CATCH CROPS AND GREEN MANURES AS BIOLOGICAL TOOLS IN NITROGEN MANAGEMENT IN TEMPERATE ZONES

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During the last decades a lot of research have been made on the use of cover crops. Cover crops are grown for many purposes, but most of the resent interest have focused on their effects on nitrogen. Studies have been made on catch crops grown to catch N from the soil and prevent leaching losses to the environment and on legume green manure crops grown to improve the N supply for succeeding crops. Many of the experiments have been agronomic studies, where choise of plant species or management strategies have been tested to identify the optimal way to grow cover crops in a specific situation. Other experiments have aimed at gaining more basic understanding of the effects of catch crops or green manure crops on N dynamics. These studies include subjects as catch crop growth, root growth, N uptake and soil depletion, kill-date, N mineralisation and pre-emptive competition, and how these factors interact with soil, climatic conditions, and the main crops in the cropping system, both in the short term and in the longer term. Together, the results from these studies have given a more comprehensive understanding of the mechanisms by which a catch crop or a green manure affect N leaching losses and N supply for succeeding crops. The principles governing the effect of catch crops on N supply for succeeding crops have been found to differ basically from the effects N effects of added organic matter. This is mainly due to the fact that a catch crop do not add N to the soil, the N which is incorporated with the catch crop has first been taken from the soil.

In the review, we discuss this new knowledge of catch crops and green manures, and how it helps us to understand why the effects obtained by catch crops are so variable. We also discuss how it can be used to develop strategies which will improve the results we obtain from catch crops and green manures, and to make them more predictable.

Many studies have been made on other effects of cover crops, on soil borne diseases, pests, weeds, soil structure, erosion, soil biology, and other nutrients than N. Though there are many studies, they are scattered over a large number of themes, and research in cover crop effects in most of these themes can be said to be at a very early stage. However, many very interesting effects have been observed, an there seems to be a significant potential for development of cover cropping also for other objectives than improved N husbandry.

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I. WHY USE CATCH CROPS—HOW DO WE WANT THEM TO AFFECT THE SYSTEM?

This review deals with the use of catch crops in temperate climatic zones, i.e., the areas where the summer period is used for crop production, whereas the winters are too cold for most crops to grow. In these conditions, the soil is often left with no plant cover during the winter period. The winter period is normally also the part of the year where the highest percolation of water through the soil occurs, due to low evaporation and in many areas high autumn and winter precipitation. The plant nutrients available in the soil can therefore be leached downwards with percolating water and eventually be lost from the root zone.

During the autumn period, after harvest of the main crop temperature and light conditions allow some plant growth, though not enough to produce commercial crops. Many attempts have been made to use this period to grow plants, which prevent nutrient leaching or improve the soil in various other ways. Such crops are often termed catch crops, cover crops or green manures.

The term cover crop is used broadly to describe non-commercial crops grown for a number of reasons, as just mentioned. In this review we use the terms catch crops and green manure crops as more specific terms. We use the term catch crops when dealing with cover crops which are grown to catch available N in the soil and thereby prevent N leaching losses, and the term green manure when dealing with cover crops which are grown mainly to improve the nutrition of the subsequent main crops.

The research interest in growing catch crops and green manures is old, but the use of such crops have decreased during the 20th century (see Renius and Entrup, 2002). The use and relevance of catch crops in farming systems developing from very extensive grassing systems or slash and burn systems to modern intensive farming has recently been analysed by Pound *et al.* (1999). They concluded that catch crops or green manures became highly important to maintain productivity as farming developed from the very extensive early forms, to systems, which were more intensive but still used little external input. During the last century, green manures and catch crops lost importance as the use of pesticides and chemical fertilisers became widespread, but are now regaining importance to cope with environmental constraints on agricultural production.

Hendrix *et al.* (1992) concluded that one of the reasons for environmental problems in conventional agricultural systems is that they have higher throughflow, lower storage capacity and less recycling of nutrients. In an attempt to design more environmental-friendly cropping systems, catch crops may add some of the storage capacity and recycling needed without requiring dramatic changes of the cropping systems.

An overview of desired and undesired effects of catch crops and green manures in high and low input agro-ecosystems is given in Table I. These will be discussed in more detail in later sections.

In accordance with this analysis, the interest in catch crops is now increasing again, after the long period of decline. During the last decades much research has been made on the use of catch crops. The renewed interest is mainly due to environmental concerns such as problems with nitrate leaching losses and soil degradation due to erosion and loss of organic matter.

Table I
Catch Crops and Green Manures in High Input and Low Input Systems; Desired and Undesired Effects

	Desired effects	Undesired effects
Catch crops in high input systems	Reduced N-leaching amount at high leaching intensities Reduced NO_3 concentrations at low leaching intensities Improved soil fertility Erosion control Improved tilth Pest control	Increased N fertiliser requirement due to: Pre-emptive competition by cover crop Immobilisation of N during cover crop decomposition
Green manures in low input systems	Increased stability of N-supply Consistent cash crop yields Soil organic matter building Increased base N mineralisation Improved soil fertility Erosion control Improved tilth Improved crop rooting depth Pest and weed control	Increased weed and pest pressure Increased N-loss due to poor synchrony Loss of cash crop when undersowing green manures

In this review we focus on the use of catch crops to prevent nitrogen-leaching losses during the winter period, and on green manures including nitrogen fixing legume species grown during the winter period to add nitrogen to the soil. We will discuss the mechanisms by which the catch crops affect nitrogen losses and nitrogen supply for succeeding crops, and based on this we will discuss how they can be used in strategies to reach agronomic and environmental goals.

A. N EFFECTS OF CATCH CROPS, SOLVING ENVIRONMENTAL PROBLEMS

To reduce nitrogen leaching losses to the environment is a very general description of the environmental effects wanted from catch crops. Nitrate lost from agriculture causes two sorts of environmental problems: (1) It increases the nitrate concentration in the deeper aquifers used for drinking water, and (2) it increases the nitrate concentration in surface waters such as streams, lakes and coastal waters. This can lead to eutrofication with various negative effects on the ecosystems.

If the goal is to keep the nitrate concentration in a ground water reservoir below the limit of 50 mg nitrate kg^{-1}, a rather high nitrate loss can be tolerated, as long as it is diluted in enough water to keep the concentration below 50 mg kg^{-1}. On the other hand, this means that if the discharge of water is low, even quite low amounts of nitrate lost by leaching may be enough to bring the concentration in the leaching water above acceptable levels. This is the situation in many drier areas, where the nitrogen leaching loss is relatively low, but may still lead to unacceptably high nitrate concentration in ground water and streams.

When protecting lakes or coastal waters, the total nitrate load rather than the nitrate concentration in the water coming from rural areas is the most important factor (e.g., Rask *et al.*, 2002). Thus, when eutrophication of lakes or coastal waters is the main problem, the high amounts of nitrate lost from areas with high precipitation will be a greater problem than the high nitrate concentrations in the leaching water from dry areas.

Therefore, the specific effect we want from a catch crop, or any other measures we apply to reduce nitrate-leaching losses depend on the local situation and problem.

B. N EFFECTS OF CATCH CROPS IN AGRICULTURE

Catch crops are expected to reduce N leaching losses from the soil, but also to improve the N nutrition of subsequent crops, an effect, which can make them attractive to farmers. However, the price of fertiliser N is low relative to the cost of growing catch crops (e.g., Bollero and Bullock, 1994; Stute and Posner, 1995a), and the introduction of cheap fertilisers is probably a main reason why catch crops have been grown so little for many years.

In the future, the ability of catch crops to supply N to main crops may again become attractive to farmers, due to an increase in organic farming, and increasing regulations also on N use also in conventional farming. In Denmark, regulations already limit the amount of N fertilisers farmers may use to 90% of the optimum supply, and strict regulations are imposed locally in water protection areas in many countries.

In organic farming systems, where inorganic fertilisers are not used, the crops are often N limited. Therefore, the economic returns for improving N-supply through the use of catch crops and green manures make them attractive (Lu *et al.*, 1999). Gaining 1 kg N extra in an organic cereal crop that will generally be N-limited (Bulson *et al.*, 1996), will typically increase grain yield with 50 kg ha^{-1}. With the prevailing premium prices on organic products, the “shadow price” of 1 kg N taken up would be in the range of US$10, based on the market value of organically grown grain. Taking the maximum efficiency of N transfer from catch crops or green manures to the following crop into account, the value of 1 kg N (additional) retained in the system can be estimated at US$3–4.

When we grow catch crops, we want them to remove nitrate from the soil water. Through this reduction of the nitrate concentration in the soil water, they will reduce the nitrate content in the water percolating from the soil. It is easy to show that catch crops do this, though the extent of the effect will depend on many factors. However, a catch crop will affect the soil also after its growth, and nitrogen mineralised from the catch crop material after its incorporation may add to subsequent leaching (Thomsen and Christensen, 1999; Wander *et al.*, 1994).

