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LEGUME LIVING MULCHES FOR THE CONTROL OF WEEDS IN ORGANIC WINTER WHEAT (*TRITICUM AESTIVUM* L.)

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"Our biggest challenge in this new century is to take an idea that seems abstract – sustainable development – and turn it, too, into a daily reality for all the world's people."

(Kofi Annan, UN Secretary-General, March 2001)

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SUMMARY

Conservation tillage, as compared to more intensive soil cultivation, is a possibility to reduce soil erosion - especially in regions with high precipitation and sloped areas - and nitrate leaching. However, it usually relies on the use of herbicides to control weeds. In contrast, the use of herbicides is forbidden in organic farming and weed control relies on non-chemical means, of which mechanical means are the most important ones. As a result, organic farming precludes contamination of surface and ground water by such chemicals but the risk of soil erosion remains an issue of concern. Therefore, conservation tillage and especially direct drilling, its most extreme form, seem to be incompatible with organic farming at first glance. However, the ecological and economical advantages of direct drilling are desirable in organic farming as well. Thus, analysing the feasibility of alternative approaches for the control of weeds for direct drilling in organic farming is necessary. Direct drilling into a living mulch (a cover crop growing during a considerable period of time of the life cycle of the main crop with the goal of reducing soil erosion and weed establishment as well as preserving plant nutrients) would be such an alternative; provided that the cash and the cover crops used in this system can be managed as to allow for adequate yields, since competition between the plant species can be expected to be strong.

The aim of this study was to investigate different legume cover crops as living mulches for winter wheat grown according to the rules of organic farming. The objectives were to test the weed suppressing ability of the cover crops and their impact on crop development and yield components of the directly drilled main crop, as well as to identify best management practices for this mixed cropping system.

Winter wheat (*Triticum aestivum* L.) was drilled into seven different living legume mulches (*Lotus corniculatus* L., *Medicago lupulina* L., *Medicago rigidula* (L.) All., *Medicago truncatula* Gaertner, *Trifolium repens* L. (cv. Barbian, cv. Milo), *Trifolium subterraneum* L.) at two sites in the Swiss midlands. Control plots without legume cover crops were also established and were either weeded by hand at regular intervals (NOWEED) or left undisturbed and thus allowing a natural (NAT) site-specific weed community to establish. Within the soil cover treatments sub-plots with different management practices were established and representative combinations of them were used to test the hypotheses.

T. repens, *T. subterraneum*, and *L. corniculatus* successfully controlled dicotyledonous, spring germinating and annual weeds (e.g. *Poa annua* L. and *Matricaria chamomilla* L. at one site and *P. annua*, *Capsella bursa-pastoris* (L.) Med. and *Stellaria media* (L.) Vill. at the other) compared to NAT. *T. repens* provided the best weed suppression but also competed strongly with the main crop, thereby considerably reducing its yield. Complete weed suppression was not observed for any of the cover crops. *M. truncatula* died during the winter and as a result the weed development was similar compared to NAT. Although wheat grown in *M. truncatula* gave the highest yield among the tested living mulches, main crop biomass and grain yield was reduced by all legumes by more than 50 % compared to NOWEED which yielded 3475 and 5015 kg ha^{-1} at each of the sites.

The impact of the different cropping systems on the total N uptake was not consistent: the N yield in the above-ground biomass in the living mulch was higher at one site and lower at the other when compared to NOWEED at the time of wheat maturity. However, the N concentration in the grains and in straw was higher in wheat grown in the living mulch (tested for *T. repens*) (2.7 and 0.5 %) compared to NOWEED (2.2 and 0.3 %) suggesting that N was not the most limiting factor for the main crop.

The tested management strategies affected the main crop, the cover crop and the companion flora, but they were not able to raise wheat yield to levels comparable to the NOWEED treatment. Increasing the distance between wheat rows (from 0.1875 to 0.3750 m) - this was required for mulching in the inter-row space - did not affect grain yield in NOWEED but increased protein content and thousand kernel weight (TKW) from 11.7 to 12.7 % and from 42.6 to 43.5 g respectively, when averaged over both sites. Mulching in the inter-rows, expected to reduce competition between the main and the cover crop, modified the weed community: at one site *M. chamomilla* and at the other *C. bursa-pastoris* were significantly suppressed while *Poa trivialis* L. was encouraged at both sites. Mulching also increased grain yield of wheat in living mulches, mainly as a result of higher tiller density. The application of manure showed some potential to increase main crop competitiveness in living mulch systems. Effects in treatments without soil cover were more distinct compared to treatments with cover crops. It is possible that the rather limited increase in wheat yield brought about by the tested management strategies is due to the fact that they became operative too late.

The weed suppressing ability of the legumes clearly substantiates the potential of living mulches for weed control. However, their negative impact on wheat growth and yield is yet too strong for the living mulches to be adopted. In order to better control the cover crops in legume living mulches and as a consequence improve wheat yield, management strategies which maintain the weed suppressing ability and which become operative early enough to benefit the main crop have to be developed.

ZUSAMMENFASSUNG

Mit reduzierter Bodenbearbeitung kann Bodenerosion und Nitratauswaschung verringert werden. In solchen Anbausystemen werden Unkräuter vorwiegend mit Herbiziden kontrolliert. Im Biolandbau, in welchem Herbizide nicht erlaubt und deshalb Gewässerkontaminationen durch diese Substanzen ausgeschlossen sind, überwiegt die mechanische Unkrautregulierung. Dadurch wird aber das Risiko der Bodenerosion erhöht. Reduzierte Bodenbearbeitung, insbesondere Direktsaat als Extremform pflugloser Bewirtschaftung, wird daher im Biolandbau nur beschränkt verwendet. Um die ökologischen und ökonomischen Vorteile der Direktsaat im Biolandbau nutzen zu können, sind neue Ansätze sowie die Prüfung deren Realisierbarkeit dringend notwendig. Die Direktsaat in einen Lebendmulch (Bodenbedeckungspflanzen, die über einen längeren Zeitraum der Vegetation der Hauptkultur wachsen und zum Ziel haben, die Bodenerosion zu vermindern, Pflanzennährstoffe zu konservieren und gleichzeitig Unkräuter zu unterdrücken) unter Biolandbau-Bedingungen wäre ein möglicher Ansatz, vorausgesetzt, dass die verfügbaren Ressourcen durch die erhöhte Konkurrenzsituation zwischen den Pflanzen mit gezielten Eingriffen für die Hauptkultur nutzbar sind und befriedigende Erträge erzielt werden.

Ziel der vorliegenden Untersuchungen war es, verschiedene Leguminosen in einem Lebendmulchsystem mit Winterweizen unter Bedingungen des Biolandbaus zu testen. Dabei wurde die Unkrautunterdrückungskraft der verschiedenen Leguminosen, deren Einfluss auf das Wachstum und die Ertragskomponenten der direktgesäten Hauptkultur sowie geeignete Bewirtschaftungsmassnahmen solcher Mischkultur-Systeme evaluiert.

Winterweizen (*Triticum aestivum* L.) wurde an zwei Standorten im Schweizer Mittelland in sieben verschiedene Lebendmulche (*Lotus corniculatus* L., *Medicago lupulina* L., *Medicago rigidula* (L.) All., *Medicago truncatula* Gaertner, *Trifolium repens* L. (cv. Barbian, cv. Milo), *Trifolium subterraneum* L.) eingesät. In Kontrollparzellen ohne Leguminosen wurden die Weizenbestände regelmässig gejätet (NOWEED) oder unbeeinflusst belassen, was zur Entwicklung der standortüblichen (natürlichen) Unkrautpopulation führte (NAT). In Teilparzellen wurden verschiedene Bewirtschaftungsmassnahmen getestet. Für die Prüfung der Hypothesen wurden repräsentative Faktorkombinationen separat analysiert.

T. repens, *T. subterraneum* und *L. corniculatus* unterdrückten dikotyle, annuelle und frühjahrskeimende Unkräuter (beispielsweise *Poa annua* L. und *Matricaria chamomilla* L. am Standort 1 und *P. annua*, *Capsella bursa-pastoris* (L.) Med. und *Stellaria media* (L.) Vill.

am Standort 2) im Vergleich zu NAT wirksam. *T. repens* unterdrückte Unkräuter am besten, konkurrierte aber auch den Winterweizen am stärksten, was den Ertrag beträchtlich reduzierte. Vollständige Unkrautunterdrückung wurde bei keiner der untersuchten Bodenbedeckungspflanzen beobachtet. *M. truncatula* überdauerte den Winter nicht und so entwickelte sich eine zu NAT vergleichbare Begleitflora. Obwohl der Kornertrag von Weizen in den Verfahren mit *M. truncatula* am höchsten war, wurde im Vergleich zu NOWEED in allen Verfahren der Kornertrag von 3475 kg ha^{-1} (Standort 1) und 5015 kg ha^{-1} (Standort 2) sowie die Biomasse des Winterweizen um mehr als 50 % reduziert.

Die zum Zeitpunkt der Weizenreife in der gesamten oberirdischen Biomasse gespeicherte Stickstoffmenge war an einem Standort in den Verfahren mit Lebendmulch vergleichbar oder höher als in der Weizenmonokultur, während am zweiten Standort das Gegenteil zutraf. Der Stickstoffgehalt in den Weizenkörnern und im Stroh war im Vergleich zu NOWEED (2.2 und 0.3 %) durch die Koexistenz mit einem Lebendmulch bestehend aus *T. repens* (2.7 und 0.5 %) höher, woraus gefolgert werden kann, dass N nicht der am meisten limitierende Faktor für die Hauptkultur war.

Die untersuchten Bewirtschaftungsmassnahmen beeinflussten die Hauptkultur, die Leguminosen sowie die Begleitflora, vermochten aber den Kornertrag des Weizens nicht auf ein zu NOWEED vergleichbares Niveau zu steigern. Die für eine mechanische Regulation des Lebendmulches benötigte Ausdehnung der Reihenabstände (von 0.1875 auf 0.3750 m) zeigte in NOWEED keinen Einfluss auf den Kornertrag von Winterweizen, erhöhte aber den Proteingehalt im Mittel beider Standorte von 11.7 auf 12.7 % und das Tausendkorngewicht (TKG) von 42.6 auf 43.5 g. Das Mulchen zwischen den Reihen reduzierte an einem Standort *M. chamomilla* und am anderen Standort *C. bursa-pastoris* signifikant, während *Poa trivialis* L. an beiden Standorten gefördert wurde. Durch das Mulchen wurde der Weizenertrag, vor allem aufgrund höherer Bestandesdichten, erhöht. Die ertragssteigernde Wirkung der Düngung auf den Weizen war ausgeprägter in Verfahren ohne Bodenbedeckung als in solchen mit. Die Bewirtschaftungsmassnahmen setzten wahrscheinlich zu spät im Wachstumszyklus des Weizens ein, um eine ausgeprägtere Wirkung auf den Kornertrag zu erzielen.

Die unkrautunterdrückende Wirkung der Leguminosen zeigt, dass Lebendmulche das Potential haben, für die Unkrautregulation eingesetzt zu werden. Aufgrund der Konkurrenzkraft gegenüber dem Weizen ist eine Umsetzung in die Praxis noch nicht möglich. Die Herausforderung solcher Systeme besteht darin, dass bei den gezielten Eingriffen die unkrautunterdrückende Wirkung der Lebendmulche beibehalten und zugleich die Entwicklungsbedingungen der Hauptkultur früher begünstigt werden.

LIST OF ABBREVIATIONS

a.s.l.	above sea level
AN	annual weed species
DI	dicotyledonous weed species
HI	harvest index
LOTCO	treatment in which winter wheat was sown into a living *Lotus corniculatus* L. mulch
M0	treatment without manure
M1	treatment with manure
MEDLU	treatment in which winter wheat was sown into a living *Medicago lupulina* L. mulch
MEDRI	treatment in which winter wheat was sown into a living *Medicago rigidula* (L.) All. mulch
MEDTR	treatment in which winter wheat was sown into a living *Medicago truncatula* Gaertner mulch
MONO	monocotyledonous weed species
N	nitrogen
NAT	treatment in which winter wheat was sown into a naturally occurring weed community
NOWEED	treatment in which winter wheat was sown into a bare soil, and weeds were controlled manually afterwards
PE	perennial weed species
RS1	narrow row spacing (0.1875 m)
RS2	wide row spacing (0.3750 m) without mechanical inter-row regulation
RS3	wide row spacing (0.3750 m) with mechanical inter-row regulation
S/A	summer and autumn germinating weed species
SD	standard deviation
SP	spring germinating weed species
TKW	thousand kernel weight
TRFRE B	treatment in which winter wheat was sown into a living *Trifolium repens* L. cv. Barbian mulch
TRFRE (M)	treatment in which winter wheat was sown into a living *Trifolium repens* L. cv. Milo mulch
TRFSU	treatment in which winter wheat was sown into a living *Trifolium subterraneum* L. mulch

1 GENERAL INTRODUCTION

It is important to develop alternatives to synthetic herbicides, which are the most used pesticides worldwide (Hall, 2004) and play a very important role in the control of weeds. The goal is to reduce environmental pollution and, at the same time, maintain the productivity of conventional agricultural systems. The cost of pesticides and the lack of concern of consumers with regard to their use have delayed the development of alternative, environmentally sound cropping systems (Theunissen, 1997). Furthermore, the run-off and leaching of pesticides into surface and ground water is a major concern in today's agriculture (Stoate *et al.*, 2001). On the other hand, continuous intense management of agricultural soil is one of the main reasons for the steady degradation of soils (Govers *et al.*, 1994) and especially for the decrease in the volume of the macropores and the unstable aggregates. This is due mainly to the use of mouldboard ploughs, usually in combination with other equipment for intense soil tillage in conventional cropping systems. Thus, soil erosion and run-off have increased, especially in regions with high precipitation and where row crops are planted in hilly areas and herbicides have left the soil bare (Hartwig & Ammon, 2002). In intensely tilled soils, the silting of the surface after heavy rainfall has also been observed.

Pesticides, synthetic fertilisers and intensive mechanisation have provided agriculture with a means for achieving an economically sound, reliable control of crops in unpredictable climates but at the risk of long-term soil infertility. The return to environmentally sound, sustainable cropping systems is a big challenge for agriculture and research. Reducing tillage intensity, adopting organic farming (Kirchmann *et al.*, 2002) and the cultivation of cover crops may be key elements for obtaining these objectives. The pay-off for agriculture would be considerable.

1.1 NO-TILLAGE

Reducing the intensity of soil tillage offers several advantages. On the one hand, it reduces costs, especially in no-tillage systems, the most extreme form of conservation tillage (Weersink *et al.*, 1992). On the other hand, the soil structure of the entire soil profile is preserved (Tebrügge & Düring, 1999; Lu *et al.*, 2000; Schmidt *et al.*, 2003) and the maintenance of plant residues on the soil surface offers an intact habitat with sufficient food for beneficial soil micro-organisms and organisms, e.g. earthworms (Chan, 2001). Plant residues are also a physical barrier to light and rain drops, minimising erosion and providing insulation against extreme temperatures, thus contributing to maintaining the moisture content of the topsoil (Teasdale & Mohler, 1993; Birstow & Horton, 1996; Teasdale, 1996). The different soil conditions influence the activity of micro-organisms and nutrient mobility. Thus, fertilisation must be adapted, in contrast to tilled soils.

As well as the abiotic changes brought about by no-tillage farming, which influence germination, the establishment of the weed population is also affected by other processes: (i) Weed seeds are not dislocated in the soil profile but accumulate on or near the soil surface where they decompose or are consumed by animals. (ii) Seeds of weed species that lay dormant in the soil cannot fulfill their life cycle. Therefore, the density of weed species and the composition of weed populations may differ in relation to soils that are regularly tilled (Buhler, 1995). Most studies investigating the impact of tillage systems on weed populations suggest that reduced soil tillage favours perennial weed species, especially anemochore and monocotyledonous species (Buhler, 1995; Streit *et al.*, 2002). However, weeds in no-tillage systems are controlled to a great extent by herbicides; mechanical control is limited.

1.2 ORGANIC FARMING

In organic farming systems, neither synthetic fertilisers nor pesticides are allowed, so they are not leached into the water. The targeted, closed on-farm cycling of nutrients implies that these are often limiting, especially on stockless farms, and losses through leaching and run-off of the organically supplied nutrients will usually be low. Nevertheless, tillage carried out mainly to control weeds may stimulate mineralisation and, when followed by intense rainfall, causes displacement of N into deeper soil layers and into the ground water (Kirchmann *et al.*, 2002). Losses of organic nutrients may also occur when the supply and the demand of the plants are not synchronised (Kirchmann *et al.*, 2002). However, crops in organic farming are less competitive than in conventional farming systems; thus weeds, which usually adapt to local conditions, have an advantage.

The lack of economic and efficient options for controlling weeds, especially perennial species, is one of the most important factors that keeps farmers from adopting organic farming (Bond & Grundy, 2001). If the formation of weed seeds is not restricted, the increase in the weed seed bank will cause major, long-term problems (Albrecht & Sommer, 1998), which are more pronounced in organic than in conventional farming systems. Since tillage is the main strategy for controlling weeds in organic farming, the risk of soil erosion increases, especially in row crops, in hilly regions and where precipitation is high. This risk is even aggravated by the fact that some summer annual crops e.g. maize, lack early vigour, and that for a longer period of time the soil between the rows is not protected by living plants. Therefore, to control weeds adequately in organic farming systems, a systematic approach is necessary (Liebman & Dyck, 1993; Bond & Grundy, 2001; Barberi, 2002; Hatcher & Melander, 2003).

The combination of minimum tillage and organic farming brings together the advantages of both systems (less soil erosion, better soil structure, reduced leaching of nutrients and pesticides into water sources). However, for the successful implementation of such a system and for long-term practicability weed control and fertiliser management will play an important role.

1.3 COVER CROPS

Various cover crops catch unused mineralised N as the main crop lies fallow, thus preserving it for the next main crop and preventing it from being leached (Thorup-Kristensen & Nielsen, 1998; Kirchmann *et al.*, 2002). With the deep rooting of cover crops and the low mineralisation of N in spring, there may be a lack of N for the following main crop; this can be prevented by using legume cover crops (Thorup-Kristensen & Nielsen, 1998). These crops may also - with the aid of their roots - stabilise the soil structure and aerate the soil. Above-ground biomass or plant residues may reduce soil erosion and water loss through evaporation (Teasdale & Mohler, 1993) and increase the occurrence of earthworms (Schmidt & Curry, 2001). As root and above-ground biomass die, the soil organic matter and long-term soil fertility will increase (Hartwig & Hoffman, 1975; Schmidt *et al.*, 2003). Regardless of the tillage system, organic matter provides food for earthworms and micro-organisms, leading to larger populations and greater diversity. Cover crops also suppress weeds more efficiently than plant residues alone, since the soil is covered for a longer period (Ilnicki & Enache, 1992). However, the efficacy of weed control depends on biomass production and on the morphology of the cover crop: prostrate plants shade weeds better than upright plants. Small-seeded weeds may react more strongly to surface cover than large-seeded weeds (Teasdale, 1996). Complete suppression of weeds by cover crops is usually not achieved. Nevertheless, depending on species, seeding density and planting time, fairly good levels of control have been reported (Teasdale, 1996; Brandsæter *et al.*, 1998). In order to complete the weed suppressing ability of the cover crops and to prevent problematic weeds from becoming established, it is necessary to combine cover crops with other means of non-chemical weed control (Abdin *et al.*, 2000; Hatcher & Melander, 2003).

