arvensis	0.03	0.16

[a] Mean crop shoot height 0.62 m (SD ± 0.13 m).
[b] Calculated for infested crops.

Brassica spp., *E. repens*, *Galeopsis* spp., *Sonchus arvensis* and *Vicia* spp. had high mean dry weights and at the same time made up for a high proportion of total above-ground phytomass, whereas *F. officinalis* and *Galium* spp. had high average dry weights whereas their proportion of total weed and crop biomass was lower than that indicated by dry weight.

Many perennial species including: *C. arvense* and *Sonchus arvensis*, occur in patches and have a higher competitiveness than indicated by their proportion of total weed and crop biomass. *Chenopodium* spp., *F. convolvulus*, *Lamium* spp., *Spergula arvensis*, and *S. media* had low mean dry weights, but occurred at high density and took up significant proportions of weed and crop biomass. Under the conditions of the surveyed spring cereal fields, the above species appeared to be the most noxious weeds. With the exception of *Spergula arvensis* and *S. media*, these weed species are also competitive in tall and dense crops (Ellenberg et al. 1991). Multivariate analysis showed that *Brassica* ssp., *Chenopodium* spp., *F. convolvulus*, *Galium* spp., and *V. arvensis* were positively related to crop dry weight. The biomass of *Galium* spp. also was clearly associated with wheat (**V**). In contrast, the abundance of the other weed species was inversely related to crop above-ground biomass, and to the crop genus wheat.

Weed species dry weights were largely the same as those reported by Salonen et al. (2001a) from a survey of organically cropped spring cereals, with two exceptions: The mean weight of *C. arvense* was only one fifth of that recorded by Salonen et al. (2001a), which indicated the ample occurrence of seedlings and relatively sparse patches of shoots emerging from perennial root systems. *Polygonum* species, such as *F. convolvulus*, *Persicaria* spp. and *P. aviculare* had much lower mean individual biomass weights than those reported by Salonen et al. (2001a). This finding may have been caused by the less ample occurrence of humus-rich mineral and organic soils investigated in this study compared with those found in the localities surveyed by Salonen et al. (2001a). The average biomasses of many weed species, such as *Chenopodium* spp., *E. repens*, *F. convolvulus*, *L. communis*, *Persicaria* spp., *P. aviculare*, *Sonchus arvensis*, and *Vicia* spp. were much lower than their respective weights recorded in the 1960s (Mukula et al. 1969), and thus indicative of more competitive crop stands. The higher competitiveness of crop stands in the present study may be a function of more intensive soil tillage, more exact seedbed preparation, better sowing technique, and more competitive crop varieties (Håkansson 2003).

4.2.5 Weed management

The number of years since conversion to organic farming appeared to be one of the few statistically significant variables that explained weed species abundance. This explanatory variable eclipsed the possible impact of agricultural management methods submitted to the same statistical analysis. This is because the duration of organic farming encapsulated agricultural measures related to preventive long-term management, such as ley cropping, fallowing, and stubble cultivation. Moreover, single short-term management decision variables such as whether or not manure was used, the way in which manure was applied, the choice of crop species, and whether or not weed harrowing was carried out, did not have any significant correlations with the abundance of single weed species. Obviously, the impact of these short-term management variables was concealed by the variable crop dry weights obtained, i.e., the competitiveness of the crop resulting from single management activities (**V**). Different weed species were related to the duration of organic farming and to low crop yield (**V**). This finding suggests that it was not the organic farming regime *per se* which resulted in high weed infestation and low yielding crops, but failures in the understanding and management of the organic cropping system.

Conversion to organic farming brings with it changes in long-term management, including the implementation of certain crop rotations and associated practices such as tillage, fertilization and weed management (Lampkin 1992). Rotations including spring-sown and autumn-sown annual crops in addition to perennial crops prevent the selection of specialized weed communities and counteract increases in weed abundance (Hald 1999b, Leeson et al. 2000). Diverse crop rotations also provide plentiful options for preventive and direct weed control measures. For example, *E. repens* declines under annual soil tillage, whereas perennial ley is efficient against weed seedlings and, supposed early cutting, against *C. arvense* and *Sonchus* spp. (Dock Gustavsson 1997, Håkansson 2003). Crop rotation in combination with regular ploughing and stubble cultivation can be sufficient in preventing the dominance of weeds (Lundkvist et al. 2008).