Though N is mineralised from the catch crop material after its incorporation, especially the first-year effect of the catch crops may often be a reduced N supply for the succeeding crop (Chapter 3). If this leads to increased N fertiliser inputs to the system, the catch crops have impaired the N balance of the field rather than improved it. Therefore, it is important to make sure that catch crops improve the N balance of the field, either by reduced fertiliser N input or by increased crop N utilisation. Only in this way we can be sure that the overall effect of a catch crop is a reduced N leaching loss.

How to grow catch crops to obtain optimal environmental and agronomic benefits will depend on factors such as local climate, soil types, main crops and farming systems and the environmental problems encountered in the local area. A more detailed discussion of management options and strategies will be developed in sections below.

II. UPTAKE OF N AND SOIL DEPLETION

In order to reach the goal of decreased environmental impact, the primary requisite for a catch crop is to take up nitrogen from the soil, and thereby reduce the nitrate content in the water percolating from the soil. Nitrogen uptake and soil depletion by catch crops vary strongly, and results show N uptake by non-legume catch crops to vary from only around 10 (Jensen, 1991; Richards *et al.*, 1996; Ranells and Wagger, 1997c) to 200 kg N ha^{-1} (Müller and Sundman, 1988; Sørensen and Thorup-Kristensen, 1993; Thorup-Kristensen, 1993b, 1994b, 2001; Jackson *et al.*, 1993; Francis, 1995; Sørensen, 1992), and in extreme examples to 300 kg N ha^{-1} (Francis *et al.*, 1998). There are three main sources of this large variation:

- Variable catch crop growth and N-uptake potential under the prevailing climatic conditions.
- Variable catch crop root growth and contact to available soil nitrogen.
- Variable amounts of available nitrogen in the soil.

A. GROWTH AND N UPTAKE POTENTIAL

Catch crops normally grow during periods of the year where conditions are not optimal for crop growth. Therefore, their growth is often limited, and this can limit their uptake capacity for nitrogen. In spite of this, it would seem that catch crop N uptake is normally limited by soil N availability rather than by N uptake capacity.

For a catch crop well supplied with N more than 1 Mg dry matter ha^{-1} can be produced in 2 weeks of active growth (Vos and Van der Putten, 1997) with 3–4% N in the dry matter. Based on such results, a few weeks of active growth would be enough for most catch crops to take up the amount of N available to them. Vos and Van der Putten (1997) found that catch crops could take up 3–4 kg N ha^{-1} day^{-1}. In most experiments only the aboveground plant material is sampled, but the roots may constitute up to approximately 50% of the total biomass production though this seems to vary strongly with plant species (Breland, 1996b). Though the N concentration in root matter is normally lower than in aboveground plant material, it may still add significantly to the total N uptake capacity of a catch crop.

In most published results with catch crops, especially when grown after cereals, the catch crop biomass production and N uptake is much lower than this. At the same time the tissue N concentration is also relatively low [1.0–2.5% of dry matter (Martinez and Guiraud, 1990; Andersen and Olsen, 1993)].

That catch crops often have higher N uptake capacity than necessary is also indicated in results showing that when fertiliser N is added to catch crops they are able to produce more biomass and take up more N than catch crops grown at lower N supply (Fig. 1 and Andersen and Olsen, 1993; Schröder *et al.*, 1997). Breland (1996a) added 40 kg N ha^{-1} to a ryegrass catch crop which had been undersown in barley, and found that the catch crop removed almost all of this from the soil within only 1 week.

Further, in many studies (e.g., Ranells and Wagger, 1997c; Vyn *et al.*, 2000; Mueller and Thorup-Kristensen, 2001) legume catch crops have been found to produce more biomass and take up much more N than non-legumes; again indicating that the N uptake by the non-legumes is limited by soil N supply. Vyn *et al.* (2000) found that while non-legume catch crops grown after wheat took up 12–31 kg N ha^{-1}, red clover produced more biomass and took up between 44 and 98 kg N ha^{-1}. In experiments made at high N supply non-legumes are often found to take up as much N as legumes, and to have high N concentrations in their biomass (Francis, 1995; Thorup-Kristensen, 1994b, 2001), indicating that in these special situations the uptake capacity may be a limiting factor.

The conclusion must be that provided a catch crop is not sown too late, the risk that it does not grow to acquire sufficient N uptake capacity is generally low.

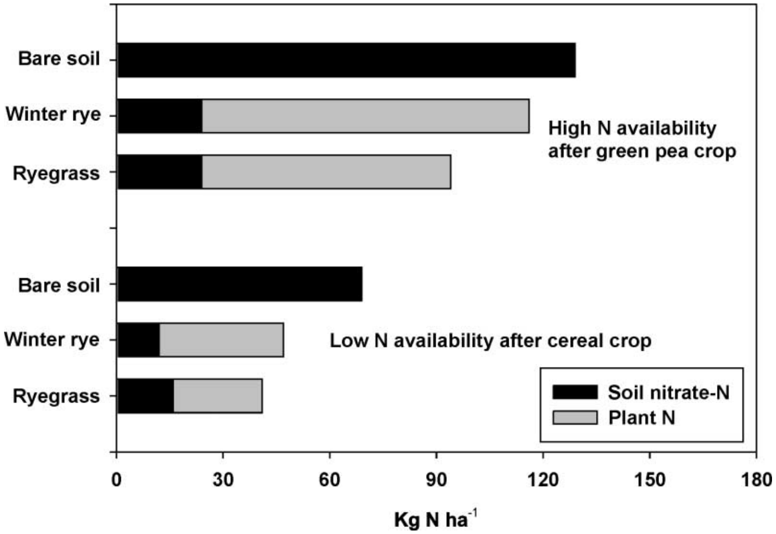


Figure 1 Catch crop performance at high or low N availability. Data are from two separate experiments (Thorup-Kristensen, 2001; Mueller and Thorup-Kristensen, 2001), but both experiments were made in the same 2 years (1996 and 1997) at adjacent sites, and the catch crops in the two experiments were sown at the same time. The main difference between the two experiments were the pre-crop (green pea or barley) and thereby soil N availability for the catch crops.

When it occurs, it will normally relate to adverse conditions such as dry soil at the time of establishment or unusually high N supply from the soil.

When catch crops due to sowing time or germination conditions get a too short growing season, their ability to deplete the soil inorganic N content is reduced. The results of Elers and Hartmann (1987), who established catch crops at five different dates during the autumn, showed that their N uptake was reduced with approximately 1 kg N ha^{-1} day^{-1} for monocot catch crops and 2 kg N ha^{-1} day^{-1} for crucifer catch crops. Also Vos and Van der Putten (1997) found the N uptake by crucifers to be much more sensitive to sowing date than N uptake by monocots. When sown early a crucifer catch crop seems to be able to deplete the soil faster than grasses or cereals (e.g., Aufhammer *et al*., 1992). It is not possible from these results to distinguish whether the reduced N uptake is mainly due to reduced uptake capacity or to reduced rooting depth at late sowing (Section “Root growth”).

In situations where much N is available for the catch crop or alternatively for leaching, e.g., after many horticultural crops, insufficient nitrogen uptake capacity is more likely to become limiting. If 200 kg N ha^{-1} or more is available for leaching, it may take a biomass production of more than 5 Mg ha^{-1} to make the crop able to assimilate the available N.

Under such high-N conditions, a catch crop will normally take up much N, and thereby have a strong effect against N leaching losses (Schröder *et al*., 1996) even though it will not deplete the soil completely.

B. Root Growth

To be able to deplete the soil, a catch crop must develop its root system to bring it into contact with the available N in the soil. Most of the soil inorganic N is normally present in the form of nitrate, and since nitrate is one of the most mobile plant nutrients in the soil, a high root length density is not necessary for plants to deplete the soil effectively (e.g., Robinson *et al*., 1994; Robinson *et al*., 1991).

Accordingly, attempts to correlate soil nitrate depletion by catch crops to their root length density have not been successful (Sainju *et al*., 1998; Van Dam and Leffelaar, 1998; Vos *et al*., 1998). On the other hand, some nitrate will be available also from deep soil layers, sometimes in quite large quantities and nitrate will often be moving downwards during the growing period of the catch crops. Therefore, developing a deep root system will bring the catch crop into contact with more soil nitrate and thus allow them to increase their N uptake. Accordingly, Thorup-Kristensen (2001) found that soil N depletion by catch crop species was highly correlated to their rooting depth, whereas it showed little correlation to root intensity.

Differences in root growth have been shown to affect the amount of nitrate left in the soil, particularly in deep soil layers (Thorup-Kristensen, 1993a, 2001; Fig. 2). This ability to deplete especially the deep soil layers better, makes deep-rooted catch crops especially valuable (Thorup-Kristensen and Nielsen, 1998), as the N taken up from deep soil layers is otherwise at larger risk of being lost by leaching.