The use of cover crops is one way of controlling weeds and optimising the management of fertiliser in systems with direct drilling and organic farming. Cover crops also make it possible to implement direct drilling in organic farming systems.

1.4 LIVING MULCHES

When cover crops grow for a considerable part or for all of the cropping season, acting chiefly as ground cover during this period, they are defined as 'living mulch' (Feil & Liedgens, 2001). In contrast to the more common undersowing, a living mulch is established before or together with the main crop. Through the existence of the living mulch, one or several environmental factors and their interactions may be modified, directly or indirectly. Soil temperature and moisture content may be more balanced in such systems compared to systems with bare and tilled soil (Teasdale & Mohler, 1993; Bristow & Horton, 1996). In line with cover crops, living mulches have the potential to decrease soil erosion (Rüttimann, 2001), increase the self-regulation of pests and diseases (Rämert, 1996; Brandsæter *et al.*, 1998; Ntahimpera *et al.*, 1998), suppress weeds (Liebman & Dyck, 1993; Teasdale, 1996; Hiltbrunner *et al.*, 2002), improve the soil structure (Duda *et al.*, 2003), and hinder the leaching of N. Non-legume cover crops such as rye may catch more N and hinder the leaching of nitrate from the soil more efficiently than legumes (Sainju *et al.*, 1998) but may also be more competitive with the main crop for N (Garibay *et al.*, 1997; Thorup-Kristensen & Nielsen, 1998). Since legumes fix N from the air, they may be better living mulches in low-input farming systems; they compete with the main crop for N to a lesser extent. Furthermore, organic farms depend on the input of N through biological processes and, as a result, legumes play a very important role in the crop rotation in order to maintain soil fertility in organic farming systems (Fukuoka, 2000; Watson *et al.*, 2002). Reports on the relevance of the N transfer from legumes to companion plants are contradictory. Fujita *et al.* (1992) report about studies with direct transfer of N (up to 25 % of the fixed N from cowpea to maize) as well as studies indicating that most N may be transferred indirectly or through the decomposition of plant residues. Though the latter is supported by later findings (Dubach & Russelle, 1994; Russelle *et al.*, 1994), which also showed, that N, transferred from decomposing legume roots or nodules, differs among legume species. However, N yield in mixtures of non-legumes and legumes may increase in contrast to monocultures (Boller & Nösberger, 1987).

Cover crops in living mulches are usually perennials (e.g. *Trifolium repens* L., *Lolium perenne* L.) but may also be self-reseeding annuals, such as *Trifolium subterraneum* L. or *Trifolium incarnatum* L. (Hartwig & Ammon, 2002). The choice of species may be influenced by ecological and economic factors. For example, self-reseeding or perennial species help to reduce the costs of seeds and the seeding operation. Depending on the site, crop rotation and weed pressure, the most appropriate combination of cover and main crop must be found if a living mulch system is to be feasible (Vandermeer, 1989). In this context, seeding date, seeding rate and cultivars play an important role.

Living mulch systems were first implemented in perennial crops (e.g. vineyards and orchards) (Feil & Liedgens, 2001). Later, investigations with row crops such as vegetables (Ilnicki & Enache, 1992; Brandsæter *et al.*, 1998) or maize (Ilnicki & Enache, 1992; Hartwig & Ammon, 2002) and small-grain cereals (White & Scott, 1991; Jones & Clements, 1993) were conducted.

Cover crops may compete not only with weeds, but also with the main crop. This may be more evident in annual than in perennial main crops. The competition of the living mulch and the main crop for water, nutrients or light can be reduced by regulating cover crops with non-lethal doses of herbicides in integrated farming systems or mechanically with strip cultivation, mowing or mulching (Garibay *et al.*, 1997; Hartwig & Ammon, 2002; Bergkvist, 2003a) in organic farming systems. On the other hand, seeding in tilled strips (Ilnicki & Enache, 1992; Garibay *et al.*, 1997), relay planting in herbicide-killed strips (Kumwenda *et al.*, 1993), or transplanting (Brandsæter *et al.*, 1998) are possible ways of increasing the competitiveness of the main crop in relation to cover crops. In order to reduce competition for water, the implementation of living mulch systems - without mechanical interference to suppress the cover crop - may be possible only in regions with more than 1100 mm yr^{-1} precipitation (Hartwig & Ammon, 2002).

Most mechanical operations between crop rows depend on a sufficient space between the rows. In particular, in small-grain cereals, distances of 0.12 to 0.18 m are too narrow for intense mechanical interference. Increasing the row distance up to 0.50 m usually decreased yields (e.g. Holliday, 1963; Furrer, 1965; Mülle & Heege, 1981; Frederick & Marshall, 1985; Joseph *et al.*, 1985; Marshall & Ohm, 1987; Johnson *et al.*, 1988; Epplin *et al.*, 1992). In some studies, however, no yield depression was observed due to increased row spacing, especially in no-tillage systems and when yield potentials were low (Crabtree & Rupp, 1980; Teich *et al.*, 1993; Lafond, 1994; McLeod *et al.*, 1996; Lafond & Gan, 1999; Becker & Leithold, 2003).

Only few investigations have been made with living mulch systems and small-grain cereals in temperate climates (White & Scott, 1991; Jones & Clements, 1993; Germeier, 2000; Schmidt & Curry, 2001; Hiltbrunner *et al.*, 2002; Bergkvist, 2003b; Neumann *et al.*, 2003). However, competition between the cover crop and the main crop has been reported by many researchers. *T. repens* is used most often, while other legumes and non-legumes have hardly been investigated (Germeier, 2000; Bergkvist, 2003b).

To benefit from the advantages of a living mulch in arable crops, main crops must be established after minimum or no-tillage. Environmental factors such as precipitation, altitude and soil characteristics are even more important factors, and the local testing of living mulch systems in organic farming is, therefore, necessary.

2 OBJECTIVES

The aim of this study was to identify legumes, which are suitable for living mulch systems in organic small-grain cropping systems. The ability of the living mulch to suppress weeds is the most important criterion. The challenge is to find a balance between a successful suppression of weeds and a minimal competition with the main crop. To meet this objective, different management regimes for both the cover and the main crop and the impact of these regimes on the main and cover crops as well as the weed community were studied.

3 EXPERIMENTAL SET-UP

As all the investigations were made within the same experiments, the experimental set-up and the cultural practices are described here, while plant sampling and analyses as well as data analyses are described in the respective chapters.

3.1 EXPERIMENTAL SITES

The study was conducted at two sites in the Swiss midlands near Zürich (Site 1: 47°19’00’’N, 8°19’10’’E, 430 m a.s.l.) and near Lucerne (Site 2: 47°10’10’’N, 8°00’50’’E, 505 m a.s.l.) in 2001/ 2002. According to the FAO scheme, the soils were a partial gleyic Cambisol at Site 1 and an orthic Luvisol at Site 2 (Table 3.1). Over the last 10 years, the annual mean temperature and precipitation were 9.9 °C and 1106 mm (Site 1) and 9.9 °C and 1077 mm (Site 2). In October 2001 and in February and June 2002, the mean air temperatures at the two sites were 2 to 3 °C higher than the 10-year average. Rainfall was distributed similarly at both sites. In 2001/ 2002 the rainfall was lower than the 10-year average by up to 60 % in the winter and by 35 % in the summer, resulting in a decrease in the annual precipitation of 10 to 15 %. The previous crops were peas (*Pisum sativum* L.) at Site 1 and lettuce (*Lactuca sativa* L.) at Site 2. After their harvest at the end of July 2001, the fields were tilled with a rotary harrow at a target working depth of 0.20 m. The soil was not tilled again until the harvest of wheat.

Table 3.1. Characteristics of the topsoil (0 - 0.2 m) at two sites.

	Site 1	Site 2
Soil type (FAO classification)	partial gleyic Cambisol	orthic Luvisol
Particle size distribution (sand-silt-clay) (%)	49.4 – 34.2 – 16.4	52.5 – 30.9 – 16.6
pH (water)	7.2	6.2
Organic matter (g kg^{-1})	22	28
P (mg kg^{-1})	88.3	88.2
K (mg kg^{-1})	92.2	201.3
Ca (mg kg^{-1})	3240.7	1250.0
Mg (mg kg^{-1})	69.2	74.9

3.2 ESTABLISHMENT OF TREATMENTS AND CROP MANAGEMENT

Birdsfoot trefoil (*Lotus corniculatus* L. cv. Rocco, Raiffeisen Zentralgenossenschaft eG, Germany) (LOTCO), medium-to-small-leaved white clover (*Trifolium repens* L. cv. Milo, DLF – Trifolium A/S, Denmark) (TRFRE M), small-leaved white clover (*Trifolium repens* L. cv. Barbian, Barenbrug, Netherlands) (TRFRE B), subclover (*Trifolium subterraneum* L. cv. Denmark, Agriculture Western Australia, Australia) (TRFSU), black medick (*Medicago lupulina* L. cv. Virgo Pajbjerg, DLF – Trifolium A/S, Denmark) (MEDLU), field medick (*Medicago rigidula* (L.) All. cv. Ampus, INRA, France) (MEDRI) and strong-spined medick (*Medicago truncatula* Gaertner cv. Salernes, INRA, France) (MEDTR) were sown on 2 August 2001 at Site 1 and on 14 August 2001 at Site 2 as cover crops; the sowing rates were 15, 15, 15, 20, 20, 20, and 20 kg ha^{-1}, respectively and the target seeding depth was 0.01 m. Two control treatments without legume cover crops were either weeded by hand at regular intervals (NOWEED) or left undisturbed and thus infested by the site-specific (natural) weed community (NAT).

Prior to the seeding of wheat, the soil cover was cut with a power mower to a target height of 0.05 m and removed from the plots. On the NOWEED plots, the weeds were burned with a Bunsen burner on 27 September and 12 October in 2001. During the growing period, these plots were weeded by hand, to remove all the weeds.

Winter wheat (*Triticum aestivum* L. cv. Titlis, FAL Zürich-Reckenholz, Switzerland) was sown at a density of 375 kernels m^{-2} (= 170 kg ha^{-1}) at both sites on 12 October 2001 using a modified Direttissima 250 no-tillage seeder (Gaspardo, Pordenone, Italy) with single disc openers. The rows were 0.1875 m (RS1) or 0.3750 m apart.

On 26 October 2001 all the plots were cut with a power mower to a target height of 0.10 m to remove plants that were shading the wheat. In treatments with 0.3750 m row spacing in half of the plots the soil cover in the inter-row space grew without interference (RS2), while in the other half the plants were cut to a target height of 0.05 m on 4 March, 4 April, 7 May and 31 May 2002 (RS3). Henceforth, mechanical interference in the inter-row space is called mulching.

Nitrogen (N) was not supplied (M0) or was applied (M1) as farmyard manure (1:1 diluted), both at wheat tillering (13 March 2002) and at shoot elongation (5 April 2002), according to the usual practice in Switzerland. Overall the manure contained 121 kg N ha^{-1} (Site 1) and 95 kg N ha^{-1} (Site 2) (Table 3.2). Although the rates of application were based on an analysis of the nutrients in the manure prior to application, unexpected dilution of the manure occurred between the applications at Site 2; thus, the manure contained less N, which resulted in a smaller amount of total applied N.

Table 3.2. Rates of application of diluted liquid manure and amounts of N_{tot}, NH_4-N, P_2O_5, and K_2O spread on plots of winter wheat at two sites.

Site	Date	Application	N_{tot}	NH_4-N	P_2O_5	K_2O
		----- m^3 ha^{-1} -----	------------------------ kg ha^{-1} ------------------------			
1	13 March 2002	37	66	38	29	109
	5 April 2002	25	55	33	29	85
2	13 March 2002	37	60	34	29	76
	5 April 2002	35	35	21	17	35

3.3 EXPERIMENTAL DESIGN

The experiments were set up as a split-strip plot with three replications. Soil cover, fertiliser level, and row spacing or mulching were the main-plot, horizontal, and vertical sub-plot factor, respectively (Table 3.3). Levels of soil cover and fertiliser were randomly distributed within the blocks and the main plot factors, respectively. In order to enable mechanical management, vertical sup-plot factors were assigned as three strips (RS1, RS2, RS3) perpendicular to the horizontal sub-plot factor and across the whole blocks. Sub-plots were 2.5 m x 5.0 m in size.

Table 3.3. Factors and levels of the experiments.

Factor	Description	Level	Abbreviation
Main-plot	**Soil cover**	*Lotus corniculatus* living mulch	LOTCO
		Medicago lupulina living mulch	MEDLU
		Medicago rigidula living mulch	MEDRI
		Medicago truncatula living mulch	MEDTR
		Trifolium repens cv. Barbian living mulch	TRFRE B
		Trifolium repens cv. Milo living mulch	TRFRE (M)
		Trifolium subterraneum living mulch	TRFSU
		Site-specific weed community	NAT
		No weeds	NOWEED
Horizontal sub-plot	**Fertilisation**	Without manure application	M0
		With manure application	M1
Vertical sub-plot	**Row-system**	0.1875 m winter wheat row spacing (= narrow row); without mulching	RS1
		0.3750 m winter wheat row spacing (= wide row); without mulching	RS2
		0.3750 m winter wheat row spacing (= wide row); with mulching	RS3

4 HYPOTHESES AND STRUCTURE OF THE STUDY

According to the revised literature the thesis is based on the following hypotheses:

1. Different legume species and varieties suppress weeds differently when grown as living mulch for winter wheat.
2. An increase in the distance between the rows of winter wheat grown without any companion plants leads to a decrease in grain yield, without, however, influencing the quality of the crop.
3. When grown as living mulch for winter wheat, different legume species and varieties have different effects on the weed community. When the space between the rows of the main crop is small, weeds are more effectively suppressed than when the rows are further apart. Mulching between widely spaced rows of the main crop suppresses weeds effectively, in contrast to no mulching. The application of liquid manure, on the other hand, favours weeds.
4. Wheat grown together with a permanent legume ground cover yields more N per area than on bare soil. The co-existence of a legume living mulch increases the protein content of the wheat grain.

In order to test these hypotheses, experiments were set up at two sites in 2001 and with an adapted repetition in 2002[1]. The screening of the legume cover crops was combined with the factors 'row spacing', 'mulching' and 'fertilisation'. The hypotheses were tested on selected combinations of the treatments considered to be representative of the others (Table 4.1).

[1] Due to unusually rapid temperature changes in the winter of 2002/2003 the repetition was cancelled in spring 2003.

Table 4.1. Structure of the study.

Chapter	Years	Sites	Soil cover									Fertilisation		Row-System		
			L. corniculatus (LOTCO)	*M. lupulina* (MEDLU)	*M. rigidula* (MEDRI)	*M. truncatula* (MEDTR)	*T. repens* cv. Barbian (TRFRE B)	*T. repens* cv. Milo (TRFRE (M))	*T. subterraneum* (TRFSU)	Site-specific weeds (NAT)	Bare soil (NOWEED)	with (M1)	without (M0)	0.1875 m row spacing, without mulching (RS1)	0.3750 m row spacing, without mulching (RS2)	0.3750 m row spacing, with mulching (RS3)
5	1	2	x	x	x	x	x	x	x	x	x	x	x	x		
6	1	2									x	x	x	x	x	
7	1	2	x			x		x	x	x	x	x	x	x	x	x
8	1	2						x			x	x	x		x	x

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5 LEGUME LIVING MULCHES FOR ORGANIC WINTER WHEAT: COMPONENTS OF BIOMASS AND THE WEED COMMUNITY

5.1 ABSTRACT

For direct drilling in organic farming systems to be beneficial, alternative strategies of weed control must be investigated. To gain information about the ability of legume cover crops to suppress weeds as well as about their impact on the main crop, experiments were conducted at two sites in the Swiss midlands in 2001/ 2002. Winter wheat (*Triticum aestivum* L.) was directly drilled in rows, 0.1875 m apart, at a seeding rate of 375 kernels m^{-2} in living mulches of black medick (*Medicago lupulina* L.), field medick (*Medicago rigidula* (L.) All.), strong-spined medick (*Medicago truncatula* Gaertner), birdsfoot trefoil (*Lotus corniculatus* L.), subclover (*Trifolium subterraneum* L.) and two cultivars of white clover (*Trifolium repens* L.). Control treatments without cover crops were also set up: naturally occurring weeds were either left on the plot (NAT) or were destroyed (NOWEED). An unfertilised treatment was compared with the usual application of fertiliser (60 m^3 ha^{-1} as liquid farmyard manure). Compared to NAT, *T. repens*, *T. subterraneum* and *L. corniculatus* suppressed the density of monocotyledonous and dicotyledonous weeds, spring germinating weeds and annual weeds at the time of wheat anthesis. *M. truncatula*, which died during the winter, did not suppress weeds compared to NAT. However, the main crop biomass and, thus, the grain yield were reduced by more than 50 % by all the cover crops compared to NOWEED. The application of manure did not significantly increase the weed biomass but it did increase the biomass of wheat. While the ability of the legumes to suppress weeds clearly shows the potential of living mulches to control weeds, their negative impact on growth and yield of wheat must be overcome before they can be implemented. More research must be conducted to reduce the competitive impact of the legumes on wheat, especially at the juvenile stage.

5.2 INTRODUCTION

In organic farming systems mechanical weed control is the most important measure for suppressing weeds. However, the repeated disturbance of the soil prevents the build-up and/ or the maintenance of a stable soil structure (Tebrügge & Düring, 1999). Furthermore, soil left bare after tillage operations is prone to erosion (Rüttimann, 2001). Hence, there is a dilemma as to whether mechanical operations should be reduced or herbicides should be used to control weeds.

The substitution of conventional farming by organic farming as well as the adoption of conservation tillage, of which no-tillage is the most extreme form, leads to changes in weed populations. Perennials may pose a problem in both organic farming and conservation tillage, in the former when ploughing is shallow and in the latter by favouring perennial weeds such as anemochore and monocotyledonous species (Buhler, 1995; Streit *et al.*, 2002). In both systems, weed establishment from seeds should be strictly avoided so as to reduce the necessity of weed control operations; a systematic approach may be more promising than concentrating on one method (Barberi, 2002) and would also increase long-term practicability (Bond & Grundy, 2001). To enable the long-term productivity of arable crops in organic farming systems, prevention of seed formation is a key factor (cf. Albrecht & Sommer, 1998).

The control of weeds is the key to the success of both no-tillage and organic farming systems with all their benefits. Soil cover between crop plants has been proposed as an environmentally sound option for suppressing weeds (Liebman & Dyck, 1993; Teasdale, 1996). Such cover plant species must be easy to control, less competitive than weeds with the main crop and meet the requirements of living mulches, as determined by Feil and Liedgens (2001). If a legume is a partner in a living mulch, then competition for nitrogen will probably be reduced (Vandermeer, 1989). During the last decade, the interest in using cover crops and mulches for organic weed control has increased (Barberi, 2002).

It has been reported that *Trifolium repens* L. and *Trifolium subterraneum* L. differ in their ability to suppress weeds (Enache & Ilnicki, 1990; Abdin *et al.*, 2000). However, successful suppression of weeds depends not only on the cover crop, but also on the composition of the weed population (Liebman & Dyck, 1993; Teasdale, 1996). Thus, it is necessary to identify combinations of main and cover crops for living mulch systems with respect to prevailing weed populations and to focus on the biomass, density and diversity of weeds (Liebman & Dyck, 1993). In the few studies on living mulches with small-grain cereals, strong competition resulted in low grain yields of directly drilled winter wheat (White & Scott, 1991; Bergkvist, 2003b).