Stubble cultivation accomplished twice in the autumn in combination with late ploughing is an efficient measure against a number of weed species found to be abundant in the coastal regions, namely volunteer crops (such as *Brassica* spp.; Pekrun & Lutman 1998), weed species germinating in the autumn (such as *Galium* spp., *Lamium* spp., *S. media*, and *Vicia* spp.; Håkansson 2003), and *E. repens* (Boström & Fogelfors 1999). If implemented in early autumn, stubble cultivation is also effective against *C. arvense* and *Sonchus arvensis* (Boström & Fogelfors 1999). Stubble cultivation is feasible in regions with long autumns, especially on dry clay soils. The cropping of late-ripening varieties shortens the period available for stubble cultivation. Due to its shorter growing period and higher soil moisture, opportunities for stubble cultivation are generally more limited in the northwest than in the south (Kurki 1982, Mukula & Rantanen 1987).

In some fields located in the northwest, the abundance of *E. repens* was so high that fallowing may be the only way to regain control, particularly for humus-rich and organic soils (Bylterud 1965). Fallowing also provides opportunities for soil amelioration, for spreading of manure, for cropping of green forage and green manure, and for the establishment of overwintering crops. Black fallow during the whole growing season is effective against weeds, but should be avoided because of the damage inflicted on soil structure and because of excessive nutrient losses. Instead, it is more reasonable to include a spring and early-summer bare fallow into the regular crop rotation, and to extend this to a whole-season fallow when necessary. Some kind of catch crop ought to be sown to utilize the nutrients mobilized during fallowing, and to prevent losses. Provided dense stands, such crops also compete well with weeds. Cutting and the termination of forage and green manure crops ought to be scheduled so that weeds are destroyed before shedding their seeds (Kahnt 1983). The first crop rotation cycles should include spring bare fallow as a preventive measure to minimize risks during conversion to organic farming.

By short-term preventive weed management and physical weed control, farmers can manage the competition between crop and weeds in favour of the former. The inverse relationship between wheat and weed abundance (**V**) contradicts previous investigations, where wheat was found to have low competitiveness against weeds (Mukula et al. 1969, Erviö & Salonen 1987). However, wheat is a profitable cash crop and is therefore given a favourable position within the crop rotation in many cases. In the fields investigated, in most cases wheat was grown in sequence after nourishing preceding crops or fallow (**V**). Significantly higher crop densities in the south (**IV**) may have contributed to higher crop competitiveness and lower weed abundance. When it is dense enough, the kind of crop species is not decisive with regard to competitiveness against weeds (Erviö 1972, Erviö 1983).

Even the biomass of *E. repens* was inversely related to crop biomass (**V**), although this weed species is known to tolerate a dense crop canopy (Pyšek & Lepš 1991). On the other hand, *Brassica* ssp., *Chenopodium* spp., *F. convolvulus* and *Galium* spp. were highly competitive against wheat (**V**). This may be explained by a higher efficiency in the utilization of soil N in terms of shoot biomass increment (Blackshaw et al. 2003). Due to its climbing growth habit, *Galium* spp. is able to compete with dense cereal stands (Haas & Streibig 1982). Another species that was able to maintain its abundance in conditions of increasing crop dry weight was *V. arvensis* (**V**), which resembles both *Chenopodium* spp. and *F. convolvulus* in that it is shade tolerant (Haas & Streibig 1982).

The seedlings and early rosette stages of annual and perennial weed species that were found to be abundant in the coastal regions can be successfully controlled by weed harrowing. However, *Galeopsis* spp. and *Galium* spp. tolerate weed harrowing more than do other weed species (**IV**; Habel 1954, Koch 1959, Kees 1962). Mechanical weed control should be carried out regularly rather than as a treatment obliged by acute weed infestation, particularly when the proportion of annual arable crops significantly exceeds that of perennial leys (Rasmussen & Ascard 1995, Bàrberi 2002). However, post-harvest stubble cultivation had been carried out on only six fields, and weed harrowing on only five out of the 30 fields that were included in this investigation (**V**). Thus, a rather large number of organic farms did not carry out thoroughly integrated weed management strategies and consistent weed control measures (Salonen et al. 2001a). This is in contrast to the pioneer stage of organic farming in Finland, when preventive, cultural and physical measures against weed infestation were frequently applied (Mela 1988).