Rooting depth is determined by a number of factors. Plant species and the duration of growth are two of the most important factors determining catch crop rooting depth (Thorup-Kristensen, 2001), and at the same time these are factors which the farmer can control. Large differences have been observed among crop species (Fig. 3). Thorup-Kristensen, 2001 estimated that 1000 day degrees after sowing crucifer catch crops would have a rooting depth of 1.5 m, winter rye and oats 0.9–1.0 m and ryegrass only 0.6 m. Also Grindlay (1995) found crucifer catch crops to have deeper rooting than monocots. The deep rooting of crucifer catch crops is observed even though they are also found to allocate a much smaller fraction of their biomass to the root system than grasses and rye (Lainé *et al*., 1993). At the same time Lainé *et al*. (1993) found that crucifer catch crops had much higher maximum nitrate uptake rates than monocots.

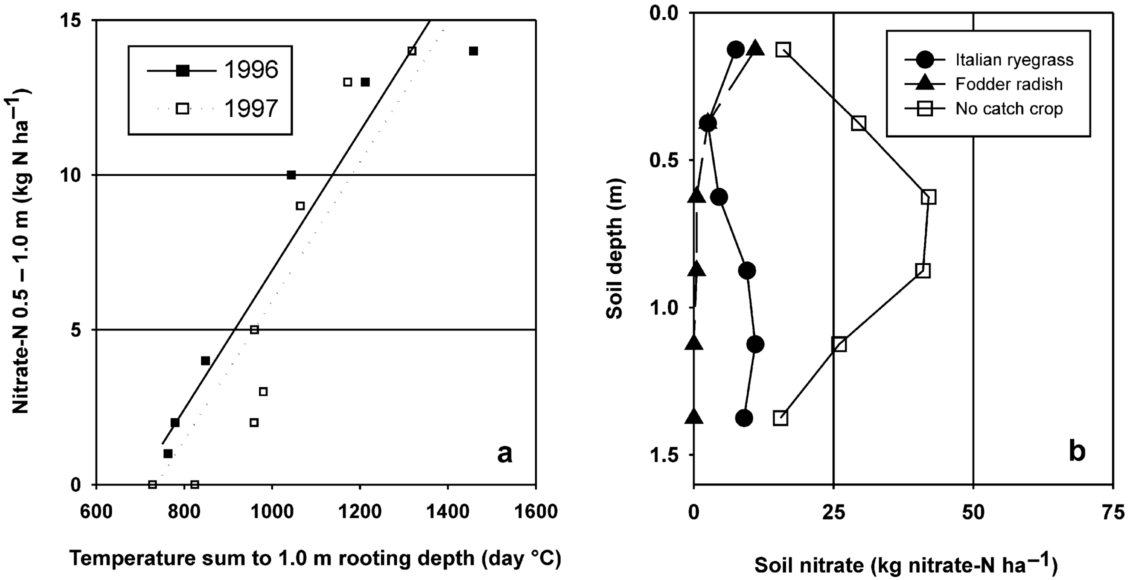


Figure 2 Effects of differences in rooting depth on the ability of catch crops to deplete the soil. (a) shows the close relationship found between temperature sum used by catch crop species to reach a rooting depth of 1.0 m and the amount of nitrate-N left in the 0.5–1.0 m soil layer. (b) shows the nitrate distribution in the soil profile and the different ability of ryegrass and fodder radish to deplete the deeper soil layers, in accordance with the observed differences in root growth [Reproduced from Plant and Soil (Thorup-Kristensen, 2001, figure 4d) with kind permission from Kluwer Academic Publishers].

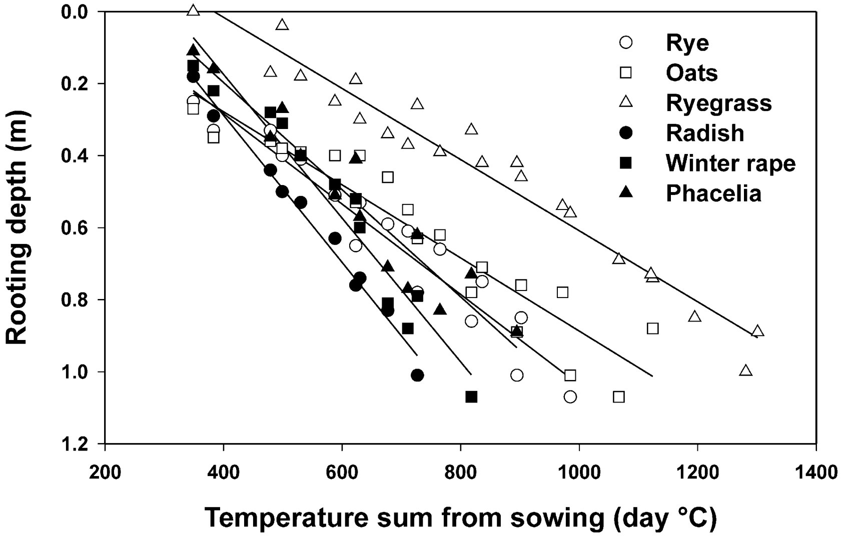


Figure 3 Root development of catch crops, showing very different rates of rooting depth development. The depth development rates varied from ca. 1 mm day^{-1} per °C for rye, ryegrass and oats to more than 2 mm day^{-1} per °C for the two crucifer crops [Reproduced from Plant and Soil (Thorup-Kristensen, 2001, figure 3) with kind permission from Kluwer Academic Publishers].

The duration of the growing season is as important as the choice of catch crop species. Postponing the sowing of a catch crop will reduce its rooting depth and its N uptake especially from deeper soil layers.

The significance of nitrate depletion from deep soil layers is unfortunately often overlooked in research results. Very often the soil sampling is not deep enough to reveal the differences which may be there (e.g., Sainju *et al.*, 1998; Vos *et al.*, 1998). Even in experiments where soil has been sampled to 1.0 m or more, the total amount of inorganic N left in the soil is often shown, without showing the effect on specific soil layers thereby disguising possible important differences in deep soil layers.

C. RELATIONSHIP BETWEEN SOIL DEPLETION AND NITRATE LEACHING LOSS

To understand the effects of catch crops on N leaching loss, it is important to keep in mind that N leaching and N leaching loss is not the same. N leaching is the process of N compounds (mostly nitrate) moving down the soil profile with percolating water. N leaching loss is the special case of N leaching where N is carried across the bottom of the rooting zone or into drains, and is thereby lost from the cropping system. One important problem about this is, that the bottom of the rooting zone is not well defined; to what depth in the soil must N be leached, before it is actually lost?

In mechanistic terms, a catch crop reduces N leaching loss through three mechanisms. (1) As catch crops take up N they reduce the nitrate concentration in the soil water. Thus, water leaching through the soil will carry less N with it. (2) Nitrogen is actively transported upwards in the catch crop roots, and in this way some of the downwards leaching which had already occurred is undone. (3) By its water use, a catch crop will reduce the amount of water percolating from the soil, and thereby the amount of N leached downwards.

The two first effects are normally the main effects, but they do not automatically reduce the N leaching loss. Basically, it can be said, that the effect of catch crops is to reduce the potential for N leaching loss rather than to reduce the leaching loss directly. The extent to which the potential for reduced N loss is turned into actual reductions in leaching loss depend on a number of factors.

Reductions in the nitrate content in the soil water in the root zone will only affect leaching loss if the surplus precipitation is high enough to leach the nitrate depleted soil water across the bottom of the root zone. Therefore, under drier conditions, a catch crop may reduce the nitrate content in the soil water strongly with little effect on actual leaching loss. One example can be seen in the results of Willumsen and Thorup-Kristensen (2001) where a catch crop experiment was performed in 2 years with very different winter precipitation. In the wet year the difference in soil nitrate content observed between catch cropped plots and uncovered plots in the autumn almost disappeared before spring since all nitrate was lost from the uncovered (control) plots by leaching during winter. In the dry year little nitrate was lost during winter, and the differences found in the late autumn were upheld until the spring. Such differences in climatic factors will greatly affect N availablility in the uncovered plots (Fig. 4).