The aim of the present study was to evaluate the influence of different legume cover crops in a living mulch system with winter wheat on weed growth and grain yield. To vary the competitiveness of the companion plants, treatments with and without fertiliser were conducted.

5.3 MATERIAL AND METHODS

5.3.1 Treatments and experimental design

This chapter focuses on the weed suppressing effect of soil covers. All of them (LOTCO, NAT, NOWEED, MEDLU, MEDRI, MEDTR, TRFRE B, TRFRE M, TRFSU) are investigated under the two levels of nutrient supply (M0, M1) but only under the main crop row spacing of 0.1875 m (RS1) (Table 4.1). As the focus here lies on the above mentioned treatments, the experimental design of the basic experiment changes and the statistical analyses in this chapter are based on a split plot design.

5.3.2 Sampling and analysis of plants

Plants were cut at ground level from 0.5 and 1.0 m^2 per plot at wheat anthesis (11 June, 2002) and at physiological wheat maturity (24 July, 2002 at Site 1 and 27 July, 2002 at Site 2), respectively. Wheat shoots were separated from the remaining plants on the field and were dried. Dried samples of the remaining plants at wheat anthesis were then separated into cover crops and into monocotyledonous (MONO) and dicotyledonous (DI) weed sub-samples. Grains of the dried wheat samples at physiological maturity were separated from the biomass and weighed.

In the last week of June 2002, the density of the weed species was assessed on an area of 0.5 m^2 in each sub-plot. Species were grouped according to class (MONO, monocotyledonous species; DI, dicotyledonous species), germination time (SP, spring germinating; S/A, summer/ autumn germinating) and longevity (AN, annual species; PE, perennial species).

5.3.3 Data analysis

To compare the effects of the living mulches on the main crop, the winter wheat biomass and grain yield of weed-free treatments (NOWEED) were taken as references but were not included in the analyses. It was assumed that there would be few differences among some of the tested cover crops. Therefore, the biomass of four representative living mulches was separated and compared with the soil cover provided by the site-specific weed population (NAT). Treatments with living mulches of *M. lupulina* (MEDLU), *M. rigidula* (MEDRI) and *T. repens* cv. Barbian (TRFRE B) were included for grain yield analyses only. For the analyses of the cover crop biomass, NAT was excluded from the analyses because a cover crop was not established on these plots. The assumption of normally distributed errors for some of the data sets was not supported by the examination of the residuals of the statistical analysis. Thus, the statistical analyses of the biomass of the cover crop, all the weed densities and the wheat grain yield were conducted on square-root transformed data. The data sets of the other parameters were log-transformed prior to analysis. However, the results are always presented on the original scale. The data were analysed using the Proc Mixed of the SAS® program package 8.0 (Littell *et al.*, 1996). Because of interactions between the site and other factors, the sites were analysed separately. Replication was set as a random factor. Means were separated by pair-wise *t*-tests ($p < 0.05$) when *F*-tests were significant at $p < 0.05$.

5.4 RESULTS

5.4.1 Impact of cover crop and fertilisation on weed biomass

The analysis of variance showed that the biomass of cover crops and monocotyledons was significantly influenced by the soil cover only at Site 2 (Table 5.1). Biomass of winter wheat was significantly affected by the application of manure at both sites.

Table 5.1. Analyses of variance (ANOVA) of the effects of soil cover (C) and fertilisation (F) on biomass of weeds (DI, dicotyledonous weeds; MONO, monocotyledonous weeds), cover crops and winter wheat in a winter wheat/ living legume mulch system.

Site	Factor	Cover crop	Weeds DI	Weeds MONO	Winter wheat
1	C	ns	ns	ns	ns
	F	ns	ns	ns	**
	F x C	ns	ns	ns	ns
2	C	***	ns	*	ns
	F	ns	ns	ns	*
	F x C	ns	ns	ns	ns

*, **, *** significant at the 0.05, 0.01, 0.001 probability levels, respectively; ns, not significant.

Due to the longer growing period at Site 1 more biomass was produced by the cover crops before winter compared to Site 2 (Table 5.2). MEDTR died during winter and only few plant residues remained on the soil surface in spring. Some of the older leaves of TRFSU died off during winter, but the plants recovered quickly in early spring. The decreasing order of produced biomass of the cover crop, as measured at wheat anthesis, was LOTCO > TRFRE M > TRFSU > MEDTR at both sites. However, the differences were significant only at Site 2.

In NAT the biomass of dicotyledonous weeds was 1756 kg ha^{-1} at Site 1 and 1135 kg ha^{-1} at Site 2. At Site 2 there was a significant reduction in the biomass of monocotyledons in the TRFRE M treatment compared to NAT, MEDTR and LOTCO.

Table 5.2. Effects of soil cover and fertilisation on biomass of dicotyledonous (DI) and monocotyledonous (MONO) weeds, cover crops and winter wheat at wheat anthesis.

Site	Factor	Level	Cover crop	Weeds DI	Weeds MONO	Winter wheat
			kg ha^{-1}			
1	Soil cover	NOWEED [1]				7838 [4]
		NAT		1756	575	1793
		MEDTR	82	944	399	2628
		TRFSU	3381	534	268	1426
		LOTCO	4647	275	486	1523
		TRFRE M	4062	480	346	714
	Fertilisation	M0 [2]	2784	605	320	1086 b
		M1	2189	700	503	2040 a
2	Soil cover	NOWEED				11365
		NAT		1135	742 a	3114
		MEDTR	0 c	675	1117 a	3092
		TRFSU	2616 b [3]	76	192 ab	2960
		LOTCO	4394 a	440	345 a	2575
		TRFRE M	3325 ab	218	42 b	1822
	Fertilisation	M0	1989	280	262	2254 b
		M1	1844	450	357	3145 a

[1] LOTCO, *Lotus corniculatus*; MEDTR, *Medicago truncatula*; NAT, treatment with site-specific weed community; NOWEED, weed-free treatment; TRFRE M, *Trifolium repens* cv. Milo; TRFSU, *Trifolium subterraneum*.

[2] M0, treatment without manure; M1, treatment with manure.

[3] For the same factor and parameter, means followed by different letters differ significantly ($P < 0.05$) according to pair-wise *t*-tests.

[4] In order to detect differences in the soil covers NOWEED was not included in the analyses.

Fertilisation increased the wheat biomass from 1086 to 2040 kg ha^{-1} at Site 1 and from 2254 to 3145 kg ha^{-1} at Site 2 (Table 5.2). Although the differences in the wheat biomass of the soil cover treatments, from the lowest to highest yielding treatments were considerable (72 % at Site 1 and 41 % at Site 2), they were not statistically significant at either site. Compared to NOWEED, the wheat biomass at wheat anthesis was smaller (by at least 65 %) in the treatments with covered soil at both sites.

The total biomass production of the systems during the growing period of the winter wheat, including the main crop, cover crop and weeds, was higher in the NOWEED plots than in all the other treatments (Table 5.2). Among treatments with covered soil, no significant differences were observed. However, treatments with wheat grown on plots covered by weeds only (NAT) tended to produce less biomass by wheat anthesis than treatments with an established legume living mulch.

Table 5.3. Analyses of variance (ANOVA) of the effects of soil cover (C) and fertilisation (F) on weed density in a winter wheat/ living legume mulch system.

		Weed class					
		Class		Germination time		Longevity	
Site	Factor	DI [1]	MONO	SP	S/A	AN	PE
1	C	*	*	***	ns	***	†
	F	ns	ns	ns	ns	ns	ns
	F x C	ns	ns	ns	ns	ns	ns
2	C	***	***	***	ns	***	ns
	F	ns	*	ns	ns	ns	ns
	F x C	ns	*	ns	ns	*	ns

[1] DI, dicotyledonous weeds; MONO, monocotyledonous weeds; SP, spring germinating weeds; S/A, summer or autumn germinating weeds; AN, annual weeds; PE, perennial weeds.
†, *, *** significant at the 0.1, 0.05, 0.001 probability levels, respectively; ns, not significant.

5.4.2 Impact of cover crop and fertilisation on weed density

There were significant effects of soil cover on the density of dicotyledonous, monocotyledonous, spring-germinating and annual weed species at both sites (Table 5.3). Only at Site 2 did manure influence the density of monocotyledonous (alone and interacting with soil cover) and annual weeds (interacting with soil cover).

Table 5.4. Effects of soil cover and fertilisation on density of weeds at wheat anthesis.

			Weeds					
			Class		Germination		Longevity	
Site	Factor	Level	DI [3]	MONO	SP	S/A	AN	PE
			plants m^{-2}					
1	Soil cover	NAT	81 a [4]	255 a	241 b	49	299 a	30
		MEDTR	85 a	283 a	407 a	80	282 a	171
		TRFSU	55 ab	5 b	41 c	49	45 b	2
		LOTCO [1]	17 b	22 b	34 c	30	27 b	10
		TRFRE M	19 b	1 b	2 d	12	7 b	0
	Fertilisation	M0 [2]	44	61	97	40	91	9
		M1	49	71	97	41	98	12
2	Soil cover	NAT	209 a	180 a	362 a	0.3	368 a	3.3
		MEDTR	106 b	180 a	325 a	4.9	325 a	1.7
		TRFSU	35 c	9 b	51 b	0.1	50 b	1.9
		LOTCO	2 d	3 b	2 c	1.2	3 c	0.5
		TRFRE M	0 d	9 b	2 c	0.2	3 c	1.3
	Fertilisation	M0	30	65 a	85	0.3	87	3.5
		M1	56	32 b	91	1.2	95	0.5

[1] LOTCO, *Lotus corniculatus*; MEDTR, *Medicago truncatula*; NAT, treatment with site-specific weed community; TRFRE M, *Trifolium repens* cv. Milo; TRFSU, *Trifolium subterraneum*.
[2] M0, treatment without manure; M1, treatment with manure.
[3] DI, dicotyledonous weeds; MONO, monocotyledonous weeds; SP, spring germinating weeds; S/A, summer or autumn germinating weeds; AN, annual weeds; PE, perennial weeds.
[4] For the same factor and parameter, means followed by different letters differ significantly ($P < 0.05$) according to pair-wise *t*-tests.

Compared to NAT, MEDTR did not reduce the density of weeds, irrespective of the grouping criteria. In fact, it increased the density of spring germinating weeds at Site 1 (Table 5.4). In contrast, LOTCO and TRFRE M significantly reduced the density of dicotyledonous, monocotyledonous, spring germinating and annual weeds compared to NAT. The ability of TRFSU to reduce weed density was as effective as the one of LOTCO and TRFRE M (for monocotyledons at both sites and spring-germinating and annual weeds at Site 1) or lay between NAT and the two above mentioned cover crops (for dicotyledonous at both sites and spring-germinating and annual weeds at Site 2). Manure only influenced the density of monocotyledons at Site 2, increasing it from 32 to 65 plants m^{-2}. At Site 2 the density of annual and monocotyledonous species in unfertilised plots of TRFRE and TRFSU was higher compared to fertilised plots, in contrast to LOTCO and MEDTR, thus explaining the significant interaction.

5.4.3 Impact of cover crop and fertilisation on yield of winter wheat

At both sites, significant differences in the soil cover and manure application affected the grain yield of wheat (Table 5.5). Compared to NOWEED, wheat yields in the living mulches were reduced by at least 70 % (Site 1) and 60 % (Site 2) (Table 5.6). Grain yields of winter wheat at Site 2 were higher compared to Site 1 in all treatments except LOTCO. Grain yields were lowest with MEDLU (33 kg ha^{-1}) at Site 1 and with LOTCO (357 kg ha^{-1}) at Site 2. At Site 2 yields of MEDTR and MEDLU were similar to NAT and significantly higher than TRFRE B, TRFRE M, MEDRI and LOTCO but were not than TRFSU which yielded intermediate. The application of manure significantly improved grain yield in living mulch treatments by 270 kg ha^{-1} at Site 1 and 326 kg ha^{-1} at Site 2.

Table 5.5. Analyses of variance (ANOVA) of the effects of soil cover (C) and fertilisation (F) on winter wheat grain yield in a winter wheat/ living legume mulch system.

Factor	Site 1	Site 2
C	*	***
F	***	*
F x C	ns	ns

*, *** significant at the 0.05, 0.001 probability levels, respectively; ns, not significant.

Table 5.6. Effects of soil cover and fertilisation on grain yield of winter wheat grown in a winter wheat/ living legume mulch system.

Factor	Level	Grain yield Site 1	Grain yield Site 2
		kg ha^{-1}	
Soil cover	NOWEED [1]	2729 [3]	4887
	NAT	814 a [4]	1892 a
	MEDTR	662 a	2037 a
	TRFSU	357 a	1570 ab
	MEDRI	349 a	1114 bc
	TRFRE B	330 a	1018 bc
	LOTCO	463 a	357 d
	MEDLU	33 b	1895 a
	TRFRE M	303 ab	908 c
Fertilisation	M0 [2]	251 b	1121 b
	M1	521 a	1447 a

[1] LOTCO, *Lotus corniculatus*; MEDLU, *Medicago lupulina*; MEDRI, *Medicago rigidula*; MEDTR, *Medicago truncatula*; NAT, treatment with site-specific weed community; NOWEED, weed-free treatment; TRFRE B, *Trifolium repens* cv. Barbian; TRFRE M, *Trifolium repens* cv. Milo; TRFSU, *Trifolium subterraneum*

[2] M0, treatment without manure; M1, treatment with manure

[3] In order to detect differences in the soil covers NOWEED was not included in the analyses.

[4] For the same factor and parameter, means followed by different letters differ significantly ($P < 0.05$) according to pair-wise *t*-tests.

5.5 DISCUSSION

With the higher biomass of the cover crop at Site 1 compared to Site 2, better suppression of weeds was expected (Table 5.2). Due to the site-specific weed populations, it is impossible to interpret the differences between the sites and cover crops. As MEDTR died over winter and covered the soil only for a short period during vegetation of the main crop (Feil & Liedgens, 2001), MEDTR is not considered to be a living mulch for winter wheat cropping. Even if the differences in the many components of the biomass were quite large, the statistical test did not show significant differences, not even for the large differences between TRFRE M or LOTCO and MEDTR. This is due to the considerable variability of the data, possibly a consequence of the increased complexity of the living mulches (Vandermeer, 1989) and the uneven distribution of weeds (Froud-Williams *et al.*, 1983). An indication of this is the ratio of the standard deviation and the mean, which was 0.23 for the NOWEED treatment and 0.49 for the LOTCO treatment at Site 1 for the wheat biomass at anthesis. Although the sampling area was almost three times larger than the area sampled by White and Scott (1991), it must be even larger or the number of replications must be increased in order to manage the variability. A reduction of weed biomass by legume cover crops has been reported in the majority of the intercropping publications reviewed by Liebman and Dyck (1993). Although our results show a similar trend, confirmation for monocotyledonous and dicotyledonous weeds was not possible because of the above-mentioned high variability.

Even if TRFSU produced the least biomass of the hardy living mulches, it considerably reduced the weed biomass compared to NAT or MEDTR. It was reported elsewhere that MEDTR is more sensitive and TRFSU less sensitive to frost than other cover crops, depending, however, on the age and the variety of the cover crop (Brandsæter *et al.*, 2000; Brandsæter *et al.*, 2002). TRFRE M generally provided the most successful weed control but also competed strongly with the winter wheat. Therefore, TRFRE M is not recommended as a cover crop in a living mulch system with winter wheat and is probably also unsuitable with other small-grain crops under similar environmental and management conditions as described in the current study. Without appropriate cover crop management, LOTCO, which had an even higher biomass production by the time of wheat anthesis compared to TRFRE M, is also not recommended for living mulches. In both cases, canopy density was reduced due to strong competition at early stages and this reduction was even greater because of lodging of the main crop caused by the continuous growth of the cover crops until wheat maturity. However, strategies for managing cover crops, which suppress weeds without suppressing the main crop, must be identified.

MEDTR did not reduce weed density, while TRFRE M, TRFSU, and LOTCO reduced it considerably (Table 5.4). As observed by Teasdale (1996), too, complete weed suppression was never observed, even with the most competitive cover crop (TRFRE M). To prevent infestation of weeds in spring, the soil must be covered until the main crop can prevent weed germination by shading (cf. Brandsæter & Netland, 1999). The sometimes less successful suppression of weeds by TRFSU compared to TRFRE M is in agreement with the findings of Brandsæter and Netland (1999).

The density of monocotyledons was influenced similarly by all hardy cover crops, while the density of dicotyledonous weeds in TRFSU was higher than the density in the other hardy legumes and lower than that in the non-hardy legumes. Like Clements and Donaldson (1997) we found a limited occurrence of dicotyledonous weeds in living mulches; in contrast to their findings, however, monocots, too, were not especially problematic in our study. The reason might be that the stands were dense and no tillage was practised before seeding, because tillage would have allowed grasses from the seed-bank to germinate and fill the empty spaces before the recovering legumes or winter wheat began to compete successfully with weed species (Bergkvist, 2003b). The density of summer or autumn germinating weeds was not influenced by the cover crops. However, due to the later sowing at Site 2, the seeding operation might have controlled weed seedlings and reduced their density compared to Site 1 (Table 5.4). In line with Fisk *et al.* (2001), the density of perennial weeds was not decreased by cover crops at Site 2. However, the higher weed density at Site 1 resulted in a marginally significant suppression of perennials by TRFRE M compared to NAT. Successful suppression of annual weeds by hardy legume mulches occurred in accordance with the results of previous studies (Fisk *et al.*, 2001) and may be a consequence of their low seed weight and their sensitivity to shade (Mohler, 1996; Barberi, 2002).

In order to prevent seed formation in arable crops in organic farming systems, the weed suppressing ability of the cover crop should be completed and a systematic approach implemented. Mechanical interference (e.g. cutting the cover crop) may be a possibility. Mechanical control of cover crops not only reduces its biomass, but also hinders the development of dicotyledonous weed species (Hiltbrunner *et al.*, 2002) as a result of their lower density. A compromise between adequate weed suppression and growth of the main crop may be achieved by identifying optimal combinations of cutting height and frequency of the cover crops. On the other hand, adjusting the technique and rates of seeding of the main crop as well as the right choice of cultivar may enable the establishment and development of more and stronger wheat plants (cf. White & Scott, 1991).

Grain yield of the weed-free plots (NOWEED) was comparable with the yields of organic farming systems in Switzerland (Maeder *et al.*, 2002) but was greatly reduced by all the legume mulches, which was also reported by others (cf. White & Scott, 1991; Jones & Clements, 1993; Bergkvist, 2003b). In contrast to a living mulch with maize, in which the effective control of the cover crop early in the season is feasible and in which the maize shoot dominates the cover crop, it is assumed that, in the present system, not only root competition for nutrients and water (Liedgens *et al.*, 2004), but also shoot interactions (Teasdale & Mohler, 1993; Lotz *et al.*, 1997) explain the lower biomass and, consequently, the lower grain yield of the main crop. Hence, the advantages of the environmentally friendly living mulch are often at the expense of the main crop and the productivity of the whole system during the winter wheat season. However, considering the whole year, biomass may be higher in the living mulch system, because, at the time of wheat harvest, the cover crop plants are well established and probably have reached full growth potential. The higher wheat yield at Site 2 might be due in part to the inherent fertility of the soil (Table 3.1) compared to Site 1. Furthermore, the later sowing of the cover crops at Site 2 and the resulting decrease in growth (Table 5.2) may have reduced competition with the main crop, resulting in higher yields of most of the living mulches too (Table 5.6). This was clear in treatments with MEDLU as the cover crop. Since the grain yield in MEDTR was higher among living legume mulches, the importance of weak competition during tillering is obvious (Bergkvist, 2003b); it is similar for winter wheat in traditional organic farming systems (Welsh *et al.*, 1999).