5 CONCLUSIONS

Previous studies reveal that, in northern conditions at least, the agronomic productivity of organic farming is restricted mainly by N deficiency and weed occurrence. In order to document the impact of these limitations on the productivity of organic farming and to propose options for the alleviation of these restrictions, I explored the following: (i) the herbage production and persistence of perennial red clover-grass leys, (ii) N supply through symbiotic fixation in perennial mixed leys, and (iii) weed occurrence in spring cereal crops. This study is based on investigations of fields subjected to regular agricultural practices. I present results on the agronomic productivity of organic crop husbandry practices in the coastal regions of Finland, point out limiting factors and suggest a number of measures to alleviate these restrictions.

Herbage production and persistence of perennial red clover-grass leys

(i) Mean clover contents in one- and two-year-old leys exceeding 50 and 30 per cent, respectively, supported herbage yields in organically managed red clover-grass leys corresponding to those levels reported for conventional farming (**II**).

(ii) Herbage yields did not differ between the south and the northwest, whereas percentages of clover in leys in the south were considerably higher than in the northwest (**II**).

(iii) A decline of herbage yield with ley age was associated with the decline of clover content in a clover-grass ley, which was caused by poor overwintering and persistence. Agricultural management ought to focus on the choice of winter-hardy varieties, the careful establishment of a mixed ley and an appropriate harvest regime (**I**, **II**).

(iv) Red clover growth, in particular, was highly variable between fields and within fields, indicating an unrealized potential for higher productivity achievable through site-specific soil amelioration measures (**II**).

(v) More than any other soil property, soil structure appeared to be a key determinant for ley growth and SNF, demonstrating that soil compaction may be a major factor restricting the productivity of organic crop production (**II**, **III**).

Nitrogen supply through symbiotic fixation

(i) The mean estimated SNF of red clover-grass leys was high enough to satisfy the N requirements of succeeding cereal crops yielding 3.5 to 4.0 t grain ha^{-1}. However, this requires that legumes are grown on 30 to 40 per cent of the arable hecterage (**III**, **synopsis**).

(ii) In a cropping system that depends on green manuring for its N supply, red clover grass leys should be terminated as long as clover contents remain high. This usually entails termination after the first or second production year. With respect to SNF, leys grown for the harvest of red clover-seed appeared to be an interesting alternative to green manure leys (**synopsis**).

(iii) On ruminant livestock farms where N is circulated both through harvest residues and in a forage-feed-manure chain, three-year-old leys appeared to be justified also from the point of N economy (**I**, **synopsis**).

(iv) The high variability of SNF between and within regions requires individual assessment of the preceding crop value of single ley crops (**III**).

(v) If the same spatial pattern of within-field variability recurs year after year, soil fertility will gradually deteriorate in specific patches and within-field variability of yields will increase (**III**).

Weed occurrence in spring cereal crops

(i) Increasing abundances of *E. repens*, *C. arvense*, and of certain noxious annual weed species represent a challenge to organic farmers to pay more attention to the integration of preventive and direct weed control measures (**IV**, **V**, **synopsis**).

(ii) Duration of organic farming and low crop dry weight were related to different weed species, illustrating that it was not the organic farming regime *per se* which resulted in high weed infestation and low-yielding crops, but failures in the understanding and management of the organic cropping system (**IV**).

(iii) The abundance of nitrophilous weed species indicated sufficient supplies of N, confirming that the preceding crop value of the red clover-grass leys grown on the farms was sufficient to sustain plant production at a relatively high level (**V**).

(iv) The abundance of individual weed species was positively related to the duration of organic farming, and negatively to crop biomass weight, thus emphasizing the importance of long- and short-term weed control management (**V**).

(v) Owing to the occurrence of different weed communities and differences in the levels of weed infestation, farmers ought to rely on concise region-, farm-, and site-specific control strategies, not at least under organic farming conditions (**IV**).