Another problem occurs especially under wet conditions, where the leaching may start in the early autumn. While the catch crop is growing and taking up nitrate from upper soil layers, surplus precipitation may create downward water movement, which causes leaching losses at the bottom of the rooting zone. Fig. 5 show an example of this effect. The catch crops were undersown in the wheat and pea/barley crops, and were well established already at the time of main crop harvest in August. In spite of this, they had little effect on nitrate-N concentration at 1.0 m depth and leaching across 1.0 m depth until January approximately 5 months later. In this example, considerable leaching was observed before they started to reduce the nitrate content in the deeper soil layers. Similarly, Aufhammer *et al*. (1992) found that catch crops undersown in field beans had little effect on subsoil 0.6–0.9 m) until early January next year. An effect of this can be seen in the results of Shepherd (1999), who found that in years where drainage started early in the autumn, catch crops were much

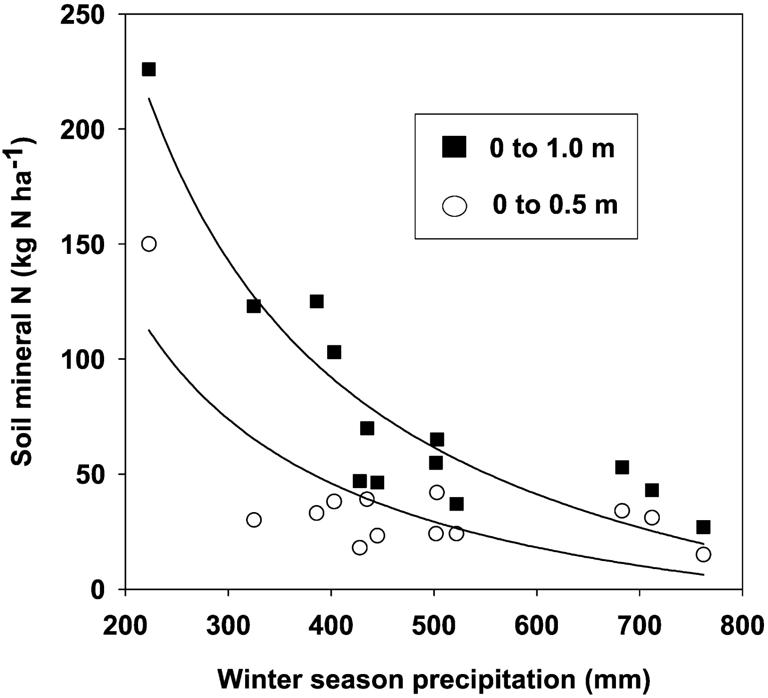


Figure 4 Spring soil nitrate-N content without catch crops as dependent on winter season precipitation. Only after one very dry season was any nitrate retention indicated within the upper 0.5 m of the soil whereas significant nitrate retention was indicated in several of the drier winters when the full 1.0 m soil layer was considered (data from various experiments made at the Danish Institute of Agricultural Science, Department of Horticulture during the period 1985–2001).

less effective in preventing leaching loss than in years where drainage started later.

This effect is one reason why deep-rooted catch crops can be expected to be especially effective; they have a better chance to reduce the nitrate concentration at the bottom of the rooting zone directly, and to do such earlier during the leaching season. This can also be seen in the results of Aufhammer *et al.* (1992) where winter rape reduced subsoil nitrate-N content earlier and stronger than winter barley or ryegrass.

To have maximum effect the catch crop should reduce the N concentration at the bottom of the rooting zone already before the main leaching period starts, and should keep the concentration low until the end of the leaching period. The last demand may conflict with the demand for catch crops to release N again early enough to make it available for the succeeding main crop (see Section "incorporation time").

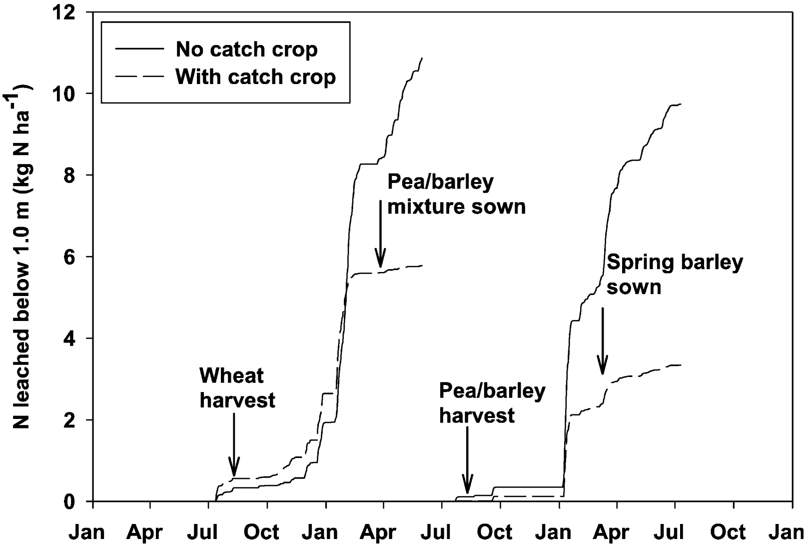


Figure 5 Effect of catch crops on temporal pattern of N leaching. It is clearly seen that the reduction of leaching is postponed relative to the active growth period of the catch crop in the autumn. In both years, the effect of a catch crop grown in the autumn were not observed until around February 1, but then continued until early summer more than 2 months after the catch crop had been killed and the next crop were established [data from the experiment of Olesen *et al.* (2000)].

D. LEGUMINOUS GREEN MANURES

In many experiments where legumes are compared to non-legume catch crops, the legumes show higher N uptake, sometimes much higher (Ranells and Wagger, 1996; Torbert *et al.*, 1996). The amount of N added to the system by biological N fixation when legume catch crops are grown varies strongly, even within experiments. Mueller and Thorup-Kristensen (2001), Ranells and Wagger (1996) and Torbert *et al.* (1996) estimated N fixation from around 30 kg N ha^{-1} to almost 150 kg N ha^{-1} depending on year and legume species. As the N uptake by legumes is not limited by N availability, the significance of a longer growth season may be bigger, as the legume can continue to take up N also after the soil has been depleted.

In experiments with high N availability, the difference in N uptake between legumes and non-legumes is generally small or absent (Thorup-Kristensen, 2001), and Torbert *et al.* (1996) showed that the advantage of legumes in N uptake disappeared as the N supply for the catch crops were increased.

Legume catch crops acquire their N both through biological N fixation and by taking inorganic N from the soil, and they reduce soil inorganic N content during the autumn as non-legumes (Mueller and Thorup-Kristensen, 2001). Breland

(1996a) added 40 kg N ha^{-1} to already established catch crops, and found that two clover species were unable to remove this from the soil, whereas ryegrass removed almost all of it from the soil within a week. This result is in accordance with Lainé *et al*. (1993), who found that unlike grasses, the nitrate uptake of two legume species was 100% dependent on the inducible uptake system. Though most experiments show less or even no difference between legumes and non-legumes in soil N depletion (e.g., Vyn *et al*., 2000), the general conclusion is that legumes are not as effective as non-legumes.

One way to utilise the N-fixing capacity of legumes without the risk of inefficient soil N depletion is to grow them in mixtures with non-legumes (Ranells and Wagger, 1997a; Janzen and Schaalje, 1992). Such mixtures often deplete the soil inorganic N pool as effectively as pure non-legume crops (Thorup-Kristensen, 2001; Willumsen and Thorup-Kristensen, 2001), but they can still add substantial amounts of N to the system by N fixation (Ranells and Wagger, 1996).

III. CATCH CROP EFFECT ON N SUPPLY FOR SUBSEQUENT CROPS

Whereas it is well documented that catch crops can considerably reduce nitrate leaching loss, their effect on N supply for succeeding crops is less clear. Legume catch crops normally increase the N supply for a succeeding crop, but looking only at non-legume catch crops, the results are less clear. In some experiments catch crops are found to increase N supply for the succeeding crop and sometimes quite large effects can be observed (e.g., Elers and Hartmann, 1987; Thorup-Kristensen, 1994b), but in other experiments consistent and sometimes large reductions in N availability have been observed (e.g., Muller *et al*., 1989; Francis *et al*., 1998). Already Mann (1959), one of the first who studied the N effect of catch crops in a systematic way, concluded that "the effect is short-lived, unpredictable and not related to factors such as the amount of catch crop dry matter or catch crop N incorporated."

The increases and decreases in N supply after catch crops have normally been explained simply as the effect of net N mineralisation or immobilisation during decomposition of the catch crop residues (e.g., Ditsch and Alley, 1991). However, examples of clearly decreased N supply have also been found in experiments where the data such as C/N ratio of the catch crops, inorganic N content in the topsoil (Schröder *et al*., 1997) or ^{15}N uptake by a succeeding crop clearly indicate that a net N mineralisation from the catch crop residues has occurred (Francis *et al*., 1998; Martinez and Guiraud, 1990; Torstensson and Aronsson, 2000; Jensen, 1991; Muller *et al*., 1989; Torstensson and Aronsson, 2000; Fig. 6). Clearly, trying to explain the effect of catch crops by the N

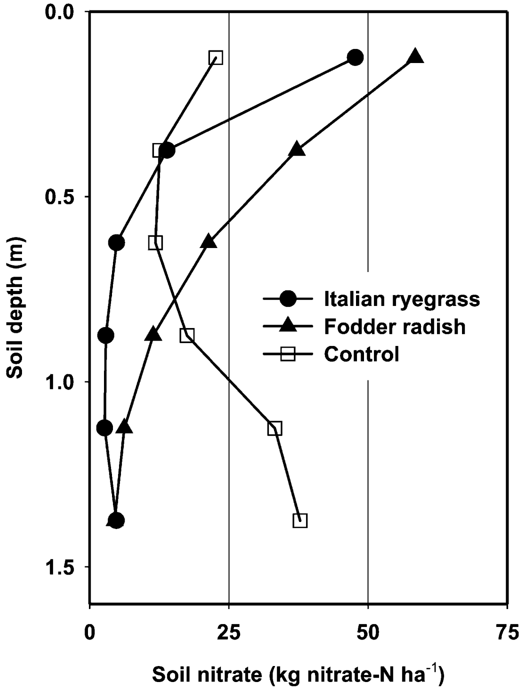


Figure 6 Amount and depth distribution of soil nitrate-N distribution in May as affected by catch crops. Fodder radish died off naturally during the winter, whereas ryegrass survived the winter. Both catch crops were incorporated around 1 April [data from the experiment of Thorup-Kristensen (2001)].

mineralisation or immobilisation caused by the catch crop residues have not lead to an understanding of the strongly variable effects of catch crops on N supply for succeeding crops observed in experiments.