Farmyard manure led to an increase in the biomass at anthesis (Table 5.2) and in the grain yield of wheat (Table 5.6), also observed by Jones and Clements (1993) when the supply of N was moderate. This may be due in part to the relatively greater competitive ability of the wheat plants in relation to the other components of the cropping system: in contrast to wheat, manure did not cause a significant increase in the biomass of the cover crops and the weeds. The expected tendency may not have been significant due to the above-mentioned variability in the data. Nevertheless, the application of farmyard manure is, therefore, a reasonable way of increasing the competitiveness and the yield of winter wheat. A decrease in the biomass of legume cover crops in fertilised plots may result in a better establishment of weeds. This would be of importance, if the competitiveness of the main crop did not increase at the same time. At Site 1, the competitiveness of the main crop was increased under fertilisation and - although biomass of the cover crop was reduced - resulted in an unchanged weed density.

5.6 CONCLUSIONS

Legume living mulches, which produce high biomass (i.e. *T. repens* and *L. corniculatus*), suppressed weeds the best. Nevertheless, none of the living mulches suppressed weeds completely. Hardy legumes successfully controlled annual, spring-germinating, monocotyledonous and dicotyledonous weed species. However, these cover crops also competed strongly with winter wheat and reduced the grain yield. Non-hardy legume mulches are unsuitable for weed control in winter wheat crops unless additional measures are taken in spring. The biomass of the annual legume *T. subterraneum* was smaller compared to the other hardy cover crops. Nevertheless, weed control was still satisfactory. Due to its self-reseeding, it has the additional advantage that the soil cover regenerates, comparable to perennial cover crops.

Moderate fertilisation with manure, as practised in the present study, did not stimulate the growth of weeds. However, it improved the competitiveness of the main crop, as reflected in superior grain yields.

Based on these results, we hypothesise that the adoption of living legume mulches in small-grain cropping systems depends on identifying a suitable combination of cover crop genotype and companion weed control means, with the aim of maintaining the ability of cover crops to suppress weeds and reduce competition with the main crop at early growth stages.

6 EFFECTS OF ROW SPACING AND LIQUID MANURE ON DIRECTLY DRILLED WINTER WHEAT IN ORGANIC FARMING *

6.1 ABSTRACT

Plant distribution is a key factor for optimising grain yield and quality of wheat. At moderate yield levels, an increase in the distance between rows did not lead to a decrease in the grain yield; this is in contrast to high yield levels. To gain information about changes in quality and yield linked to changes in row spacing in organic farming systems, experiments were conducted at two sites in the Swiss midlands in 2001/ 2002. Winter wheat (*Triticum aestivum* L.) was directly drilled in rows which were 0.1875 and 0.3750 m apart at the same seeding rate per area. An unfertilised treatment was compared with a treatment with the usual application of 60 m^3 ha^{-1} of liquid farmyard manure. While wider row spacing did not reduce the grain yield, the thousand kernel weight and the grain protein content increased from 42.6 to 43.5 g and from 11.7 to 12.7 % respectively, compared to the narrow row spacing. On average, liquid manure raised the yield (from 3725 to 4765 kg ha^{-1}) and the grain protein content (from 12.0 to 12.5 %) at both experimental sites. Doubling the space between the rows, from 0.1875 to 0.3750 m, seems to be a good strategy for managing directly drilled winter wheat in organic farming systems.

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6.2 INTRODUCTION

At adequate density, the yield of uniformly distributed crop plants can be optimised by suppressing weeds (Johri *et al.*, 1992; Weiner *et al.*, 2001) and deploying nutrients. Decreasing the space between the rows, from 0.200 to 0.064 m, increased the grain yield of winter wheat by 5 to 16 % in a number of experiments in northeastern USA (Frederick & Marshall, 1985; Joseph *et al.*, 1985; Marshall & Ohm, 1987; Johnson *et al.*, 1988). A similar yield increase was found in Switzerland when the row spacing was decreased from 0.222 to 0.125 m (Furrer, 1965). These effects of row spacing are not restricted to temperate climates, however. In the Midwest of the USA (Koscelny *et al.*, 1990) and in semi-arid regions of Australia (Doyle, 1980) the grain yield of wheat increased with decreasing distance between the rows. In both temperate (Mülle & Heege, 1981) and continental (Tompkins *et al.*, 1991) climates the linear negative correlation between an increase in row spacing and grain yield is assumed to occur by increasing the space from 0.1 to 0.2 m (temperate climate) and from 0.09 to 0.36 m (continental climate).

It is generally accepted that the yield increases when the rows are narrowly spaced (distance between rows is similar to distance between plants in row) compared to the yield when the rows are more widely spaced (distance between rows is much greater than distance between plants in row) (Holliday, 1963; Epplin *et al.*, 1992). Some studies, however, do not support this findings. For example, in the Canadian prairies (Lafond, 1994; McLeod *et al.*, 1996; Lafond & Gan, 1999), in the Midwest of the USA (Crabtree & Rupp, 1980) and in Ontario (Canada) (Teich *et al.*, 1993) the yield did not decrease when the row spacing was increased from 0.10 to 0.36 m, from 0.50 to 0.75 m, or from 0.1 to 0.2 m, respectively. The yields were different in these regions, whereas those reported by Teich *et al.* (1993) are comparable to those reported for organic farming systems in Switzerland (Maeder *et al.*, 2002).

Yield components (density of ears, kernels per ear and thousand kernel weight (TKW)) vary when crops are planted in different spatial arrangements because the latter affect the morphology and development of the plants (Marshall & Ohm, 1987; Johnson *et al.*, 1988). Therefore, cereals grown in widely spaced rows may compensate for the lower density of heads and, thus, produce yields similar to the moderate yields of cereals grown with narrow row spacing (Lafond, 1994). However, the variability in the yield response to row spacing depends to a great extent on the genotype and the environment (Marshall & Ohm, 1987).

In central Europe the row spacing varies from 0.12 to 0.18 m for wheat and most small-grain cereal crops. However, in organic farming systems, the distance between the rows is often up to 0.50 m in order to facilitate mechanical weed control.

There is still a lack of information about the way in which a wider inter-row space affects the quantitative and qualitative yield of wheat in organic farming systems in a humid, temperate climate. Therefore, the aim of this study was to determine whether greater distances between rows, with and without diluted liquid manure, influence the development and yield of directly drilled winter wheat under organic farming conditions in the Swiss midlands, in contrast to conventional (narrow) row spacing.

6.3 *MATERIAL AND METHODS*

6.3.1 Treatments and experimental design

This chapter focuses on the change in row spacing (RS1, RS2) at two nutrient levels (M0, M1) in the wheat monocrop (NOWEED) (Table 4.1). Since the focus is on selected treatments, the experimental design of the basic experiment changes and the statistical analyses are based on a split plot design.

6.3.2 Sampling and analysis of plants

The number of winter wheat plants and shoots per m^2 were determined on an area of 0.5 m^2 at stages 13 (20 November 2001) and 29 (13 February 2002), according to the BBCH scale (Lancashire *et al.*, 1991). At the final harvest (stage 89; 24 July 2002 at Site 1 and 27 July 2002 at Site 2), the ear density was measured twice on an area of 0.5 m^2. To determine the shoot biomass on 28 February (stage 29), 4 April (stage 31) and 12 June (stage 65) in 2002, plants were cut at ground level on an area of 0.5 m^2; at stage 89, the ears were cut at ground level from an area of 1.0 m^2. The dry matter was measured after drying the samples to constant weight. At maturity, the ears were threshed in the laboratory (Saatmeister, Kurt Pelz, Bad Godesberg, Germany). The dry matter of the seeds was determined and the seeds were counted by a numigral seed counter (Chopin SA, Villeneuve-la-Garenne, France). The thousand kernel weight was calculated from the seed weight and the number of kernels. The grains were ground with a Cyclotec Tecator 1093 (Tecator AB, Sweden) and analysed for total N with a LECO CHN-1000 auto analyser (LECO Corporation, St. Joseph, MI, USA). The content of grain protein was calculated by multiplying the N concentration by 5.7 (Williams, 1984).

6.3.3 Data analysis

One-way analyses of variance (ANOVA) were performed using the Proc Mixed of the SAS® program package 8.0 (Littell *et al.*, 1996). Because of significant interactions between the sites and treatments, separate statistical analyses were performed for each site; replication was set as a random factor.

6.4 RESULTS

6.4.1 Sites

The analyses of variance showed that the application of manure had a greater effect on most parameters at Site 1 than at Site 2 (Tables 6.1 and 6.2). The row spacing significantly affected the wheat biomass at anthesis and the protein content in the grains.

Table 6.1. Analyses of variance (ANOVA) of the effects of row-system (RS) and fertilisation (F) on canopy density and shoot biomass of winter wheat.

		Canopy density			Shoot biomass			
Site	**Factor**	**stage 13**	**stage 29**	**stage 89**	**stage 29**	**stage 31**	**stage 65**	**stage 89**
1	**RS**	†	ns	ns	ns	ns	*	ns
	F			ns		†	**	***
	F x RS			†		ns	ns	ns
2	**RS**	ns	*	ns	ns	ns	*	ns
	F			ns		ns	†	ns
	F x RS			ns		ns	ns	ns

†, *, **, *** significant at the 0.1, 0.05, 0.01, 0.001 probability levels, respectively; ns, not significant.

Shoot biomass, grain yield, harvest index (HI), thousand kernel weight (TKW), kernels ear^{-1} and grain protein content were higher at Site 2 than at Site 1 (Tables 6.3 and 6.4). The rate of plant establishment, calculated from the seeding rate and the plant density at stage 13, was 71 % at Site 1 and 78 % at Site 2. At this stage, the plant density of RS2 was 28 % higher at Site 2 than at Site 1, in contrast to the RS1 plots where the plant density was comparable at both sites (Table 6.3). By the time the wheat reached maturity, there were 90 ears m^{-2} more at Site 2 than at Site 1. Although the density of the canopy in early spring was similar at both sites, the shoot biomass at Site 2 was twice as high as that at Site 1, which resulted in an average biomass of the single shoot of 65.5 mg at stage 29 (end of tillering) at Site 2 but only 36.0 mg at Site 1. By the harvest (stage 89) the average biomass of the single shoot was 3.0 g at Site 1 and 3.2 g at Site 2. Other yield-determining factors were also higher, and this resulted in an increase of 44 % in grain yield at Site 2 compared to Site 1.

Table 6.2. Analyses of variance (ANOVA) of the effects of row-system (RS) and fertilisation (F) on grain yield, harvest index (HI), thousand kernel weight (TKW), kernels ear^{-1}, grain protein content and protein yield of winter wheat.

Site	Factor	Grain yield	HI	TKW	Kernels ear^{-1}	Grain protein	Protein yield
1	RS	ns	ns	*	ns	*	†
	F	***	*	†	*	ns	***
	F x RS	ns	ns	ns	ns	ns	ns
2	RS	ns	ns	ns	ns	**	†
	F	ns	ns	†	ns	*	ns
	F x RS	ns	ns	ns	ns	ns	ns

†, *, **, *** significant at the 0.1, 0.05, 0.01, 0.001 probability levels, respectively; ns, not significant.

6.4.2 Effect of row spacing

In late autumn 2001 (stage 13), row spacing did not have a significant effect on plant density at either site (Table 6.3). However, there tended to be more plants on the RS1 plots than on the RS2 plots at Site 1. At the end of tillering (stage 29), the canopy density on the RS1 plots was 35 % higher than on the RS2 plots at Site 2. More tillers on the RS1 plots degenerated, and, by maturity, there were no significant differences in the density of the ears between the two treatments. At anthesis (stage 65), the shoot biomass was significantly higher in RS2 compared to RS1 by 19 and 13 % at sites 1 and 2, respectively. The average tiller weight of the mature wheat increased significantly from 3.1 to 3.3 g as a result of the greater row space at Site 2, while at Site 1 the effect of the increase from 2.8 to 3.1 g was insignificant. Grain yield, harvest index (HI), the number of kernels ear^{-1} and protein yield were not significantly affected by the distance between the rows (Table 6.4). When the

Table 6.3. Density of plants, tillers and ears and the shoot biomass as affected by row spacing and fertilisation at two sites at different times of the year.

			Canopy density			Shoot biomass			
Site	Factor	Level	stage 13	stage 29	stage 89	stage 29	stage 31	stage 65	stage 89
			plants m^{-2}	tillers m^{-2}	ears m^{-2}	kg ha^{-1}			
1	Row-system	RS1 [1)]	290	589	326	216	821	8327 b	9155
		RS2	241	563	317	206	949	9950 a	9950
	Fertilisation	M0 [2)]			297		705	6731 b	7319 b
		M1			346		1065	11546 a	11786 a
2	Row-system	RS1	279	777 a [3)]	409	437	1179	10320 b	12854
		RS2	308	577 b	415	421	1164	11648 a	13613
	Fertilisation	M0			398		1152	9934	12346
		M1			426		1191	12034	14121

[1)] RS1, narrow row spacing (0.1875 m); RS2, wide row spacing (0.3750 m).
[2)] M0, treatment without manure; M1, treatment with manure.
[3)] Means followed by different letters differ significantly ($P < 0.05$) according to pair-wise t-tests on same date and for same factor.

distance between the rows was increased, the concentration of grain protein increased significantly from 12.4 to 13.2 % at Site 2; at Site 1, there was an increase in both the TKW (from 41.6 to 42.6 g) and the protein content of the grain (from 11.1 to 12.2 %).

6.4.3 Effect of diluted liquid manure

By the harvest, the density of the ears on the unfertilised plots (348 tillers m^{-2}) was not significantly lower than the density of the ears on the fertilised plots (386 tillers m^{-2}) (Table 6.3). At Site 1 fertilisation significantly increased the shoot biomass at anthesis (stage 65) (from 6731 to 11546 kg ha^{-1}) and by maturity (stage 89) (from 7319 to 11786 kg ha^{-1}). At Site 2, only a marginally significant increase was observed at stage 65. The average tiller weight of the mature wheat increased significantly from 2.5 to 3.4 g as a result of fertilisation at Site 1, while at Site 2 the increase from 3.1 to 3.3 g was insignificant. Furthermore, the grain yield, kernels ear^{-1} and HI were significantly influenced at Site 1 only. Fertilisation resulted in an increase in grain yield (49 % at Site 1 and 15 % at Site 2) and kernels ear^{-1} (23 % at Site 1 and 4 % at Site 2) (Table 6.4). In contrast to the HI, which decreased significantly from 38.1 to 35.4 % at Site 1, the TKW and protein content generally increased at both sites as a result of the manure. Whereas the TKW did not change significantly at either site, the protein content increased significantly at Site 2 (from 12.4 to 13.1 %), in contrast to Site 1 (p = 0.448). The protein yield increased at both sites, though the increase was significant only at Site 1. Interactions between row spacing and fertilisation with manure were not significant for any of the studied parameters at either site.

Table 6.4. Grain yield, harvest index (HI), thousand kernel weight (TKW), kernels ear^{-1}, grain protein content and protein yield as affected by row spacing and fertilisation at two sites.

Site	Factor	Level	Grain yield	HI	TKW	Kernels ear^{-1}	Grain protein	Protein yield
			- kg ha^{-1} -	-- % --	-- g --	-- no. --	-- % --	- kg ha^{-1} -
1	**Row-system**	**RS1** [1)]	3349	36.9	41.6 b	24.8	11.1 b	376
		RS2	3601	36.6	42.6 a	26.3	12.2 a	442
	Fertilisation	**M0** [2)]	2795 b	38.1 a	41.6	22.9 b	11.5	323 b
		M1	4156 a [3)]	35.4 b	42.6	28.2 a	11.8	495 a
2	**Row-system**	**RS1**	4901	38.3	43.6	27.4	12.4 b	607
		RS2	5129	37.8	44.5	27.8	13.2 a	680
	Fertilisation	**M0**	4656	38.0	43.3	27.0	12.4 b	582
		M1	5374	38.1	44.8	28.2	13.1 a	705

[1)] RS1, narrow row spacing (0.1875 m); RS2, wide row spacing (0.3750 m).
[2)] M0, treatment without manure; M1, treatment with manure.
[3)] Means followed by different letters differ significantly ($P < 0.05$) according to pair-wise t-tests on same date and for same factor.

6.5 DISCUSSION

6.5.1 Sites

According to the official organic farming trials in Switzerland (2001 and 2002), the average grain yield of the variety Titlis is 4270 kg ha^{-1} (M. Menzi, FAL Zürich-Reckenholz, personal communication). The yields in this experiment are, therefore, comparable to on-farm yields under local conditions, although 28 % more kernels m^{-2} were seeded in the official trials than in the present experiment. The yields are also similar to the average yield in organic farming systems in Switzerland (Maeder *et al.*, 2002). The higher grain yield at Site 2 than at Site 1 is due mainly to the higher number of ears m^{-2} (Table 6.3), the higher single shoot biomass at wheat maturity and the higher TKW (Table 6.4).

6.5.2 Effect of row spacing

The coefficient for tillering was similar in the RS1 and RS2 treatments at Site 1; at Site 2, however, the tillering coefficient was much higher in RS1 than in RS2 (Table 6.3). In general, the greater competition in the row of the RS2 treatments compared to the RS1 treatments had a negative effect on tiller formation until stage 29 (Holliday, 1963; Frederick & Marshall, 1985). Later fewer tillers m^{-2} had degenerated in RS2 by the time wheat reached maturity and no differences between the ears m^{-2} in RS1 and RS2 were observed, which is in agreement with some of the findings for wheat cultivars of Marshall and Ohm (1987) but in contrast to the findings of Johnson *et al.* (1988).

The increase in shoot biomass tended to be higher in RS2 than in RS1 at later than at earlier growth stages until the flowering of wheat (stage 65) (Table 6.3). By flowering in the RS2 treatment the shoot biomass was significantly higher, indicating, that resources for plant growth were better used for plant biomass.

Similar to findings in continental climates (Crabtree & Rupp, 1980; Lafond, 1994; McLeod *et al.*, 1996) and in a temperate climate (Teich *et al.*, 1993), a change in grain yield was not significant when the distance between the rows was larger (Table 6.4). At the moderate yield level in the present experiment, the grain yield tended to be slightly higher in RS2. The seeding rates in this study were not increased in the RS1 treatments; thus, the potential for higher yields when high seeding rates are combined with RS1 was probably not exhausted (Marshall & Ohm, 1987).

A higher TKW in RS2 compared to RS1 has been found for other wheat cultivars (Marshall & Ohm, 1987). However, in that study, it was lower than the average of this variety in the official tests. This may have been due to the unusually high temperatures in June and the rather low precipitation during the grain filling period (Spiertz & Devos, 1983). The higher TKW and the slightly higher number of kernels ear^{-1} accounted for the insignificant yield increase in the RS2 treatment, which indicates that negative effects of a low canopy density on grain yield may be partially compensated at later developmental stages. When the space between the rows was increased, the grain protein content increased significantly at both sites; the values were similar to those of the official tests under organic farming conditions (Table 6.4). However, an increase in the distance between the rows leads to an 8.5 % rise in grain protein, which is quite considerable. The increase in protein content may have been caused by the increase in shoot dry weight in RS2 compared to RS1, as determined at flowering of wheat. Later, more nutrients were stored and translocated from the vegetative parts to the grains; reported values vary from 30 to 50 % (cf. Spiertz & Ellen, 1978). Another explanation may be the availability of nutrients in the greater inter-row space during the grain filling period (anthesis to maturity) in RS2 compared to RS1 (Baeumer, 1992; Lafond, 1994); the low precipitation in the summer of 2002 diminished the risk of nutrients being leached from the larger inter-row space. Since the protein yield ha^{-1} of the RS2 plots tended to be higher than the protein yield ha^{-1} of the RS1 plots, the availability and uptake of N were not limiting factors in this experiment.