General agricultural management

(i) The agronomic productivity of ley and spring cereal crops managed by full-time famers with an interest in organic farming was on the same level as that of average conventional farming. Given the many options for further improvements of the agronomic performance of organic crop husbandry, organic farming offers a good foundation for the development of sustainable agriculture (**II**, **IV**).

(ii) Crop performance and weed infestation varied markedly between individual farms, reflecting different impacts of biophysical resources, business planning, equipment and agronomic capability. Extension, education and management planning may contribute to higher agronomic productivity of organic farming (**I**, **II**, **IV**, **V**).

(iii) Soil structure appeared to be a main explanatory variable for crop growth. Soil structure is enhanced by perennial crops and animal manure. The application of animal manure also implies a re-distribution of OM and nutrients removed by harvest, constituting an excellent management measure for decreasing between- and within-field variability of soil properties. Moreover, the application of animal manure allows for a higher share of cereals in the crop rotation, breaking legume disease cycles. Consequently, the main threat to the sustainability of conventional and organic farming in Finland is the spatial separation of animal husbandry and crop production (**II**, **III**).

Further research

(i) The winter-hardiness especially of the red clover component appeared to be poor, indicating that the development of more persistent red clover varieties is an important task for plant breeding (**I**, **II**).

(ii) The proportion of red clover to grasses in mixed leys was highly variable, highlighting the question as to whether the proportion between red clover and different grass species can be influenced through differentiating impacts of nutrient applications (**II**).

(iii) Within-field variations of crop growth appeared to be mainly caused by spatial variations of soil properties. Relationships between crop growth and soil properties therefore need to be studied using spatial and temporal perspectives (**II**).

(iv) In order to assess the N supply by SNF to succeeding non-legume crops accurately, more research is needed on the fate of fixed N accumulated in SOM (**III**).

(v) The increase in the occurrence of certain weed species with the duration of organic farming underlines the necessity to evaluate the preventive weed-control effects of certain crop rotations in combination with certain tillage measures (**V**).

The degradation of agroecosystems and surrounding ecosystems poses questions for the sustainability of the conventional agricultural paradigm. A review of literature showed that organic farming improves the sustainability of food production in many respects, including the management of resources for agricultural production, care for the biotic and abiotic environment, and consideration of social and health effects. However, human population growth sets specific challenges for organic crop husbandry to increase its agronomic productivity.

On the farm level, successful crop husbandry generally relies on the expertise and the commitment of farmers. Conventional farming can rely on curative interventions, such as the application of fertilizers in a form immediately available to plants, and also the use of powerful pesticides. In contrast, the agronomic productivity of organic farming requires long-term integration of different management measures that aim at enhanced soil fertility and preventive crop protection. Thus, organic crop husbandry relies on a design that specifically fits agronomic management into the context of individual farms and fields.

Environmental conditions for agricultural production differ on national, regional, and often even on local scales. Certain climate and soil conditions may predispose to deficiencies of certain nutrients and/or occurrence of certain pests. This needs to be reflected by spatial and temporal adaptations of organic farming regulations. In some cases the productivity of organic crop husbandry seems to be restricted by principles that may be hard to justify on a scientific basis. For example, the ban on easily soluble P fertilizers renders organic farming in Finland dependent on apatite, involving transport and spreading, and thus consumption of P in a form hardly available to plants.

In a wider perspective, sustainable agriculture cannot be exercised in isolation, but presupposes interaction with a sustainable society. This includes practical issues, such as the cycling of OM and plant nutrients, and utilization of energy from agricultural sources. Barriers to the adoption of sustainable agriculture may derive not only from biophysical limitations but also from social influences and economic determinants. Thus, research and education play a crucial role in the development of sustainable agriculture.

Sustainable food supply presupposes structural and behavioural changes throughout the whole food chain. Food supply aligned to regional production and seasonal conditions has a substantial potential to reduce transportation distances, and thus to reduce resource consumption and environmental degradation. Regionalization of food production improves the food security, food sovereignty and resilience of societies. Another important step to improve efficiencies in the use of land, water, nutrients and energy, and to reduce negative environmental impacts, is to reduce the intake of animal-based foods by moderate changes towards a more vegetarian diet based on appropriate staple-crops.

At the heart of sustainable development are insight, responsibility, and changes in personal lifestyle. Science is morally committed to contribute to sustainable development.

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