The main problem is that mineralisation and immobilisation only includes the effect of catch crop on soil inorganic N content from the time of their incorporation and onwards. This is similar to the way in which the effect of addition of organic manures is understood. But contrary to added manures, catch crops affect the soil also before they are "added to the soil." During their growth catch crops remove mineral N from the soil, and before the catch crop is killed, soil mineral N content is therefore normally lower than if no catch had been grown. In short, catch crops do not add N to the soil, they take N from the soil and subsequently return it to the soil.

The effect of a catch crop on N supply for the succeeding crop (N_{eff}) is the combined effect of the N depletion made before catch crop incorporation and the N release due to mineralisation after incorporation (Thorup-Kristensen, 1993b; Thorup-Kristensen and Nielsen, 1998). Whether this combined effect of a catch crop will lead to increased or decreased N supply for a succeeding crop is the result of complex interactions between the characteristics of the catch crop, the soil, the climate and the succeeding crop.

These interactions are complex, and may lead to counter-intuitive results; e.g., results where a negative N_{eff} (see Eq. 1 below) is found even though a significant net N mineralisation from the catch crop residues is observed. As an example, Torstensson and Aronsson (2000) estimated that before incorporation N_{inorg} was 25 kg N ha^{-1} lower below catch crops than in control plots, whereas the subsequent mineralisation from the catch crops was only 14 kg N ha^{-1}. Thus the mineralisation was not high enough to compensate for the effect of the catch crop N uptake. This negative effect of the catch crop soil N depletion on N supply for the succeeding crop has been termed pre-emptive competition (Thorup-Kristensen, 1993b). In the experiments of Francis *et al*. (1998) catch crops which had taken up more than 200 kg N ha^{-1} and had C/N ratios below 15 clearly reduced N uptake of the succeeding crop. Soil analysis showed that the content of inorganic N in the soil was reduced with approximately 100 kg N ha^{-1} by the catch crops before their incorporation, and the mineralisation from the catch crops was not high enough to compensate for this.

Though the mechanisms behind such results are complex, they are the predictable result of well-known processes. This is illustrated by the fact that plant and soil models such as the Danish DAISY model (Hansen *et al*., 1991) was found to be able to simulate these interactions (Thorup-Kristensen and Nielsen, 1998) based on its simulation of N mineralisation, water and nitrate movement in the soil and root growth of crops and catch crops. Probably any other model simulating these factors based on generally accepted principles would be able to simulate the same phenomena.

In spite of these more complex effects of catch crops, a number of papers discuss the effects of catch crops on the supply of N and other nutrients for succeeding crops as if they were added manures. No distinction is made between experiments where catch crops were grown and incorporated at the same plot and experiments where the catch crop material were added to plots where no catch crop had been grown (e.g., Ditsch and Alley, 1991; Thomsen, 1993; Yadvinder *et al*., 1992). This can lead to serious misinterpretations of the experimental results. In the example mentioned earlier (Torstensson and Aronsson, 2000) measurements including only the effect of N mineralisation after catch crop incorporation would have predicted a positive effect of 14 kg N ha^{-1}, whereas the effect observed in the field was a negative effect of 11 kg N ha^{-1}.

Catch crops also affect N availability through other processes (e.g., Jackson, 2000) such as denitrification and ammonia volatilisation, but though these processes may be environmentally important (see Section "Gaseous losses of N"), they do not seem to be important for the effect of catch crops on N supply for succeeding crops.

A. CALCULATING THE N EFFECT, N_{EFF}

As discussed earlier, two of the main effects determining N_{eff} of a catch crop are its effects through N depletion of the soil (pre-emptive competition) and the effect of the subsequent N mineralisation.

Both of these effects are related to the N uptake of the catch crop. The mineralisation from a catch crop depends on the amount of N it has taken up and the fraction of this, which is mineralised to become available for the succeeding crop. The effect of the soil N depletion, i.e., the pre-emptive competition also relates to the amount of N taken up by the catch crop, and the fraction of this N which would otherwise have been retained in the soil and available for the succeeding crop. Based on this, Thorup-Kristensen (1993a,b) found that the effect of growing a catch crop on the N supply for the succeeding crop (N_{eff}) can be calculated as:

$$N_{eff} = N_{upt} \cdot m - N_{upt} \cdot r \tag{1}$$

where N_{upt} is the amount of N taken up by the catch crop, m is the fraction of this N that is mineralised to become available for the succeeding crop, and r is the fraction of this N which would have been retained in the root zone and directly available for the succeeding crop if it had not been taken up by the catch crop.

The fact that N_{eff} is determined by these two main effects has important implications not only for the total amount of available N as described by Eq. (1), it also has important effects on other factors such as depth distribution of the available N (see Section “Depth distribution of inorganic N”).

B. WHAT DETERMINES PRE-EMPTIVE COMPETITION

High pre-emptive competition is observed where most of the N taken up by a catch crop would have been retained within the rooting zone if no catch crop had been grown. In Eq. (1), the factor r will be close to 1.0 under low leaching conditions and close to 0 under high leaching conditions. A number of factors determine this retention.

Soil type and the precipitation surplus during the cool season strongly affects how much of the mineral N is leached or retained (Burns, 1984), so that under conditions with low precipitation and high soil water holding capacity the N retention is high. In the data of Francis *et al.* (1998) as well as from the dry year of the experiment of Willumsen and Thorup-Kristensen (2001), the content of inorganic N in the soil in the control plots actually increases during the winter season, indicating very small leaching losses and r values close to 1.

These are factors that the farmer cannot affect, but as soil type and general climate are known, the catch crop strategy can be adapted to the local conditions.

The rooting depth of the succeeding crop also affects pre-emptive competition, as less precipitation is needed to leach all of the mineral N from the root zone of a shallow rooted crop than from the root zone of a deep rooted crop. Thus pre-emptive competition is lower and N_{eff} of a catch crop is higher when it is followed by a shallow-rooted crop than by a deep-rooted crop (Thorup-Kristensen and Nielsen, 1998; Willumsen and Thorup-Kristensen, 2001).

Finally, the alternative retention of N is not a constant for all N taken up by a catch crop. N taken early during catch crop growth or from deep soil layers has lower r values than N taken late or from upper soil layers. This also has consequences for optimal management of catch crops (see Section "incorporation time").

C. WHAT DETERMINES N MINERALISATION

Measurements of N mineralisation from catch crops have shown mineralisation varying from more than 50% mineralisation of catch crop N during the first few months (Breland, 1994a; Dou *et al*., 1994) to immobilisation during early stages of catch crop decomposition (Thorup-Kristensen, 1994a). Generally, N mineralisation from catch crops and green manures are fast, with much of the mineralisation occurring within 1–2 months. In extreme examples, Breland (1994a) and Dou *et al*. (1994) found that as much as 80% of catch crop N was mineralised during the 4 weeks after incorporation.

From our own experiments we have seen substantial transfers of N to the subsequent cash crop (Table II; Thorup-Kristensen, 1994b). In one trial, above ground cover crops were removed from the field, and then reintroduced in other plots in increasing amounts, where carrots were subsequently grown. This allows direct estimation of the N mineralisation from the green manure (Fig. 7), and it was estimated that 34% of the N added with the green manures were present as plant N or inorganic N in the soil at the end of the growing season.