6.5.3 Effect of diluted liquid manure

The effect of mineral fertiliser on grain and protein yield as well as on protein content is well documented (Hunter & Stanford, 1973; Johnson *et al.*, 1973; Fowler *et al.*, 1989a; Fowler *et al.*, 1989b) and is supported by our observations with manure. The greater effect of manure on shoot biomass and on most of the yield-determining factors may be due to some extent to the greater supply of N (121 kg ha^{-1} N_{tot}) at Site 1 than at Site 2 (95 kg ha^{-1} N_{tot}). On the other hand, the average yield was higher at Site 2 than at Site 1 (Table 6.4). The diminishing marginal return of N with increasing yield may, therefore, also have contributed to the weaker effect of the manure. The yield increase as a result of fertilisation was associated with an increase in all the yield components: number of ears m^{-2}, TKW and number of kernels ear^{-1} (Baeumer, 1992). As expected, the manure improved the grain protein content (Johnson *et al.*, 1973), although quantitatively to a lesser extent than the difference between RS1 and RS2; this was more distinct at Site 2 than at Site 1. However, fertilisation had, quantitatively, a greater impact on grain and protein yield ha^{-1} than increasing the space between the rows. The average shoot weight of the mature wheat increased as a result of fertilisation. Therefore, as discussed for the effect of row spacing, the greater capacity for storing nutrients in the shoots of plants of fertilised plots may have contributed to the significant increase in the grain protein content (cf. Spiertz & Ellen, 1978). The difference in the average shoot weight of the fertilised and the unfertilised treatments was higher at Site 1 than Site 2, and the protein increase was more distinct at Site 2 than at Site 1. Thus, in addition to the storage capacity of nutrients in the shoot, other factors, such as the root system, may be as important for the N uptake and the protein production.

Before the manure was spread, the average tiller biomass in early spring was comparatively low at Site 1. The low density of the winter wheat canopy, especially at Site 1, combined with the low biomass of the tillers in the spring probably led to a decrease in the final yields and may explain the differences with regard to Site 2. This is also obvious from the significant positive correlation of grain yield with tiller biomass in early spring ($r = 0.82$) and with the number of tillers at maturity ($r = 0.85$). Therefore, to obtain good grain yields of winter wheat, it is important that healthy, well-developed shoots form by the end of the winter.

6.6 CONCLUSIONS

When the seeding rates were the same, an increase in the distance between the rows (from 0.1875 to 0.3750 m) did not lead to a decrease in the yield or quality of the grain (e.g. TKW and protein content) of winter wheat under organic farming conditions. To some extent, an increase in the space between the rows tended to increase the yield (by increasing TKW) and quality (by increasing protein content) of the grain. As expected, the application of liquid manure increased the grain yield through an increase in the TKW and the number of kernels ear^{-1}; the grain protein content also increased.

Since N is often limited in organic farming systems, sources of N other than manure must be found. In particular, living mulch systems with legume cover crops might be a possibility for importing additional N into the soil and, at the same time, for controlling weeds and reducing soil erosion.

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7 IMPACT OF LIVING LEGUME COVER CROPS ON WEEDS IN ORGANIC WHEAT FARMING

7.1 ABSTRACT

To gain information about the impact of legume cover crops on the weed community in a winter wheat/ living mulch system, experiments were conducted at two sites in the Swiss midlands in 2001/ 2002. Winter wheat (*Triticum aestivum* L.) was directly drilled in rows that lay 0.1875 and 0.3750 m apart at the same seeding rate per area as in living mulches consisting of *Trifolium repens* L. (TRFRE), *Trifolium subterraneum* L. (TRFSU), *Medicago truncatula* Gaertner (MEDTR) and *Lotus corniculatus* L. (LOTCO) and in a treatment without legume cover and with the site-specific weeds (NAT). In half of the treatments with wide row spacing the vegetation in the inter-row was mechanically regulated (mulching). An unfertilised treatment was compared with the common application of 60 m^3 ha^{-1} of liquid farmyard manure. Living mulches of TRFRE, TRFSU and LOTCO effectively suppressed e.g. *Poa annua* L. and *Matricaria chamomilla* L. at Site 1 and *P. annua*, *Capsella bursa-pastoris* (L.) Med. and *Stellaria media* (L.) Vill. at Site 2 in contrast to NAT. MEDTR died during winter and hardly suppressed any weeds. Fertilisation had no tangible effect on the weed community. Mulching significantly suppressed *M. chamomilla* at Site 1 and *C. bursa-pastoris* at Site 2 but encouraged *Poa trivialis* L.. In order to maintain the weed suppressing ability without creating temporal spaces for weeds to germinate, the routine use of legume cover crops as living mulches depends on the development of strategies which allow for its adequate tending.

7.2 INTRODUCTION

In organic farming systems, herbicides are not applied, and weed control is, for the most part, done mechanically. However, the repeated disturbance due to intense soil tillage prevents the build-up and/ or the maintenance of a stable soil structure (Tebrügge & Düring, 1999). Furthermore, soils left bare after tillage operations are prone to erosion (Rüttimann, 2001). Hence, there is a dilemma as to whether to reduce soil tillage or to use herbicides.

The transition from conventional farming systems to organic farming as well as the adoption of conservation tillage, of which no-tillage is the most extreme form, leads to a change in the weed community. In both organic farming and conservation tillage, perennials may be a problem if ploughing is shallow (organic farming) or when anemochore and monocotyledonous species are promoted (no-tillage) (Buhler, 1995; Streit *et al.*, 2002). In both systems, the establishment of weeds should be strictly avoided to decrease the necessity of weed control. A systematic approach may be more promising than concentrating on a single method (Barberi, 2002) and would also increase long-term practicability (Bond & Grundy, 2001).

The strict control of weeds is the key to the successful and beneficial implementation of no-tillage and organic farming systems. Soil cover between the crop plants has been proposed as an environmentally friendly way of suppressing weeds (Liebman & Dyck, 1993; Teasdale, 1996). Such cover plant species must be easy to control and must conform to living mulches, as defined by Feil and Liedgens (2001). Competition for nitrogen can be reduced by using legumes. Living mulches of *Trifolium repens* L. and *Trifolium subterraneum* L. differ with regard to the suppression of weeds (Enache & Ilnicki, 1990; Abdin *et al.*, 2000). Success depends not only on the cover crop, but also on the weed species (Liebman & Dyck, 1993). Usually however, complete suppression of weeds is not achieved (Teasdale, 1996). As a result, it is necessary to study combinations of main and cover crops for living mulch systems in relation to locally prevailing weed populations and to focus - besides biomass - on diversity and density of weeds as well (Liebman & Dyck, 1993). Attention must be paid to the dynamics of and the change in the weed populations when alternative methods of weed control are implemented (Liebman & Dyck, 1993). Such an investigation would show whether suppressed species lead to a wider variety of problematic weeds.

To date only few investigations of living mulches in a cropping system with small-grain cereals have been carried out. They focussed on the control of the cover crop to optimise yields (White & Scott, 1991; Bergkvist, 2003b). It is surprising that so little information is available about how measures taken to improve crop yield affect weed diversity (Hiltbrunner *et al.*, 2002).

The aim of the present study was to investigate the impact of different legume mulches and main crop management factors on the weed community in a winter wheat/ living mulch system in the Swiss midlands.

7.3 MATERIAL AND METHODS

7.3.1 Treatments and experimental design

This chapter focuses on the impact of six different soil covers (LOTCO, NAT, NOWEED, MEDTR, TRFRE, TRFSU) - at two levels of nutrient supply (M0, M1) and three levels of the row-system (RS1, RS2, RS3) - on the weed community (Table 4.1). Due to a reduction in the number of soil covers, the design of the basic experiment is not changed and statistical analyses are based on a split-strip plot design.

7.3.2 Plant sampling

From 24 to 28 June 2002, the number of weed species and their abundance was assessed within an area of 0.5 m^2 in each sub-plot.

7.3.3 Data analyses

7.3.3.1 Univariate analysis

The effects of the treatments on the number of weed species were determined using the Proc Mixed of the SAS® program package 8.0 (Littell *et al.*, 1996). Due to significant interactions between the site and other factors, the analyses were performed separately for each site. Replication (block) was set as a random factor. Means were separated by pair-wise *t*-tests ($p < 0.05$) when the *F*-tests were significant at $p < 0.05$.

7.3.3.2 Multivariate analysis

The impact of the environmental variables (soil cover, fertilisation, row-system) on the weed community was determined by ordination by means of the redundancy analysis (RDA) and partial RDA with CANOCO for Windows, version 4.51 (Ter Braak & Smilauer, 2002). Since the weed communities at both sites were very different, they were analysed separately. The linear ordination methods (principal component analysis [PCA] and RDA) were chosen, because a preliminary detrended correspondence analysis (DCA) resulted in a short gradient length at Site 1 (2.2 SD) and Site 2 (2.6 SD) (Leps & Smilauer, 2003). The objective of RDA is to maximise predictions for a set of response variables Y (species data), given a set of factor variables X (environmental data). The method is essentially a PCA, in which the sampling unit scores of the response variable set are restricted to linear combinations of the factor variable set (Kenkel *et al.*, 2002). The significance of the environmental variables is assessed by Monte Carlo testing (bootstrapping) of the axis associated with these variables, using the axis eigenvalue as the test statistic (Ter Braak & Smilauer, 2002). In line with the experimental design, replications were set as covariables and defined as blocks. Partial RDA was used to decompose the variance explained by each of the environmental variables separately, after eliminating the variation due to the other variables and interactions by defining them as covariables.

To display the data, diagrams were produced with CanoDraw for Windows 4.1 (Ter Braak & Smilauer, 2002). Based on RDA, the diagrams consist of biplots showing the linear correlations between the species and the environmental variables (Ter Braak, 1994). As the environmental variables (soil covers on five levels) are qualitative (dummy variables), they appear as centroids of the site points belonging to the five levels. Since row-system, fertilisation and the interactions only contributed a low fraction of the variance, two ordination diagrams (for both sites), based on the model with the five soil cover treatments, are presented.

In addition, a t-value biplot can be used to approximate the t-values of the regression coefficients, which would be obtained from a multiple regression with a particular species being the response variable and the environmental variables the predictors (Ter Braak & Looman, 1994). Species encircled by the Van Dobben circles for a particular explanatory variable are significantly affected, either positively or negatively (Ter Braak & Looman, 1994). Significant effects of environmental variables on weed species were taken from t-value biplots.

7.4 RESULTS

Six monocotyledonous and 19 dicotyledonous species were identified at Site 1 and six monocotyledonous and 21 dicotyledonous species at Site 2 (Table 7.1). The most common species at Site 1 were *Poa annua* L., *Lolium multiflorum* L. and *Matricaria chamomilla* L. and at Site 2, *P. annua, L. multiflorum* and *Capsella bursa-pastoris* (L.) Med..

Compared to the other living mulches, MEDTR died during the winter; therefore only few plant residues were left on the soil surface in spring. Some of the oldest leaves of TRFSU died off during the winter, but TRFSU recovered quickly in early spring. The analysis of variance showed that the number of weed species was significantly affected by the soil cover, while no influence of the row-system was observed (Table 7.2). The effect of manure was significant at Site 1 only.

Table 7.1. Species (and their abbreviations (Bayer code)) at two sites (June 2002).

	Bayer code	Scientific name	Site 1	Site 2
Annual monocotyledonous species	apesv	*Apera spica-venti* (L.) P.B.	x	
	lolmu	*Lolium multiflorum* Lam.	x	x
	poaan	*Poa annua* L.	x	x
	trzsp	*Triticum spelta* L.		x
Perennial monocotyledonous species	dacgl	*Dactylis glomerata* L.	x	x
	holla	*Holcus lanatus* L.	x	
	phlpr	*Phleum pratense* L.		x
	poatr	*Poa trivialis* L.	x	x
Annual dicotyledonous species	aphar	*Aphanes arvensis* L.	x	
	capbp	*Capsella bursa-pastoris* (L.) Med.	x	x
	cergl	*Cerastium glomeratum* Thuill.		x
	chepo	*Chenopodium polyspermum* L.	x	
	cldar	*Calendula arvensis* L.		x
	gaete	*Galeopsis tetrahit* L.		x
	galap	*Galium aparine* L.		x
	gasci	*Galinsoga ciliata* (Rafin.) Blake		x
	gerdi	*Geranium dissectum* Juslen.	x	x
	lapco	*Lapsana communis* L.	x	x
	match	*Matricaria chamomilla* L.	x	
	medlu	*Medicago lupulina* L.		x
	myoar	*Myosotis arvensis* (L.) Hill	x	x
	sonss	*Sonchus* spp. [1)]	x	x
	steme	*Stellaria media* (L.) Vill.		x
	verar	*Veronica arvensis* L.	x	
	vioar	*Viola arvensis* Murr.	x	x
Perennial dicotyledonous species	cicin	*Cichorium intybus* L.	x	
	lotco	*Lotus corniculatus* L.	x	
	medsa	*Medicago sativa* L.	x	
	plala	*Plantago lanceolata* L.	x	x
	plama	*Plantago major* L.	x	x
	ranre	*Ranunculus repens* L.		x
	rorsy	*Rorippa sylvestris* (L.) Bess.		x
	rumcr	*Rumex crispus* L.	x	
	rumob	*Rumex obtusifolius* L.	x	x
	tarof	*Taraxacum officinale* Weber in Wiggers	x	x
	trfpr	*Trifolium pratense* L.		x
	trfre	*Trifolium repens* L.	x	x

[1)] Including perennial species.

The weed community was most diverse with NAT, where the highest number of species was found at both sites (Table 7.3). Differences between NAT and MEDTR were not observed, while LOTCO and TRFRE - (when) compared to NAT - significantly reduced the number of weed species from 5.9 to 3.3 and 3.1 species m^{-2} at Site 1 and from 4.6 to 2.4 and 1.5 species m^{-2} at Site 2.

Table 7.2. Analyses of variance (ANOVA) of the effects of soil cover (C), row-system (RS) and fertilisation (F) on number of weed species at two sites (June 2002).

Factor	Site 1	Site 2
C	**	***
RS	ns	ns
RS x C	ns	ns
F	*	ns
F x C	ns	†
RS x F	ns	ns

†, *, **, *** significant at the 0.1, 0.05, 0.01, 0.001 probability levels, respectively; ns, not significant.

The application of manure increased the number of weed species from 3.9 to 4.4 m^{-2} at Site 1, while no effect was observed at Site 2 (Table 7.3). The row-system did not have a significant effect on number of species, resulting in an average of 4.1 species m^{-2} at Site 1 and 3.1 species m^{-2} at Site 2.

Table 7.3. Mean number of weed species as affected by soil cover and fertilisation in a winter wheat/ living mulch system at two sites (June 2002).

Factor	Level	Site 1	Site 2
		Number of weed species m^{-2}	
Soil cover	NAT [1)]	5.9 a [3)]	4.6 a
	MEDTR	4.8 a	4.4 a
	TRFSU	3.5 ab	2.6 b
	LOTCO	3.3 b	2.4 b
	TRFRE	3.1 b	1.5 c
Fertilisation	M0 [2)]	3.9 b	3.2
	M1	4.4 a	3.0

[1)] LOTCO, *Lotus corniculatus*; MEDTR, *Medicago truncatula*; NAT, site-specific weed community; TRFRE, *Trifolium repens*; TRFSU, *Trifolium subterraneum*.
[2)] M0, treatment without manure; M1, treatment with manure.
[3)] For the same factor and site, means followed by different letters differ significantly ($P < 0.05$) according to pair-wise *t*-tests.

Based on the redundancy analysis (RDA), the investigated factors and their interactions explained 78.5 % of the total variance in the composition of the weed community at Site 1 and 84.3 % at Site 2 (sum of the "SS" without residuals and blocks, Table 7.4). Soil cover explained more than 50 % of the variance at both sites. Row-system explained another 2.0 % of the variance at Site 1 and 12.8 % at Site 2, while the effect of fertilisation was fairly weak and not significant. The non-significant effect of fertilisation allowed for the pooling of the data of both nutrient levels. Of the interactions of the studied factors, only soil cover x row-system was significant at Site 2.

Table 7.4. Decomposition of the variance in the weed species data obtained by redundancy analysis (RDA). Sum of squares (SS) are expressed as percentage of total variance in the species data (df, degrees of freedom; *P*-value, Monte Carlo significance level, 499 permutations) at two sites.

		Site 1			Site 2		
Source	**df**	**SS**	**F-ratio**	***P*-value**	**SS**	**F-ratio**	***P*-value**
Block	2	2.6	1.155	0.326	1.0	0.424	0.816
Soil cover (C)	4	69.9	55.363	0.002	50.8	29.211	0.002
Row-system (RS)	2	2.0	3.247	0.002	12.8	14.691	0.002
Fertilisation (F)	1	0.3	0.833	0.520	0.6	1.478	0.212
C x RS	8	3.2	1.328	0.094	16.0	7.516	0.002
C x F	4	1.1	0.846	0.682	1.4	0.607	0.848
RS x F	2	0.4	0.180	0.964	0.8	0.370	0.836
C x RS x F	8	1.6	0.624	0.962	1.9	0.960	0.550
Residual	58	18.9			14.7		
Total	*89*	*100.0*			*100.0*		

In the ordination diagrams, based on a model without interaction terms, 99.6 and 99.5 % of the variance is displayed through the soil cover at sites 1 and 2 respectively (Figures 7.1 and 7.2). To interpret the correlations between the species and a given environmental variable in the biplot, the environmental variable point is projected onto the species arrows by a perpendicular line (MEDTR and poaan, Figure 7.2). If the projection point is on the same side of the origin as the direction indicated by the species' arrow, then the species is encouraged by the environmental variable. In contrast, projection points on the other side of the origin indicate that the species is suppressed by the environmental variable (TRFRE and poaan, Figure 7.2). It is shown that 20 of 25 species at Site 1 (Figure 7.1) and 16 of 27 species at Site 2 (Figure 7.2) are on the same side of the origin as NAT, meaning that they were encouraged by this treatment. *P. annua* (poaan), *M. chamomilla* (match) and *Plantago major* L. (plama) were most positively associated with NAT at Site 1, while at Site 2 the most positively associated species in NAT were *C. bursa-pastoris* (capbp), *Trifolium repens* L. (trfre) and *P. annua* (poaan). Similar to NAT, many of the species in MEDTR were encouraged at sites 1 (20) and 2 (17). This is in contrast to TRFRE, TRFSU and LOTCO, to which a maximum of 11 species were positively associated at both sites (Figures 7.1 and 7.2).

Nevertheless, among the tested living mulches only two weed species were significantly encouraged in TRFRE at Site 1 according to the t-value biplot analysis (Table 7.5). At Site 1 legume mulches of TRFRE, TRFSU and LOTCO, which survived the winter, significantly suppressed *P. annua* (poaan), *M. chamomilla* (match) and *P. major* (plama) compared to NAT, while at Site 2 they suppressed *P. annua* (poaan), *C. bursa-pastoris* (capbp) and *Cerastium glomeratum* Thuill. (cergl) (Table 7.5). Furthermore, TRFRE and LOTCO also suppressed *Stellaria media* (L.) Vill. (steme). Although MEDTR no longer covered the soil after winter, it still suppressed some weed species significantly, but fewer compared to the hardy living mulches. Living mulch of TRFRE suppressed most weed species at both sites.