Table II
Nitrate-N to Different Soil Depths in May after Catch Crops, and N Uptake in the Subsequent Barley Crop

	Soil nitrate-N (kg N ha^{-1})			Estimated N_{eff} (kg N ha^{-1})	
	Control	Italian ryegrass	Fodder radish	Italian ryegrass	Fodder radish
0–0.25 m	23	48	58	25	35
0–0.5 m	35	62	96	27	61
0–1.0 m	65	69	128	4	59
0–1.5 m	136	77	139	−59	3
Barley N uptake	107	85	153	−22	46

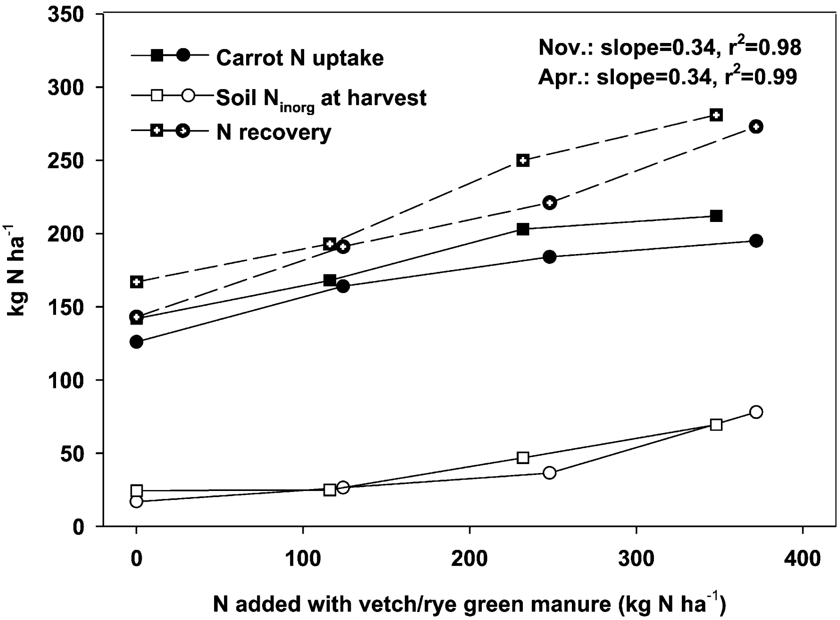


Figure 7 Carrot N uptake (closed symbols) and residual soil inorganic N content at carrot harvest (open symbols) as a function of N content in green manure added to the plots in November (circles) or April (rectangles). The N recovery (carrot N + soil inorganic N at harvest, shown with dashed lines) are plotted with regression line estimates [data from the experiment of Thorup-Kristensen and Van den Boogaard (1999)].

There are a number of reasons for the variation in N mineralisation. Quality of the catch crop plant material is a major determinant for the mineralisation of catch crop N, but also other factors such as temperature, humidity, soil type and the degree of mixing of soil and catch crop at incorporation have been found to be of importance.

One of the most important parameters determining N mineralisation from catch crops in the field is the C/N ratio (Kuo and Jellum, 2000; Jensen, 1992; Ranells and Wagger, 1996; Thorup-Kristensen, 1994a; Wagger, 1989; Frankenberger and Abdelmagid, 1985). In most examples the C/N ratio of catch crop materials is in the range of 10–30. At low C/N ratios very fast N release may occur, and more than 50% of the plant N may become mineralised within a couple of months (e.g., Marstorp and Kirchmann, 1991). At higher C/N ratios immobilisation of N is found during the early stages of plant matter decomposition. The estimated balance point between mineralisation and immobilisation varies among studies, from around 15 (Marstorp and Kirchmann, 1991; Thorup-Kristensen, 1994a) in some studies to more than 20 in others (Frankenberger and Abdelmagid, 1985).

Though the C/N ratio is important, it does not in any precise way predict N mineralisation under field conditions. Even with low C/N ratio legume materials mineralisation of only 10–20% of the plant N content can be observed (e.g., Ladd *et al*., 1981).

Other quality parameters of the catch crop material may also be important. Studies have shown contents of lignin or polyphenols to affect N mineralisation from plant material (Fox *et al*., 1990). However, catch crops normally consist of young plant material and high contents of such compounds or very high C/N ratios are rarely found.

Others have studied water solubility of the C and N compounds of the plant material as a quality parameter, which may affect turnover and N mineralisation (Magid *et al*., 1997; Mueller *et al*., 1998a). The water-soluble fraction was assumed to be the easily decomposable part and the non-soluble fraction assumed to be more recalcitrant parts such as cell wall components. Thus, the fraction of water-soluble C and N in plant materials could be an important input for model simulations of N mineralisation (Mueller *et al*., 1998b), but further studies have revealed that parts of the insoluble fractions are also decomposed very rapidly (Mueller *et al*., 1998b; Neergaard *et al*., 2002).

Contents of soluble compounds may also be important in another way, as they can quickly be released and removed from the remaining more recalcitrant fractions of the plant material. When catch crops are decomposing aboveground (Quemada and Cabrera, 1996; Sanderson *et al*., 1999) the soluble compounds may be removed by rain, when it is decomposing in the soil it may be removed by diffusion or mass flow due to water movement. When N is released in this way and removed from the remaining residues, it will reduce the N availability for the turnover of the more recalcitrant residues. In this context a distance of a few centimetres is enough to ensure that immobilisation will be effectively hampered. An example of this effect is shown by Wang and Bakken (1997), though in their experiment it was plant uptake rather than mass flow which removed released N from the remaining plant residues.

Some catch crops may even contain much of their N as nitrate. The content of nitrate-N may constitute from practically nothing to more than 25% of the total N content depending on catch crop species (Lainé *et al*., 1993; Thorup-Kristensen, 1994a; Van Dam and Lantinga, 1998). Thus in some catch crops, a large fraction of the catch crop N was in mineral and highly mobile form even before incubation.

Soil humidity and temperature strongly affects the conditions for the soil organisms, and thereby also decomposition of plant material. Temperature fluctuations may make the plant matter more susceptible to decomposition through freeze-thaw cycles (Breland, 1994a) and humidity through drying–rewetting cycles (Van Gestel *et al*., 1993).

A general assumption has been that N mineralisation will be low when the soil temperature is below 5°C, and simulation models are built reflecting this perception. However, field data with catch crops have indicated that N is released fast also when they are incorporated into cold soil in the winter (Breland, 1994a; Thorup-Kristensen, 1994b; Müller and Sundman, 1988). This has led to more detailed studies of N mineralisation in cold soil (Andersen and Jensen, 2001; Magid *et al*., 2001; Van Schöll *et al*., 1997; Vigil and Kissel, 1995).

Magid *et al*. (2001) examined the decomposition of *Medicago lupulina*, *Melilotus alba* and *Poa pratensis* at 3, 9, and 25°C. No retardation of N mineralisation was observed at low temperatures, and in the analysis of variance of mineralised N the residue type contributed 10 times as much to the regression as temperature did. Contrary to this, the evolution of CO_2 was sensitive to temperature, and residue type and temperature were found to be equally important. The least retardation of carbon mineralisation at low temperature was found with *M. alba* that had a relatively low cellulose content, and a higher content of low molecular compounds. A decrease in the bioavailability of C-rich polymers at low temperatures (Nicolardot *et al*., 1994), and thus a preferential utilisation of N-rich low molecular substances is one possible explanation for the difference in temperature sensitivity for C and N mineralisation. Andersen and Jensen (2001) studied gross N mineralisation during decomposition of catch crops at 3 and 9°C. These studies confirmed that while immobilisation processes were much retarded at low temperatures the mineralisation of N was only slightly affected.

In order to further explore decomposition at low temperatures (Magid, personal communication) examined changes in plant residue quality during decomposition at 3 and 9°C over a 140 day period (see Fig. 8).

The N loss from rye was practically unaffected by temperature (3 or 9°C) and it lost 60–65% of its N content during the first 35 days of decomposition (Fig. 8a). N loss from ryegrass was strongly affected by temperature, and the loss was faster at 3°C than at 9°C (Fig. 8b). During the early stages N loss was observed at 3°C while N immobilisation was observed at 9 °C, but after the first 35 days there was little difference in the N loss from ryegrass at the two temperatures. For both materials the C/N ratio of the remaining residues was higher at 3° than at 9°C during most of the decomposition period (Fig. 8c and d). This indicates that the difference in temperature affected the decomposition process as such, and not only the rate at which C and N loss occurred.

These results confirm the field observations that N mineralisation from easily decomposable plant material can occur rapidly even in cold soil as also found by Van Schöll *et al*. (1997). This has a number of consequences for the optimal management of green manure crops and catch crops in cool temperate climate regions. As substantial nitrification has also been shown even at 3°C (Magid *et al*., 2000; Van Schöll *et al*., 1997), this mineralisation at low temperatures can allow early leaching losses as also indicated by field data.