According to the t-value biplot analysis, the row-system did not have a consistent effect on weed species at both sites. For example, at Site 1, *C. bursa-pastoris* (capbp) and *L. multiflorum* (lolmu) were significantly encouraged in the RS1 treatment compared to RS2, in contrast to Site 2 where no weed species were significantly encouraged in RS1 (Table 7.5).

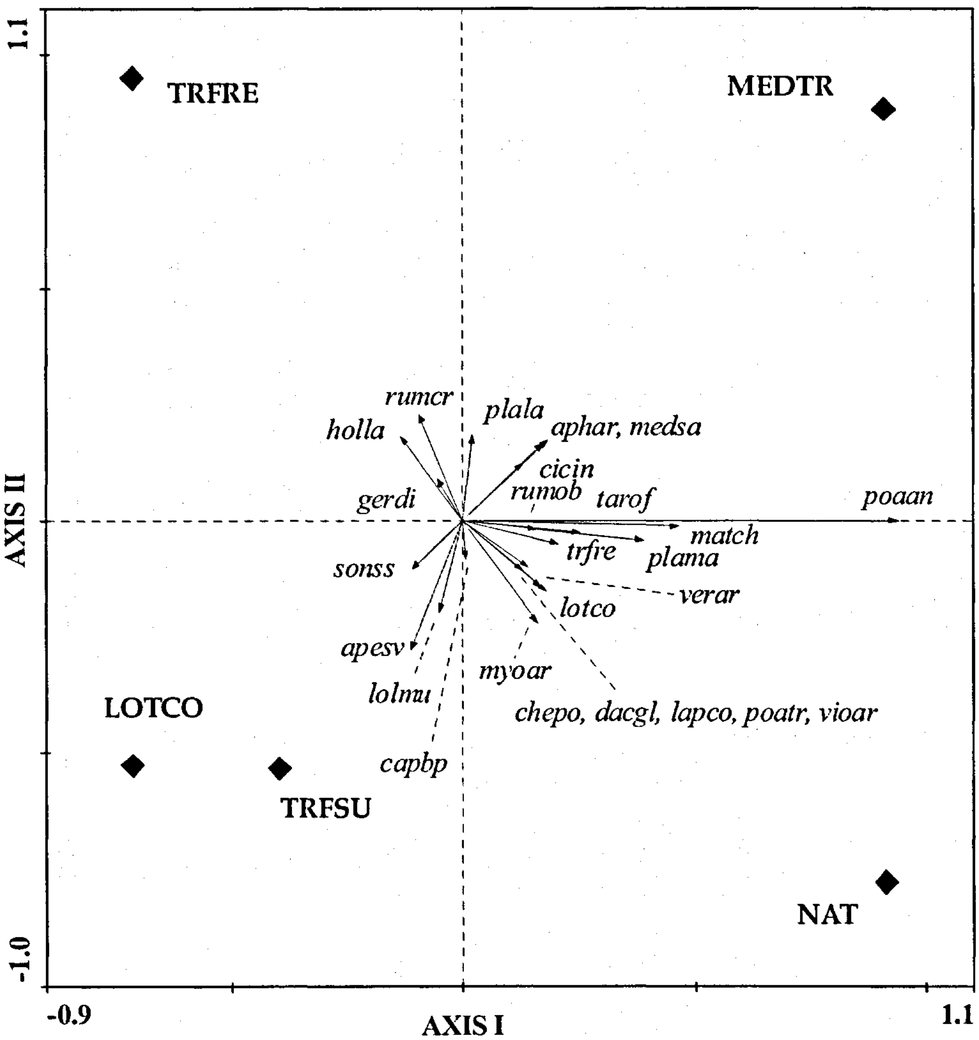

Figure 7.1. RDA-based ordination diagram (= correlation biplot) of weed species in a winter wheat crop cultivated in five soil covers (environmental variables): LOTCO, *Lotus corniculatus;* MEDTR, *Medicago truncatula;* NAT, site-specific weed community; TRFRE, *Trifolium repens*; TRFSU, *Trifolium subterraneum*. Site 1 (June 2002). Eigenvalues of the first three axes are 0.691, 0.004, and 0.002. The abbreviations of the species are given in Table 7.1.

Poa trivialis L. (poatr) was encouraged by RS3 at both sites compared to RS2. However, the most frequent dicotyledonous species at sites 1 (*M. chamomilla*) and 2 (*C. bursa-pastoris*) were effectively suppressed in RS3 compared to RS2. Considering the combined effect of soil cover and row-system, weed communities were significantly influenced by a change in row-system in TRFSU at both sites and in MEDTR and NAT at Site 2, while in TRFRE and LOTCO there was no significant change in the weed community when the row-system was changed (Table 7.5).

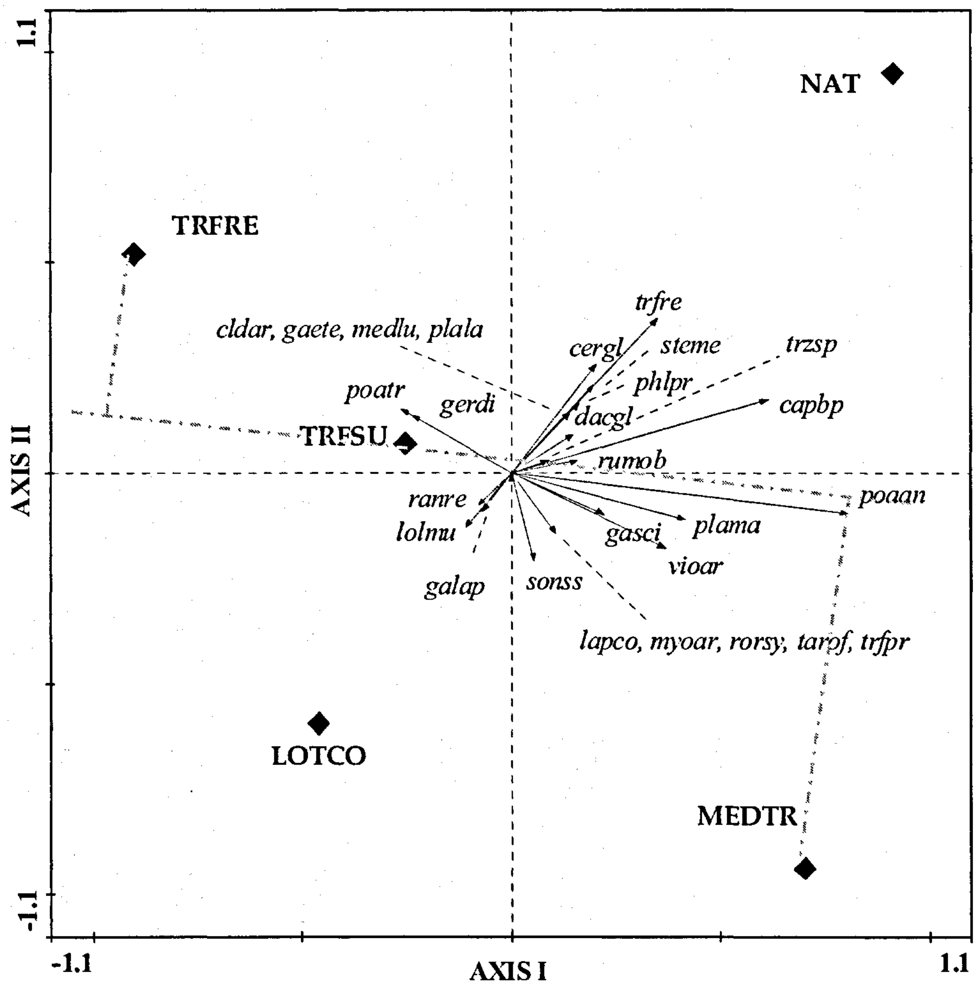

Figure 7.2. RDA-based ordination diagram (= correlation biplot) of weed species in a winter wheat crop cultivated in five soil covers (environmental variables): LOTCO, *Lotus corniculatus;* MEDTR, *Medicago truncatula;* NAT, site-specific weed community; TRFRE, *Trifolium repens;* TRFSU, *Trifolium subterraneum.* Site 2 (June 2002). Eigenvalues of the first three axes are 0.484, 0.021, and 0.002. The abbreviations of the species are given in Table 7.1.

Table 7.5. Significantly encouraged or suppressed weed species evaluated from t-value biplots as a result of soil cover, row-system, and combinations of both in winter wheat/ living mulch systems at two sites (June 2002).

Factor	Level	Site 1		Site 2	
		encouraged	suppressed	encouraged	suppressed
Soil cover (C)	NAT [1)]	ref. [3)]	ref.	ref.	ref.
	MEDTR	-	apesv	-	capbp, trfre, cergl
	TRFSU	-	poaan, match, plama	-	poaan, capbp, trfre, cergl
	LOTCO	-	poaan, match, plama	-	poaan, capbp, trfre, steme, cergl, phlpr
	TRFRE	holla, rumcr [4)]	poaan, match, plama, lotco, myoar, verar	-	poaan, capbp, plama, vioar, steme, cergl, (trfre)
Row-system (RS)	RS1 [2)]	capbp, lolmu	rumcr	-	cergl
	RS2	ref.	ref.	ref.	ref.
	RS3	poatr, plama	match, rumcr	poatr, poaan, phlpr, trfre	capbp
C*RS	NAT RS1	-	-	-	-
	NAT RS2	ref.	ref.	ref.	ref.
	NAT RS3	-	-	-	capbp, plama
	MEDTR RS1	-	-	-	capbp
	MEDTR RS2	-	-	-	capbp
	MEDTR RS3	-	-	-	capbp, plama
	TRFSU RS1	-	poaan, plama	-	capbp, poaan, plama
	TRFSU RS2	-	poaan, plama	-	capbp, poaan
	TRFSU RS3	-	poaan	-	capbp, plama
	LOTCO RS1	-	poaan, match	-	capbp, poaan, plama
	LOTCO RS2	-	poaan, match	-	capbp, poaan, plama
	LOTCO RS3	-	poaan, match	-	capbp, poaan, plama
	TRFRE RS1	-	poaan, match	-	capbp, poaan, plama
	TRFRE RS2	-	poaan, match	-	capbp, poaan, plama
	TRFRE RS3	-	poaan, match	-	capbp, poaan, plama

[1)] LOTCO, *Lotus corniculatus*; MEDTR, *Medicago truncatula;* NAT, treatment with site-specific weed community; TRFRE, *Trifolium repens;* TRFSU, *Trifolium subterraneum.*

[2)] RS1, narrow row spacing (0.1875 m); RS2, wide row spacing (0.3750 m) without mechanical inter-row regulation; RS3, wide row spacing (0.3750 m) with mechanical inter-row regulation.

[3)] Reference within the factor. Effects of other levels are analysed in relation to this level.

[4)] The abbreviations of the species are given in Table 7.1.

7.5 *DISCUSSION*

At both sites, the number of weed species in the non-hardy MEDTR was similar to that found in NAT (Table 7.3). In contrast, hardy legume mulches controlled weed species much better, although differences among them were also observed. The stronger effect of hardy legumes on the suppression of weeds compared to MEDTR could be seen at the number of weed species (univariate analyses) and at the weed community (multivariate analyses). Even though most of the species that were significantly suppressed were annuals, some perennials were also suppressed (Table 7.5). Most of the suppressed species were dicotyledonous weeds, which made up the major part of the weed community. As observed by others (Clements & Donaldson, 1997; Bergkvist, 2003b), monocotyledons and especially *P. annua* established in most legumes. In this study, they still were significantly reduced by hardy legumes and did not cause severe problems. Monocotyledons (*P. trivialis*) predominated mainly when mulching was applied and after living mulches were successfully established. As observed by Bergkvist (2003b), the application of soil tillage before the seeding of the main crop can greatly reduce the competition of the living mulch with the main crop but results in a very considerable increase in the number of weeds. Therefore, special care must be taken in the management of living mulch (shallow soil tillage, mulching interval, mulching depth) and its interaction with the environment in order to guarantee that the ability of the ground cover to suppress weeds is not lost. In most cases, cover crops with high biomass production suppressed weeds most efficiently (Zink & Hurle, 1990; Liebman & Dyck, 1993). Complete weed suppression, however, was not observed in any living mulch; even in TRFRE, which suppressed most weeds, some weed species were always able to establish (cf. Teasdale, 1996) (Figures 7.1 and 7.2). The two species encouraged in TRFRE at Site 1 were perennials, which are difficult to control without herbicides and tillage; thus, the adequate seeding time and the management of the cover crops for living mulch purposes may be important to guarantee the successful prevention of germination and the suppression of perennial weeds in particular. Other researchers also found that TRFSU was less effective than TRFRE in suppressing weeds (Theunissen, 1997; Brandsæter & Netland, 1999). This was probably due to morphological differences in the two species, including hardiness, which in turn cause different levels of competition in early spring (Brandsæter *et al.*, 2000; Brandsæter *et al.*, 2002). Since better weed suppression by TRFRE was accompanied by strong competition with the main crop, the advantages of better weed control were set off by a lower grain yield (cf. chapter 5). Nevertheless, biomass produced before wheat seeding is important for weed suppression. It is necessary that this suppression - which is influenced not only by the species (Ilnicki & Enache, 1992), but also by the age of the cover crop (Brandsæter *et al.*, 2000; Brandsæter *et al.*, 2002) - continues. The lack of photosynthetically active leaf area of the cover crop may result in a slow development in spring - a development which mainly depends on resources from the roots - and thus enabling more weeds to become established.

Although changes in the row-system did not influence number of weed species per m^2, effects on the weed community were observed but they differed at both sites (Table 7.5). Mulching suppressed dicotyledonous and annual weed species to a greater extent than perennial weeds. The influence of the row-system was more distinct in treatments with heterogeneous plant populations, i.e. MEDTR and NAT, also resulting in a significant interaction of cover crop and row-system at Site 2 (Table 7.4). As observed by Ross *et al.*

(2001), a successful suppression of the dicotyledonous species brown mustard (*Brassica juncea* (L.) Czern.) by cover crops was sometimes enhanced by mowing, but this enhancement depended on the site and the cover crop. A change in the prevailing conditions in a living mulch system - by mechanical interference or the use of a different cover crop species - may have a selective suppression effect (Liebman & Dyck, 1993). If these suppressed species are lacking, the weed community may react differently to a change in management and as a result, an increase in other species, as a consequence of more favourable growing conditions, is possible. Although 15 of the identified species occurred at both sites (Table 7.1) the fact that some species were not suppressed at one of the sites can not necessarily be attributed to the inability of the cover crop to suppress weeds but rather be determined by the remaining species, the site, and their interactions. The weed suppressing effect of some living mulches may therefore have site-specific (= weed community-specific) character (Ross *et al.*, 2001). The change in row space and fertilisation had hardly any effect in this study; thus, competition between the cover crop and the weed community was much more important in determining the weed community. Nevertheless, the above mentioned management operations may have a stronger effect on the weed community at another site.

According to the classification of Landolt (1977) species that occur chiefly on rich soils (mainly N) were found at both sites (e.g. *L. multiflorum*, *Rumex* spp., *Galeopsis tetrahit* L., *Sonchus* spp., *Galium aparine* L.). Although at Site 1 the number of weed species per m^2 was increased as a result of fertilisation (Table 7.3), multivariate analyses did not reveal a significant effect on the weed community or on individual species (Table 7.4). The competition for light and space by cover crop plants might have been stronger for the weeds than the competition for plant nutrients supplied by manure.

7.6 CONCLUSIONS

Legume cover crops which are similarly competitive and produce similar amounts of biomass, suppress the same weed species. The change in the weed community, however, is site-specific. Legume mulches, which die during the winter in our climate (e.g. MEDTR) provide insufficient weed control. In general, TRFRE provided the best weed suppression; TRFSU, which was less prolific and has a shorter life cycle, controlled weeds satisfactorily and no mulching was required to reduce its competitiveness with the main crop. Under the experimental conditions, TRFSU is considered to be the most suitable legume living mulch, combining adequate weed suppression with the least competition with winter wheat. As mulching not only completed weed suppression of the living mulches but also encouraged some weed species, cover crop management must be improved to retain the benefit of weed suppression by the living mulch, without favouring problematic weeds, especially perennials, which are difficult to control without herbicides and without soil tillage.

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8 NITROGEN YIELD AND NITROGEN CONCENTRATION OF WINTER WHEAT (*TRITICUM AESTIVUM* L.) IN A WHITE CLOVER (*TRIFOLIUM REPENS* L.) LIVING MULCH

8.1 ABSTRACT

The import of nitrogen into low-input cropping systems can be raised by increasing the occurrence of legume species in the crop rotation, for example by growing the crop together with a living legume mulch. Experiments were conducted at two sites in the Swiss midlands in 2001/ 2002. Winter wheat (*Triticum aestivum* L.) was drilled directly in 0.3750 m wide rows, in a bare soil (NOWEED) and in a living mulch of white clover (*Trifolium repens* L.) (TRFRE). The living mulch was regulated mechanically (mulched) in half the treatments. An unfertilised treatment was compared with a treatment with 60 m^3 ha^{-1} of farmyard manure. The N concentration of wheat grains and straw increased in TRFRE compared to NOWEED from 2.2 to 2.7 % (grains) and 0.3 to 0.5 % (straw) respectively. Due to the lower tiller density in TRFRE, however, the biomass of winter wheat was lower than in NOWEED; thus, the N yield of winter wheat was generally lower at both sites. Nevertheless, the total N yield in the above-ground biomass (winter wheat and living mulch) of TRFRE (122 kg ha^{-1}) was similar to or higher than that of NOWEED (99 kg ha^{-1}) at Site 1. The reverse was true at Site 2 where on average the total N yield of TRFRE was 111 kg ha^{-1} and that of NOWEED 145 kg ha^{-1}. In treatments with TRFRE, both mulching (at both sites) and fertilisation (Site 2 only) increased the biomass of wheat and, as a result, the N yield of wheat compared to the wheat grown in TRFRE without mulching or fertiliser respectively. Since the N concentration in wheat grown in TRFRE was higher than in NOWEED, N was not the most limiting resource; thus, the yield potential of winter wheat in the living mulch system was not reached.

8.2 INTRODUCTION

Due to a bare soil and the use of agrochemicals, conventional cropping practices may lead to a loss of nutrients and pesticides through leaching and run-off (Stoate *et al.*, 2001). Both low-input and organic farming systems may help to solve these problems when the plant nutrient supply is sufficient of plant nutrients for the development of the crop in order to attain an adequate crop yield. In such farming, therefore, it is important that the available resources, especially nitrogen (N), are utilised fully (Watson *et al.*, 2002).

The sowing of a main crop into a living soil cover, also referred to as a living mulch (Masiunas, 1998; Leary & DeFrank, 2000; Feil & Liedgens, 2001; Hartwig & Ammon, 2002), has been proposed as an environmentally safe cropping strategy. In living mulches, however, plants may compete with the main crop for smaller amounts of available soil resources. Water (Fujita *et al.*, 1992; Hartwig & Ammon, 2002) and N (Garibay *et al.*, 1997; Hartwig & Ammon, 2002) are usually the main limiting factors.

Thus far, the yields of small-grain cereals in living mulches have, for the most part, been disappointing (White & Scott, 1991; Clements *et al*, 1995; Bergkvist, 2003b). To achieve high-quality cereals in organic farming, not only the choice of cultivar and the level of N fertilisation (Johnson *et al.*, 1973), but also the use of legume cover crops may prove to be a suitable tool.

There are various mechanisms by which a cover crop can influence the N availability and, therefore, the grain quality of the main crop in a living mulch (Feil & Liedgens, 2001): uptake of N before and after the sowing of the main crop, limited N mineralisation as a consequence of reduced tillage and net immobilisation or mineralisation of N depending on the C/N ratio of the cover crop residues. As the species involved are tapping N from different sources (legume: N_2, non-legume: NO_3^-), competition may be weaker due to niche separation (Vandermeer, 1989). In the case of legume cover crops, N derived from symbiotic N_2 fixation may be transferred directly to a companion crop in the current growing season (direct transfer), or the N in the soil and its availability to the companion non-legume may increase in the current season (indirect transfer) or be transferred to subsequent crops (residual transfer) (Stern, 1993). Reports of direct N transfer in cropping systems other than living mulches are contradictory (Patra *et al.*, 1986; Fujita *et al.*, 1992; Stern, 1993; Dubach & Russelle, 1994; Russelle *et al.*, 1994).

Only little information is available on N relationships in wheat/ living mulch systems (Brandt *et al.*, 1989; Schmidt & Curry, 1999; Bergkvist, 2003a); thus, the allocation of N by the system components must be understood if management strategies leading to stable yields and high quality crops are to be developed. The aim of this study was to verify whether the N concentration of the grain and the total amount of stored N in the kernels and shoots of wheat as well as in the whole system increases in a winter wheat/ living legume mulch compared to a wheat monoculture.

8.3 MATERIAL AND METHODS

8.3.1 Treatments and experimental design

In this chapter the number of treatments of the basic experiment is considerably reduced: Two types of soil cover (NOWEED, TRFRE), two nutrient levels (M0, M1) and two row-systems (RS2 and RS3) are analysed in order to test the according hypotheses (Table 4.1). However, the experimental design remains the same (as in the basic experiment) and analyses are based on a split-strip plot design.

8.3.2 Sampling and plant analysis

Shoot samples were cut at ground level at the time of the physiological maturity of the wheat plants (24 July 2002 at Site 1 and 27 July 2002 at Site 2). The sampling area of each plot of winter wheat was 1.0 m^2 and that of the ground cover 0.5 m^2. The samples were dried to constant weight. The number of shoots was counted before the wheat was separated into grain and straw. The dry weight of all the components was determined. The grains were ground with a Cyclotec Tecator 1093 (FOSS Tecator, Hoganas, Sweden), and the plant material was ground first with a cutting mill (Retsch GmbH & Co. KG, Haan, Germany) then a sub-sample thereof was ground with a Cyclotec Tecator 1093. The determination of the N concentration was conducted with a LECO CHN-1000 auto analyser (LECO Corporation, St. Joseph, MI, USA).

8.3.3 Data analysis

The mass and concentration of N of the sub-samples of wheat and non-wheat biomass were statistically analysed using the Proc Mixed of the SAS® program package 8.0 (Littell *et al.*, 1996). As significant interactions between sites and treatments occurred, the analyses were performed separately for each site. Replication was set as a random factor. To account for the abnormal distribution of the residuals, the statistical analyses of the parameters biomass and wheat density were conducted on square root-transformed data. However, the results are always presented on the original scale. To avoid misinterpreting the means when the interactions of the factors were significant, additional statistical analyses were performed for each factor.

8.4 RESULTS

The results achieved by the analyses of variance of the effects of soil cover, fertilisation, inter-row space management (mulching) and their interactions are listed in the Appendix (chapter 12). The wheat grain yield was significantly higher in NOWEED than in TRFRE (Table 8.1). Without mulching (RS2) very few grains were produced in the unfertilised treatments. By the time wheat reached maturity, the biomass of the non-wheat parameters in TRFRE was quite high, ranging from about 2700 to 5000 kg ha^{-1}, while the weed biomass in NOWEED was usually below 100 kg ha^{-1}. The total biomass was always higher in NOWEED than in TRFRE. In TRFRE mulching decreased the non-wheat biomass, while the wheat biomass increased at both sites. Fertilisation increased the components of the wheat biomass, which led to a significant increase in the total biomass in the NOWEED (Site 1) and the TRFRE (Site 2) treatments.

Table 8.1. Biomass components in bare soil (NOWEED) and living mulch (TRFRE) winter wheat cropping as affected by mulching of cover crops in the inter-row space and by fertilisation.

Biomass components	Soil cover	Site 1				Site 2			
		RS2 [1]		RS3		RS2		RS3	
		M0 [2]	M1	M0	M1	M0	M1	M0	M1
		kg ha^{-1}							
Wheat grain	TRFRE	245 b [3]	619 b	900 b	1427 b	172 b	1100 b	612 b	1487 b
	NOWEED	2765 a	4419 a	2751 a	4232 a	4781 a	5445 a	4326 a	4610 a
Wheat straw	TRFRE	466 b	1043 b	1445 b	2185 b	404 b	1916 b	1284 b	2611 b
	NOWEED	4467 a	8205 a	4563 a	7279 a	7913 a	8952 a	6774 a	7381 a
Non-wheat	TRFRE	4999 a	4196 a	3273 a	3213 a	4222 a	2995 a	3044 a	2740 a
	NOWEED	106 b	48 b	57 b	96 b	138 b	106 b	111 b	75 b
Total	TRFRE	5831 b	5946 b	5773	6846 b	5035 b	6074 b	5117 b	6857 b
	NOWEED	7344 a	12679 a	7387	11608 a	12857 a	14511 a	11221 a	12076 a

[1] RS2, treatment without mulching; RS3, treatment with mulching.
[2] M0, treatment without manure; M1, treatment with manure.
[3] For the same factor and parameter, means followed by different letters differ significantly ($P < 0.05$) according to pair-wise t-tests.

The living mulch significantly reduced the density of wheat in seven of eight cases (Table 8.2). On the other hand, mulching led to a higher wheat density in TRFRE, which was more pronounced at Site 1 than at Site 2, while in NOWEED mulching had no effect. The application of manure increased the density at Site 1 in NOWEED, while at Site 2 the increase in TRFRE was marginally significant.

Table 8.2. Wheat density in bare soil (NOWEED) and living mulch (TRFRE) winter wheat cropping as affected by mulching of cover crops in the inter-row space and by fertilisation.

	Site 1				Site 2			
	RS2 [1]		RS3		RS2		RS3	
Soil cover	M0 [2]	M1	M0	M1	M0	M1	M0	M1
	ears m^{-2}							
TRFRE	84 b [3]	96 b	203	179 b	37 b	132 b	83 b	164 b
NOWEED	270 a	363 a	248	343 a	392 a	436 a	346 a	361 a

[1] RS2, treatment without mulching; RS3, treatment with mulching.
[2] M0, treatment without manure; M1, treatment with manure.
[3] For the same factor and parameter, means followed by different letters differ significantly ($P < 0.05$) according to pair-wise *t*-tests.

In most cases the grain N concentration was significantly higher in TRFRE than in NOWEED (Table 8.3). In general, there was a significant or marginally significant increase in the N concentration of the straw in TRFRE, with the exception of the fertilised treatment without mulching at Site 2. Neither mulching nor the application of manure affected the N concentration of the wheat grains or the straw in NOWEED and TRFRE.

Table 8.3. Nitrogen concentration of wheat components in bare soil (NOWEED) and living mulch (TRFRE) winter wheat cropping as affected by mulching of cover crops in the inter-row space and by fertilisation.

Wheat		Site 1				Site 2			
com-		RS2 [1]		RS3		RS2		RS3	
ponents	Soil cover	M0 [2]	M1	M0	M1	M0	M1	M0	M1
		%							
Grain	TRFRE	2.7 a [3]	2.7 a	2.7 a	2.7	2.7 a	2.7 a	2.6	2.7 a
	NOWEED	2.1 b	2.2 b	2.0 b	2.3	2.3 b	2.4 b	2.3	2.4 b
Straw	TRFRE	0.5 a	0.5 a	0.5	0.5 a	0.6 a	0.6	0.6 a	0.6
	NOWEED	0.3 b	0.3 b	0.3	0.3 b	0.4 b	0.4	0.3 b	0.4

[1] RS2, treatment without mulching; RS3, treatment with mulching.
[2] M0, treatment without manure; M1, treatment with manure.
[3] For the same factor and parameter, means followed by different letters differ significantly ($P < 0.05$) according to pair-wise *t*-tests.

The N yield of the wheat grains was significantly or marginally significantly higher in NOWEED than in TRFRE by the time wheat reached maturity (Table 8.4). The relative difference was much greater at Site 2 than at Site 1. The same was true for the N yield in the straw. When wheat reached maturity, the soil cover contained more than 68 kg N ha^{-1} in TRFRE at both sites and in all treatments, while in NOWEED a maximum of 3.6 kg N ha^{-1} had accumulated in the above-ground biomass of the non-wheat plants. At Site 1, the total amount of N in TRFRE was similar to or higher than in NOWEED, while at Site 2 the results were different: in NOWEED more N was accumulated in total in fertilised treatments without mulching compared to TRFRE.

Table 8.4. Nitrogen yield of the components in bare soil (NOWEED) and living mulch (TRFRE) winter wheat cropping as affected by mulching of cover crops in the inter-row space and by fertilisation.

Com-ponents	Soil cover	Site 1				Site 2			
		RS2 [1)]		RS3		RS2		RS3	
		M0 [2)]	M1	M0	M1	M0	M1	M0	M1
		kg ha^{-1}							
Grain N	TRFRE	7.5 b [3)]	17.1 b	24.3	39.3	5.6 b	30.7 b	17.5 b	40.2 b
	NOWEED	57.7 a	97.3 a	56.6	101.6	108.0 a	130.6 a	98.2 a	110.0 a
Wheat straw N	TRFRE	2.5 b	4.9 b	7.2	11.4 b	3.1 b	10.9 b	7.8	14.9
	NOWEED	13.5 a	26.5 a	13.8	25.6 a	30.5 a	36.3 a	23.3	32.8
Non-wheat N	TRFRE	122.2 a	98.6 a	74.5 a	78.4 a	105.3 a	70.9 a	71.6 a	67.6 a
	NOWEED	2.1 b	0.6 b	0.9 b	1.1 b	3.6 b	2.6 b	3.4 b	1.8 b
Total N	TRFRE	133.1 a	120.8	107.4	129.3	114.4	112.7 b	96.8	123.4
	NOWEED	73.6 b	124.5	71.3	128.3	142.5	169.6 a	125.3	144.8

[1)] RS2, treatment without mulching; RS3, treatment with mulching.

[2)] M0, treatment without manure; M1, treatment with manure.

[3)] For the same factor and parameter, means followed by different letters differ significantly ($P < 0.05$) according to pair-wise *t*-tests.

At Site 1 in TRFRE, mulching (RS3) - compared to the undisturbed treatment (RS2) - resulted in a marginally significant increase in the N yield of the wheat components. As a result of fertilisation, there was an increase in the N yield of the wheat components in NOWEED at Site 1 and in TRFRE at Site 2.

8.5 DISCUSSION

The yield of winter wheat of TRFRE was generally lower than the average wheat yield of NOWEED (Table 8.1). The lower yield of winter wheat drilled directly into a white clover living mulch was also found by others (White & Scott, 1991; Clements *et al.*, 1995; Bergkvist, 2003b). The yield reduction in TRFRE was due not only to the low wheat density (Table 8.2), but also to the fact that fewer kernels per ear formed in TRFRE than in NOWEED. Although the N concentration in the wheat grains and the straw increased in TRFRE (Table 8.3), the N yield of the wheat grains did not increase when compared to NOWEED. The expected reduction caused by the lower yield of wheat was, at least in part, compensated by the higher concentration of N in the grains in TRFRE than in NOWEED, a result also found by others under certain conditions (Brandt *et al.*, 1989; Bergkvist, 2003a) (Table 8.4). In this study, the concentration of N in the wheat grains was higher, probably due to the variety used, than the one found by Bergkvist (2003a) and Brandt *et al.* (1989), who reported a concentration of 1.5 %. The slightly higher yield in the experiments of Bergkvist (2003a) compensated for the lower N concentration, thus resulting in similar N yields. If we assume that even at early growth stages N was taken up by the plants and then translocated to the grains (Spiertz & Ellen, 1978), N was probably not the most limiting factor responsible for the low canopy density (White & Scott, 1991; Bergkvist, 2003a). The canopy density was low and the living mulch consisted of a legume; thus, the competition for N was always much weaker. In addition, Bergkvist (2003a) found that the amount of inorganic N in the soil increased in the living mulch systems but not in systems where wheat was grown on a bare soil. Since the wheat density and thus the biomass were lower in TRFRE than in NOWEED, the amount of required N also decreased. Competition in the wheat row until the end of tillering (Welsh *et al.*, 1999; Bergkvist, 2003a) probably caused the lower density of the wheat canopy in the living mulch, either through a lower rate of plant establishment or a lower tillering coefficient, which could not be remedied later by mulching or fertilisation. Since the number of grains per unit area was determined in spring, more N was available for each grain. Whether the increase in the N concentration is due to N transfer from the legume, to limited demand of the legume, or to the low wheat tiller density has yet to be determined.

The lack of an effect of mechanical regulation of the inter-row space on the main crop yield (Site 2) was also reported by Bergkvist (2003a). There are two possible explanations. The disturbance of the white clover was probably insufficient or was spatially restricted and, thus, did not have a positive effect on the wheat crop. Another explanation may be that the regulation occurred too late to have a positive effect on the yield. However, in a maize crop, stronger control of the living mulch increased the amount of stored N in the main crop, mainly due to the higher dry matter production (Garibay *et al.*, 1997).

Fertilisation of the main crop can stimulate wheat growth and reduce the biomass of the living mulch (White & Scott, 1991). Although this was observed at Site 2 only, where the cover crops were seeded later than at Site 1, fertilisation greatly reduced the N yield of the cover crop in treatments without mulching (Table 8.4). As a result, the total N yield in RS2 was the same or lower in TRFRE in fertilised treatments compared to unfertilised treatments. Considering that approximately 45 % of the total N supplied with the manure was available to the main crop in the year of the application (Walther *et al.*, 2001), the difference in the total N yield between M0 and M1 in NOWEED at Site 1 is explained by the uptake of N from the manure. This is in contrast to NOWEED at Site 2 and to TRFRE with mulching at both sites where only some of the N in the manure was reflected in the difference of the total N yield between M0 and M1. In treatments, in which the cover crop was not mown, fertilisation seemed to have no effect on the total N yield in the above-ground biomass. This was probably due to the high proportion of legumes, which was not affected by fertilisation. The legumes were already well developed and the small number of weak wheat plants would have had little effect on the total N yield even if biomass production had increased due to fertilisation.

Nevertheless, the management of the main crop changed the competition between the main and the cover crop to the benefit of the main crop: Fertilisation at Site 2 and mulching at Site 1 led to a higher wheat density by wheat maturity, possibly through better shoot survival (Table 8.2). As a result, the biomass of the grains and the straw also increased; to some extent, the legume cover crops were suppressed (Table 8.1). Since we found no effect of fertilisation or mulching on the N concentration of the wheat components, the increase in the biomass similarly increased the N stored in the above-ground biomass. Therefore, the increase in the N stored in the grains was influenced more by the grain biomass than by the slight changes in the N concentration, as also observed by Brandt *et al.* (1989).

Although in NOWEED the production of above-ground biomass was always higher than in TRFRE, at Site 1 the total N yield was similar or even higher in TRFRE than in NOWEED, while at Site 2 the reverse was true (Table 8.4). Since legumes have a higher N concentration in the biomass than wheat, the total N yield of a system may increase with the increasing proportion of legumes in the living mulch. As a result, in the unfertilised treatment of TRFRE of unmown cover crops at Site 1, the total N in the above-ground biomass was higher than in NOWEED but was not higher than in the other treatments. Over a year, the total amount of N incorporated in the plant biomass in a living mulch would probably be higher than in the wheat monocrop; after the harvest of the wheat, the legume plants continue to grow and to fix N. Even if N accumulated in this way is not reflected in the short run in the wheat grains, as in this experiment, a considerable amount of N is stored in the biomass of the legumes and is available to the subsequent crop. If this biomass is left on the field it may influence the long-term fertility of the soil.

8.6 CONCLUSIONS

Since the N concentration of the wheat straw and grains in a living white clover mulch (TRFRE) was significantly higher than in wheat grown in a bare soil (NOWEED), N was not the most limiting factor and the grain yield potential in the living mulch systems was not reached. If properly managed, mulching and fertilisation can increase the competitiveness and the yield of the main crop. The comparison of NOWEED and TRFRE at the wheat harvest shows that the total N yield of the above-ground biomass is comparable in both systems, although this is at the expense of grain yield in the living mulch. Due to the lower tiller density and, thus, the lower yield of wheat in a living mulch, the N yield of the wheat was also considerably reduced. Therefore, seeding techniques must be improved to enable the establishment of more plants and eliminate competition in the intra-row space. Whether a living white clover mulch increases the grain N concentration, also at higher yield levels, has yet to be determined.

9 GENERAL DISCUSSION AND CONCLUSIONS

The main objective of this study was to test different legume cover crops with regard to their weed suppressing ability in a living mulch system with winter wheat (chapters 5 and 7). As hypothesised, the tested cover crops showed different effects on weed biomass, density and community as it had also been observed by Liebman and Dyck (1993) and Ross *et al.* (2001) for some species. Hardy legume cover crops suppressed weeds efficiently in contrast to the non-hardy cover crop (*Medicago truncatula* Gaertner), because decomposing residues led to a decrease in the suppressive ability and to altered soil conditions (Teasdale & Mohler, 1993) which in turn allowed weeds to germinate in spring, an effect which was also observed elsewhere with other non-hardy cover crops (Zink & Hurle, 1990; Teasdale, 1996). In agreement with Fisk *et al.* (2001), an increase in the biomass of the cover crop led, in general, to a the better suppression of weeds. Among the hardy species, *Lotus corniculatus* L. and *Trifolium repens* L. suppressed weeds most efficiently and in many cases better than *Trifolium subterraneum* L., an effect also observed by Brandsæter and Netland (1999) and Enache and Ilnicki (1990). On the other hand, competition with the main crop was strongest for the above mentioned hardy cover crops and supports the finding by White and Scott (1991) and by Bergkvist (2003b) that *T. repens* has the potential to cause serious yield depressions. With *T. subterraneum* as cover crop, grain yield was higher and weed suppression still quite successful compared with *L. corniculatus* and *T. repens*. The differences at both study sites allowed to infer that the weed suppressive ability of the cover crops also depends on the weed community as described by Liebman and Dyck (1993) and Teasdale (1996) and therefore is site specific (Ross *et al.*, 2001). It is concluded that *T. subterraneum* was, among the tested cover crops and management operations, the best suited for controlling weeds in winter wheat canopies.

The risk that weeds establish in annual hardy cover crops which are dying before the harvest of winter wheat was inversely proportional to the biomass of cover crops that remained after the various management operations in the different treatments had been conducted (Zink & Hurle, 1990). However, an intense weed emergence during the ripening of the main crop may be potentially harmful to the following crop in no tillage systems under organic farming conditions. This risk may be minimised by the use of perennial or self-reseeding cover crop species which guarantee the existence of a renewed living, weed suppressing soil cover before the harvest of wheat. Such cover crops contribute to the controlling of the weeds during the most crucial period of their management: the time between the ripening of the current crop and the time when the subsequent crop is thus far developed that it is able to suppress the weeds on its own. This period of time also includes the phase where weak competition with the main crop is necessary in order to obtain good yields of the main crop (Welsh *et al.*, 1999). The establishment of living mulches just before the sowing of the main crop (Brandsæter *et al.*, 1998) or the undersowing of cover crops later in the growing season of the main crop (Ohlander *et al.*, 1996) may reduce the competition with the main crop, but may also result in little weed suppression during the season of the main crop. The cover crop develops faster in relation to the weeds which hinders the germination of weeds as the soil is quickly covered (Zink & Hurle, 1990). Hence, the successful control of weeds in living mulches depends on biomass production before the main crop seeding, on the life cycle and on the early vigour of the cover crop (Liebman & Dyck, 1993).