In the biological literature there is little general recognition of differences in temperature sensitivity in the decomposition of various substrates. Katterer *et al*. (1998) reviewed more than 20 experiments on temperature dependence of plant

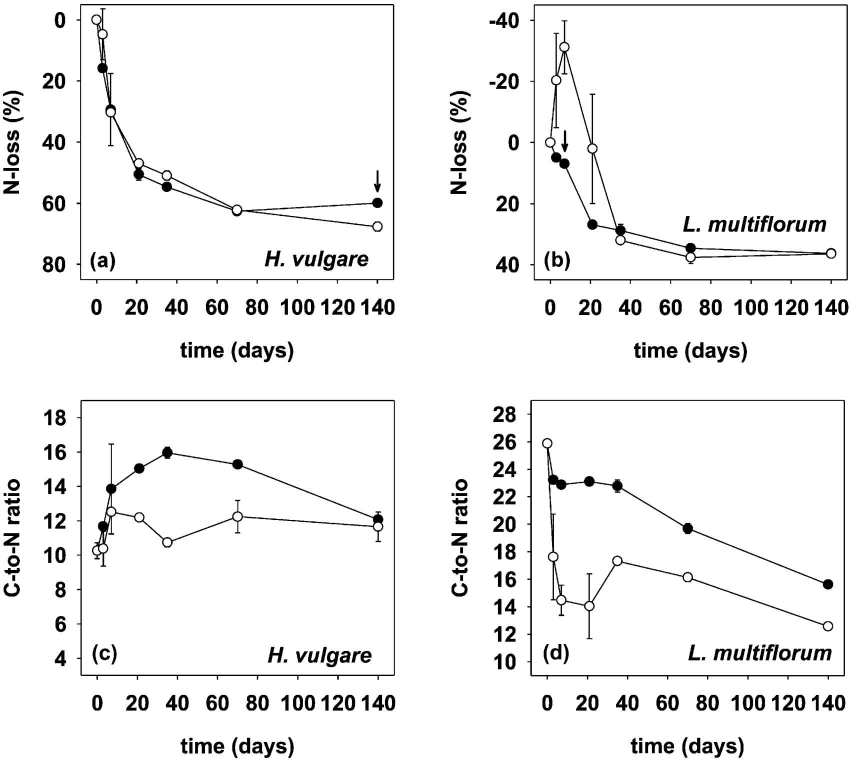


Figure 8 Decomposition of barley and ryegrass at 3°C (●) and 9°C (○): [(a) and (b)] N-loss (%) of initial added N versus time, [(c) and (d)] C/N ratios of remaining plant residues versus time (Magid, unpublished data).

residue decomposition and found that modelling of CO_2 evolution data could best be achieved by a two compartment parameterisation of the organic resource, assuming that the rate constants for each compartment would be similarly affected by temperature.

In accordance with Katterer *et al.* (1998) the generally recognised soil organic matter models used in integrated analysis of management and environmental issues are build on the assumption that organic resources can be conceptually divided in homogenous compartments characterised by first order rate decay and constant nutrient ratios (Parton *et al.*, 1988). Therefore, the temperature dependency of N mineralisation in such models is the same as that of C mineralisation.

To be able to simulate the effects of incorporation of catch crops or other green plant materials into cold soil, simulation models must be changed to simulate the fast N mineralisation at low temperatures.

It may be a matter of concern, that the conditions in laboratory studies may be too far removed from the field situation. Typically, the residues to be studied in the laboratory are dried and ground and mixed thoroughly with the soil. Further, temperature is kept constant, and often high compared to the normal conditions at the time of catch crop incorporation in the field. Soil humidity is also kept constant, and mass-flow of water in the soil does not occur.

In the field, larger pieces of living plant material are mixed inhomogenously with the soil by incorporation. Further, much of the decomposition may occur even before incorporation, as it will clearly happen with catch crops which are winter killed in the field before incorporation (Thorup-Kristensen, 1994b). But it also happens with catch crops which are incorporated as living plants, as they may loose considerable amounts of leaf litter during growth.

Most often the materials used in incubation studies are mixtures of all the aboveground plant parts. Only few have studied the N mineralisation from the plant roots (Franzleubbers *et al*., 1994a,b; Thomsen, 1993). Roots have a different morphology than stems and leaves, which often make them less prone to microbial invasion and decomposition (Neergaard *et al*., 2002).

Some of these differences between the laboratory studies and the conditions in the field have been investigated (Esala, 1995; Breland, 1994a,b, 1996a), and have been found to affect the results. Breland (1994a) and Jensen (1994) studied effects of particle size and distribution. Jensen (1994) found that the normal practice of grinding straw material prior to incubation led to a much higher N immobilisation compared to the same straw materials cut in pieces.

The extent of errors which may occur when using laboratory incubation data for modelling catch crop N release under field conditions is not clear, but they may be large in some situations (Thorup-Kristensen and Nielsen, 1998). It is therefore very important that the models are carefully tested and calibrated against field data before their simulations of the field effects can be trusted.

D. DEPTH DISTRIBUTION OF INORGANIC N

As discussed above, the N_{eff} of a catch crop in the field is determined by the two main effects pre-emptive competition and mineralisation, and this combined effect can be described with Eq. (1). However, not only the total amount of inorganic N available from the soil is affected; but also its depth distribution is strongly affected (Fig. 9b and c). This occurs as the normally positive effect of N mineralisation is reflected mainly as an increased content of inorganic N in the upper soil layers where the mineralisation occurs. Contrary to this, the negative effect of pre-emptive competition is mainly reflected as a reduced content of inorganic N in deeper soil layers (Thorup-Kristensen, 1993b). The reduced content of inorganic N in the deeper soil layers is found as catch crops prevent

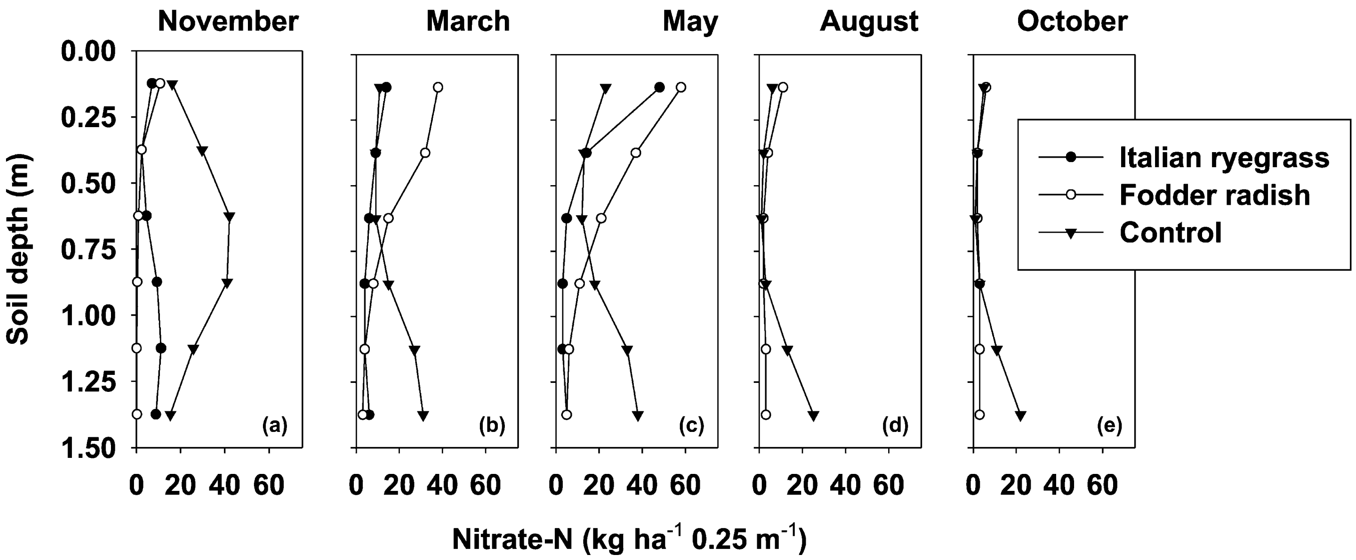


Figure 9 Nitrate-N distributions in the soil profile at five dates during and after catch crop growth. The catch crops followed a green pea crop, and were sown in early August. The soil nitrate measurements were made in November under the still growing catch crops (a), in March just before incorporation of the catch crops (b), in mid-May approximately 6 weeks after catch crop incorporation and approximately 3 weeks after sowing of a barley crop (c), in August just after harvest of the barley crop (d), and in October under a new catch crop (e) consisting of a grass clover mixture which had been undersown in the barley crop [data from the experiment of Thorup-Kristensen (2001)].

N leaching to deeper soil layers, and to some extent due to direct catch crop N uptake from deeper soil layers.

This altered depth distribution of inorganic N is shown in Fig. 9 and Table II. The difference in nitrate-N between control plots and catch crop plots in May is an estimate of N_{eff}. Estimated in this way for the full 1.5 m soil layer, the results indicate that N_{eff} of the fodder radish catch crop was close to zero, whereas the N_{eff} of ryegrass was strongly negative (Table II).

But this consideration depends strongly on the soil layer considered. If a soil layer of only 0.25 m or 0.5 m is considered, the data indicate a clearly positive N_{eff} by both of the catch crops. If a soil layer of 1.0 m is considered, ryegrass had almost no effect, whereas fodder radish still had a clearly positive N_{eff}. The nitrate-N data from August (Fig. 9d) indicate that the barley crop had an effective rooting depth of between 1.0 and 1.5 m. In accordance with this, ryegrass reduced the N uptake by the barley crop with approximately 20 kg N ha^{-1} whereas fodder radish increased the N uptake of barley with approximately 45 kg N ha^{-1}.