If the focus lies on weed control only, cover crops in living mulches may be considered an adequate tool, as frequently proposed (Enache & Ilnicki, 1990; Ilnicki & Enache, 1992; Liebman & Dyck, 1993; Fisk *et al.*, 2001) and already shown under different circumstances (Ilnicki & Enache, 1992; Jones & Clements 1993; Liebman & Dyck, 1993; Garibay *et al.*, 1997; Fisk *et al.*, 2001; Hartwig & Ammon, 2002).

Another important objective of this study was to characterise the impact of various crop and cover crop management strategies on the development of weed populations (chapter 7) and winter wheat (chapters 6 and 8). Mulching of the cover crops had a greater impact on weed populations than fertilisation or the distance of the inter-row space of the wheat crop. As already observed in earlier studies, mulching can complete the weed suppressing effect of cover crops by reducing the density of dicotyledonous weed species (Ross *et al.*, 2001; Hiltbrunner *et al.*, 2002) but can also, as shown in the present study, favor monocotyledons. It is known that the different cover crops tested in the present study require different cutting intervals and heights as best management practices (e.g. *T. repens* vs. *L. corniculatus*). The design of the present experiments did not allowed for this distinction, however. Therefore, in some treatments mulching did not complement the cover crops' weed suppressivity but harmed the cover crop while e.g. in *T. repens* the growth of the cover crop was stimulated and generally a dense stand resulted. Nevertheless, at Site 1 which showed a very dense living mulch, conditions for the germination of *Rumex crispus* L. were favourable as well and *R. crispus* could not be suppressed afterwards by *T. repens* anymore. Inappropriate management of living mulches may result in uncovered patches where weeds, or in general plants which require light to germinate, may establish themselves and occupy the empty spaces (e.g. *Poa annua* L., *Poa trivialis* L., *Rumex* spp., *Taraxacum officinale* Weber in Wiggers) and therefore influence the composition of the flora (Clements *et al.*, 1995; Teasdale, 1996); a phenomenon also known from meadow studies (Dietl, 1986; Lehmann *et al.*, 1994; Dietl, 1997). Thus it is hypothesised that heavy infestation of weeds (mainly monocotyledons) reported from other living mulch studies (Clements *et al.*, 1995; Bergkvist, 2003b) occurred mainly when the management of the cover crops was not taking into account the needs of the cover crops in terms of their weed suppressing ability and when the seed bank contained seeds to germinate and occupy the empty spaces. Hence, the hypothesis that mulching in the inter-row space suppresses weeds in general, can only be confirmed in part.

As already observed in other experiments (White & Scott, 1991; Jones & Clements, 1993; Clements *et al.*, 1995; Hiltbrunner *et al.*, 2002; Bergkvist, 2003b), the wheat density and the grain yield are greatly reduced in the living mulch treatments when no other means are applied. To check the suitability of wider inter-row spacings, which in living mulch systems would facilitate mechanical regulation, and thus, reduce the competitive effect of the cover crop on the main crop, a complementary analysis of a wheat monocrop was conducted (chapter 6). In accordance with other studies at various row space distances, the increase of the inter-row space from 0.1875 to 0.375 m did not reduce the grain yield (Crabtree & Rupp, 1980; Teich *et al.*, 1993; Lafond, 1994; McLeod *et al.*, 1996; Lafond & Gan, 1999), but improved protein content and thousand kernel weight. An effect of the same magnitude was achieved by the use of farmyard manure. The wheat yield level in the present study was higher than in most of the studies which support these findings. Although wheat varieties with the potential for high protein contents, which are required for high quality bread wheat, are available in Switzerland (Menzi *et al.*, 2004), it is important to reap this benefit without an input of high amounts of fertiliser. Especially for organic and low input farming systems where the inadequate availability of N caused by the limited supply results in an unsatisfactory crop yield and quality. The hypothesis that a larger inter-row space would decrease the wheat yield of a monocrop without having any influence on grain quality was thus rejected, at least for sites where the conditions for moderate yields prevail, as it is the case in the present study. It is concluded that wider spaced rows are a suitable strategy for managing winter wheat in organic farming systems, and could also be a possibility in a living mulch system in order to facilitate mechanical operations with the aim to decrease cover crop competitiveness and without running the risk of reducing the yield potential.

Increasing the inter-row spacing of winter wheat from 0.1875 to 0.375 m in living mulches *per se* was of no benefit to grain yields since the yield depression in narrow rows and in unmulched wide rows was equally high. The wider row spacing enabled more light to reach the leaves of the cover crop and allowed living mulches to develop well. Under these circumstances, the mulching increased the wheat density when compared to no mulching, but the grain yield was not improved to such an extent as to achieve a level typical for organic farms in Switzerland (Maeder *et al.*, 2002). Though, growing winter wheat at a wider row space in a living mulch of *T. repens* resulted in significantly higher N concentration of the grains and the straw compared to a bare soil crop. Similar effects were observed by Bergkvist (2003a) and Brandt *et al.* (1989).

Fertilisation and mulching had only little effect on the N concentration of the grains and the straw of winter wheat grown in a living mulch when compared to a wheat crop grown in a living mulch without any additional management operations. Nevertheless, considering the whole system, N stored in the biomass of the living mulch partly compensated for the reduced N contained in the main crop, which is likely to have been influenced by the pronounced reduction of the tiller density of wheat and consequently, the wheat biomass. The superproportional reduction of the wheat biomass in the living mulch treatments, as compared to the monocrop, prevented a surplus of total N yield to be observed in most of the analysed treatments. Thus, we rejected the hypothesis that the N yield of wheat is increased in a wheat/legume living mulch system as compared to a wheat monocrop. Whether the observed increase in the N concentration in the grains and the straw was a consequence of N transferred from the legume or of other mechanisms, such as the availability of unused N in the soil during the grain filling period, remains unclear. This should be investigated in experiments where the grain yields of the two cropping systems are comparable.

As the applied management means (fertilisation, mulching) were not effective enough to improve the canopy densities and enable satisfactory grain yields, it is assumed that the competitive impact of the living mulch on the wheat crop is most critical before the end of tillering; the most relevant period for yield formation (Welsh *et al.*, 1999; Bergkvist, 2003b). Thus, to begin to implement management practices at this stage may be too late for them to have a positive impact on yield. The increased N concentration of the grains and the straw indicates that very likely N was not the most limiting factor and other factors need to be changed in order to improve the practicability of living mulch systems with winter wheat (increase competitiveness of the main crop in relation to the cover crop). Therefore, both the tested means should be improved and new ones should be added.

Possible approaches in order to decrease cover crop competitiveness:

- The use of half-hardy cover crops (e.g. environmentally less adapted varieties) or the use of mixtures of legume cover crops with different life cycles (e.g. non-hardy/ winter annual/ perennial). The competition between the cover crop and the wheat before and during tillering (end of autumn until end of winter) is expected to be reduced in a natural way and without any tillage and leading to an increase in weed suppression compared to the use of only non-hardy species (Liebman & Dyck, 1993; Welsh *et al.*, 1999).
- Adaptation of cutting time, frequency, and height of the cover crop plants. In organic farming direct practices of weed control, such as herbicides and plant growth regulators coming from natural sources, are not allowed yet. Thus, an improvement in the existing mechanical (or thermal) practices is required (Liebman & Dyck, 1993). In order to make use of the weed suppressing ability of the cover crops, management should focus on meeting the needs of the cover crop for its best development and on guaranteeing minimal competition with the main crop during the most critical growth period of the latter (Welsh *et al.*, 1999; Leary & DeFrank, 2000). Jones and Clements (1993) realised higher yields than we did in the present study by cutting the living mulch before the sowing of the main crop but without any additional mulching during the wheat crop season.
- The realization of overall or strip wise shallow tillage of the cover crop. It is expected that this will reduce the competitiveness of the cover crop in the space occupied by the main crop (Ilnicki & Enache, 1992; Liebman & Dyck, 1993; Teasdale, 1996; Garibay *et al.*, 1997). These operations have do be carried out carefully since soil disturbance and temporary lack of soil cover increase the risk for weed infestation (Bergkvist, 2003b).

Possibilities to improve main crop competitiveness:

- The choice of better suited cultivars. More competitive cultivars or cultivars with a higher tillering capacity would exploit the natural potential of the existing cultivars (Liebman & Dyck, 1993). The higher density of wheat tillers or the use of cultivars with longer leaves and shoots would increase the ability of the main crop to make better use the available resources e.g. light which otherwise is used by the cover crop.

- Optimisation of the seeding density and the seeding depth. As today cultivars are selected for monocultures and recommendations are mostly made for systems with tilled soils, with more complex cropping and with multiple species, optimum seeding density and seeding depth might have to be adapted to the prevailing conditions (White & Scott, 1991; Jones & Clements, 1993).
- Sowing with different openers or strip-band tillage might decrease competition in the root zone close to the seeds, increase the availability of N through mineralisation and loose soil which in turn decreases resistance of root penetration (Ilnicki & Enache, 1992; Garibay *et al.*, 1997). At the same time the amplitude of the soil temperature and of moisture is increased (Teasdale & Mohler, 1993; Bristow & Horton, 1996; Teasdale, 1996) which could also be an advantage to the main crop.
- Banding of manure near the main crop rows instead of broadcast application might increase the slightly stimulating effect of fertilisation observed in this study when wheat is grown at a wider inter-row space. Yield improvements were observed in strip-band tilled maize systems in Switzerland when fertiliser was banded (Garibay *et al.*, 1997).

10 CONCLUDING REMARKS

We chose to work in an organic farming system in which living plants covered the soil permanently and where the main crop was sown without any soil disturbance into this green cover. In such systems many yield determining factors interact in a complex way. With the present thesis we learned that holistic approaches are the only way to 'solve problems' in more 'natural' and complex cropping systems: The goal of successfully controlling weeds in organically grown winter wheat with living mulches poses new challenges (increase in the canopy density of wheat). The development of winter wheat/ living mulch systems therefore is an iterative process: Now that some effective weed suppressing cover crops have been evaluated and identified, adequate management techniques such as seeding technique, mulching time and interval have to be adapted in order to achieve economically feasible yields. Later on, with the development of the technique cover crops again should be evaluated... It may be that with the new approaches other cover crops turn out to be better suited to such systems. Such an iterative process is intrinsically time consuming but unavoidable.

Although wheat yield was one of the central issues addressed, it is certainly not the only criteria to be considered for the evaluation of a living mulch system. The use of cover crop biomass can be of economic interest for the farmer, e.g. as forage for cattle or sheep (Jones & Clements, 1993; Garibay *et al.*, 1997) or as green manure when left on the field (Fukuoka, 2000). Furthermore, the protection of the top soil and particularly its structure, the increased biodiversity which contributes to the self-regulation of diseases and pests as well as the increasing contents of soil organic matter can improve long-term fertility and therefore the farmer's income.

Active co-operation among all interested actors (e.g. farmers, researchers, breeders, politicians) can contribute to the improvement of the practicability of living mulch systems. The practicability depends on the identification and the use of suitable cover and main crop genotypes as well as management practices which minimise negative impacts on the main crop while at the same time maintaining the weed suppressing ability of the cover crop (Liebman & Dyck, 1993). Finally, economic evaluations will be needed to validate the complete output of living mulch systems.

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12 APPENDIX

Table 12.1. Analyses of variance (ANOVA) of the effects of soil cover (C), row-system (RS) and fertilisation (F) on biomass of winter wheat straw, biomass of non-wheat, and grain yield.

			Site 1						Site 2					
Parameter	**Analysed by**	**Level**	**C**	**RS**	**RS x C**	**F**	**F x C**	**RS x F**	**C**	**RS**	**RS x C**	**F**	**F x C**	**RS x F**
Grain	**Site**		**	ns	*	***	ns	ns	***	ns	**	***	**	ns
	S (within site)	**RS2** [1)]	***			**	ns		***			ns	ns	
		RS3	†			**	ns		***			*	†	
	F (within site)	**M0**	***	†	†				**	ns	†			
		M1	**	ns	†				†	ns	*			
Straw	**Site**		**	ns	†	***	*	ns	***	ns	**	**	*	ns
	S (within site)	**RS2**	***			**	ns		***			ns	ns	
		RS3	*			*	ns		*			†	ns	
	F (within site)	**M0**	***	†	ns				***	ns	†			
		M1	***	ns	*				**	ns	*			
Non-wheat	**Site**		*	ns	**	ns	ns	ns	***	†	ns	ns	ns	ns
	S (within site)	**RS2**	***			ns	ns		***			*	*	
		RS3	***			ns	ns		***			ns	ns	
	F (within site)	**M0**	***	*	†				***	†	ns			
		M1	***	†	*				***	ns	ns			
Total	**Site**		ns	ns	ns	***	***	ns	**	†	*	ns	ns	ns
	S (within site)	**RS2**	*			**	*		***			ns	ns	
		RS3	ns			**	*		***			†	ns	
	F (within site)	**M0**	ns	ns	ns				**	*	ns			
		M1	*	ns	†				***	ns	†			

[1)] M0, treatment without manure; M1, treatment with manure; RS2, treatment without mulching; RS3, treatment with mulching.
†, *, **, *** significant at the 0.1, 0.05, 0.01, 0.001 probability levels, respectively; ns, not significant.

Table 12.2. Analyses of variance (ANOVA) of the effects of soil cover (C), row-system (RS) and fertilisation (F) on density of winter wheat.

			Site 1						Site 2					
Parameter	**Analysed by**	**Level**	**C**	**RS**	**RS x C**	**F**	**F x C**	**RS x F**	**C**	**RS**	**RS x C**	**F**	**F x C**	**RS x F**
Density	**Site**		***	**	***	*	*	ns	***	ns	**	***	**	ns
	S (within site)	**RS2** [1)]	***			†	ns		***			**	*	
		RS3	**			ns	*		***			*	†	
	F (within site)	**M0**	**	*	*				***	ns	†			
		M1	**	ns	*				***	ns	†			

[1)] M0, treatment without manure; M1, treatment with manure; RS2, treatment without mulching; RS3, treatment with mulching.
†, *, **, *** significant at the 0.1, 0.05, 0.01, 0.001 probability levels, respectively; ns, not significant.

Table 12.3. Analyses of variance (ANOVA) of the effects of soil cover (C), row-system (RS) and fertilisation (F) on N concentration of winter wheat grain and straw.

			Site 1						Site 2					
Parameter	**Analysed by**	**Level**	**C**	**RS**	**RS x C**	**F**	**F x C**	**RS x F**	**C**	**RS**	**RS x C**	**F**	**F x C**	**RS x F**
Grain	**Site**		***	ns	ns	ns	ns	ns	†	ns	ns	†	ns	ns
	S (within site)	**RS2** [1)]	ns			ns	ns		***			ns	ns	
		RS3	**			ns	ns		ns			ns	ns	
	F (within site)	**M0**	ns	ns	ns				ns	ns	ns			
		M1	**	ns	ns				ns	ns	ns			
Straw	**Site**		***	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns
	S (within site)	**RS2**	ns			ns	ns		ns			ns	*	
		RS3	**			ns	ns		ns			†	†	
	F (within site)	**M0**	ns	ns	ns				***	ns	ns			
		M1	***	†	ns				*	ns	†			

[1)] M0, treatment without manure; M1, treatment with manure; RS2, treatment without mulching; RS3, treatment with mulching.
†, *, **, *** significant at the 0.1, 0.05, 0.01, 0.001 probability levels, respectively; ns, not significant.

Table 12.4. Analyses of variance (ANOVA) of the effects of soil cover (C), row-system (RS) and fertilisation (F) on the mass of nitrogen in winter wheat grains, straw, and non-wheat.

			Site 1						Site 2					
Parameter	**Analysed by**	**Level**	**C**	**RS**	**RS x C**	**F**	**F x C**	**RS x F**	**C**	**RS**	**RS x C**	**F**	**F x C**	**RS x F**
Grain	**Site**		†	ns	*	ns	ns	ns	***	ns	*	ns	ns	ns
	S (within site)	**RS2** [1)]	†			***	**		***			ns	*	
		RS3	ns			ns	ns		***			†	ns	
	F (within site)	**M0**	ns	ns	ns				***	ns	ns			
		M1	†	ns	**				***	ns	†			
Straw	**Site**		***	ns	**	***	***	ns	***	†	*	**	ns	ns
	S (within site)	**RS2**	***			***	**		***			**	ns	
		RS3	ns			***	*		**			†	ns	
	F (within site)	**M0**	**	ns	ns				**	ns	ns			
		M1	**	ns	**				**	ns	ns			
Non wheat	**Site**		***	**	**	ns	ns	†	***	*	ns	*	ns	ns
	S (within site)	**RS2**	***			ns	ns		***			**	*	
		RS3	*			ns	ns		***			ns	ns	
	F (within site)	**M0**	***	*	†				**	*	*			
		M1	***	ns	*				*	ns	ns			
Total	**Site**		***	ns	ns	***	**	ns	**	ns	ns	*	ns	ns
	S (within site)	**RS2**	**			ns	**		***			*	ns	
		RS3	**			ns	ns		†			ns	ns	
	F (within site)	**M0**	***	ns	ns				*	†	ns			
		M1	**	ns	**				*	ns	ns			

[1)] M0, treatment without manure; M1, treatment with manure; RS2, treatment without mulching; RS3, treatment with mulching.
†, *, **, *** significant at the 0.1, 0.05, 0.01, 0.001 probability levels, respectively; ns, not significant.

EPILOGUE

North American Indians treated their land as if it were on loan to them from their children. In the last decades the intensification of agricultural production, due mainly to the growing demand for food of a growing population, has led to an increasing disregard for nature. Natural processes take place without human interference. The reactions of a system to disturbance are difficult to predict (Vester, 1978). Agricultural production, for example, interferes with natural processes and has caused environmental problems, a consequence of the intensive use of chemicals and soil tillage.

To maintain the productivity of soils, more sustainable cropping systems are needed. At the same time consumers have a role to play in protecting the environment. Paying more attention to the needs of the environment is difficult when farmers have to farm greater areas of land almost every year to make a living. Natural methods of management have always existed (e.g. earthworms aerate the soil and legumes import nitrogen into the plant/ soil system). Hence, the application of conservation tillage in organic farming, together with the use of cover crops or living mulches provides an opportunity to benefit from these natural processes. Acceptance and use may be greater if the prices of the products on the market are low and farmers have to decrease their production costs.

I have conducted these investigations in the hope that natural processes will play an increasingly important role in agricultural production systems. My goal is to contribute to finding a way to combine the economic and ecological production of foodstuff, according to the motto: Work with nature, not against it.

Rümlang, June 2004

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1994 – 1995	Training at a dairy farm in Alberta (CANADA)
1995 – 2000	Studies at the Department of Agricultural and Food Sciences, Swiss Federal Institute of Technology (ETH), Zürich
2000	Diploma in Agricultural Sciences (Major in Plant Science)
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2001	Teaching Certificate in Agricultural Sciences
2001	Training at the Swiss federal research station for agroecology and agriculture (FAL), Zürich
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