It is obvious from these data why N_{eff} depends on the rooting depth of the succeeding crop. If the succeeding crop had a rooting depth of 0.5 m or less, both catch crops are estimated to have a positive N_{eff} (Table II), but with deeper rooting, the estimated N_{eff} is reduced, and with rooting depths of 1.5 m, ryegrass is estimated to have a clearly negative N_{eff}. Thus the conclusion is that the same catch crop may have a positive N_{eff} if it is followed by a shallow rooted main crop, and a negative N_{eff} if it is followed by a deep rooted catch crop. In accordance with this, Willumsen and Thorup-Kristensen (2001) found that a winter rye catch crop increased the N uptake by shallow rooted onion crops, but reduced the N uptake by deep rooted white cabbage crops.

Basically, legume catch crops have the same effect of concentrating available N in the topsoil. But as they take their N not only from the soil, but also adds further N to the system by biological N fixation, the risk of an overall negative N_{eff} is much less than with non-legumes.

Figure 9 may also be used to illustrate why the N_{eff} of catch crops depends on soil type and precipitation. It is clear from the data from March and May how some of the nitrate present in upper soil layers in November has been leached to between 1.0 and 1.5 m during the winter season. On more sandy soils, or with higher winter precipitation the nitrate will leach even deeper, and the negative effect of catch crops observed in the deep soil layers in the spring will be reduced. This will lead to a more positive N_{eff} especially for deep rooted crops. With less precipitation on the other hand, more of the autumn N will be retained in the soil, and it may be found closer to the surface, i.e., the risk of negative N_{eff} will be higher.

The importance of the winter precipitation on N availability for subsequent crops is further shown in Fig. 10. Here it becomes apparent that while the use of cover crops can ensure a rather stable delivery of N to the subsequent crops regardless of winter precipitation, soil inorganic N content varies strongly

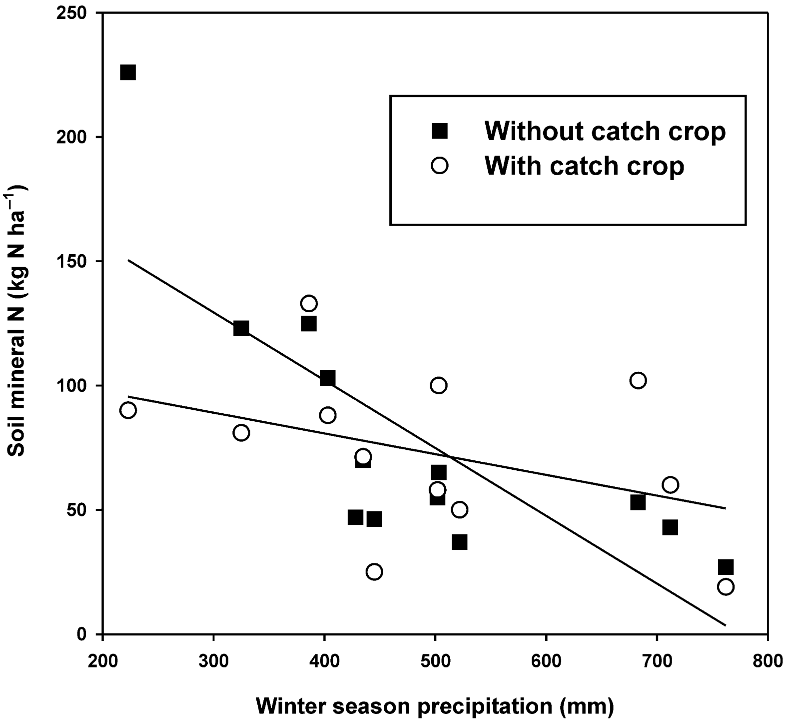


Figure 10 Spring soil nitrate-N content versus winter season precipitation with or without catch crops. The data shows spring soil nitrate N to be less sensitive to precipitation with than without catch crops. After dry winters catch crops tended to reduce soil nitrate-N content, whereas after wet winters they tended to increase it. Data from various experiments made at the Danish Institute of Agricultural Science, Department of Horticulture during the period 1985–2001.

depending on winter precipitation when no catch crop is grown. Without a catch crop, most of the available N is lost from the soil in the wet winters but most is retained in the dry winters. Thus, after dry winters a negative N_{eff} was estimated but after wet winters a positive N_{eff} was estimated.

E. GASEOUS LOSSES OF N

During their decomposition green materials have been shown to loose NH_3-N through volatilisation due to high NH_4 concentrations in the decomposing tissues (Harper *et al.*, 1995; Larsson *et al.*, 1998). After mineralisation as NH_4-N the nitrification–denitrification cycle may result in losses of N_2O (Aulakh *et al.*, 1991; Quemada and Cabrera, 1995; Larsson *et al.*, 1998; Rosecrance *et al.*, 2000).

Larsson *et al.* (1998) found substantial ammonia (17–39% of applied N) emissions from decomposing grass and alfalfa mulches, and nitrous oxide emissions were seen to exceed those from bare soil (1% of added N). Harper *et al.* (1995) found minimal ammonia emissions from clover mulches, and Whitehead *et al.* (1988) found ammonia emission to be strongly temperature dependent. It would seem likely that ammonia emissions are small when a catch crop or green manure are incorporated in a cool moist soil, compared to the mulching situation. Baggs *et al.* (2000) studied the fate of nitrogen from incorporated cover crops and green manure residues in field trials in NE Scotland. Under the prevalent cool conditions they found very small differences in N_2O emissions between plots with or without cover crops. Generally, emissions were lower on the planted plots when they effectively lowered NO_3 concentrations in the soil system, but somewhat higher during their decomposition phase.

F. FIELD EFFECTS

Various measures have been used to estimate the field effect of catch crops. The effect has also been measured as the effects on spring soil inorganic N content or on crop N uptake. Though these methods have their drawbacks, e.g., in deciding measurement depth for soil inorganic N content, they may be the most direct measures of N_{eff}, which we can make. However, they do not tell the farmer how much the N fertilisation of the crops may be reduced due to a catch crop, as the uptake of N from chemical fertilisers is also well below 100%. Therefore, a number of experiments have been designed to determine a "fertiliser replacement value" (e.g., Stute and Posner, 1995a). Apart from the effect on the first succeeding crop, catch crops also increase the N supply for later crops. Finally, in a number of experiments the N mineralisation from catch crops residues have been studied by ^{15}N techniques or by difference methods, but as discussed above, a measure of N mineralisation is not an estimate of the N_{eff} of a catch crop.

Though exceptions exist, the various field estimates of N_{eff} are rarely high. Many examples can be found where soil tests or measurements of N uptake in subsequent crops indicate that only between 0 and 25% of catch crop N can be used in the next year (Andersen and Olsen, 1993; Ladd *et al.*, 1981, 1983; Vyn *et al.*, 1999, 2000). A number of results even show a clearly negative N_{eff} (e.g., Francis *et al.*, 1998; Muller *et al.*, 1989; Sørensen, 1992), and in some experiments N_{eff} varies strongly with catch crop species, with negative N_{eff} of some species and positive N_{eff} of others (Vyn *et al.*, 1999, 2000; Willumsen and Thorup-Kristensen, 2001; Table IV).

1. Recovery of Catch Crop N

An issue of considerable agronomic interest is the efficacy of various fertilisers, whether organic or inorganic. For the commonly used compound N fertilisers a transfer of approximately 50% is typically found during the first season, and only a small residual effect can be measured in later years, indicating that considerable losses must have occurred. Even under the most carefully observed addition and subsequent management of the crops in research experiments, using ^{15}N as a tracer, the recovery of ^{15}N from compound fertiliser was most often less than 60%, which was comparable to recovery from ^{15}N in stored urine, while recovery of ^{15}N labelled faeces was lower, in the range of 9–17% (Parton *et al.*, 1988; Sørensen *et al.*, 1994; Sørensen and Jensen, 1996, 1998; Theunissen, 1995; Thomsen *et al.*, 1997).

From our own experiments we have seen substantial transfers of N to the subsequent cash crop, although we have only one trial that seems appropriate for quantification (Fig. 7). In this trial above ground cover crops were removed from the field, and then reintroduced in other plots in increasing amounts, where carrots were subsequently grown. The resulting response curve indicates an efficacy of transfer of 34% during the first season after cover crop incorporation.

This result cannot be generalised, but is consistent with a number of experiments where the succeeding crop has shown a very substantial positive response to green manures. Thus it would seem that the efficacy of cover crops might be on the same level as that commonly found for animal slurries (mixtures of urine and faeces).

Very little data on efficacy of cover crops in temperate agro-ecosystems are available. Paustian *et al.* (1992) inferred from experiments covering a 30 year period that the long-term efficacy of transfer of N from green materials to subsequent crops would be near 40%. After a 6-year experiment Schröder *et al.* (1996) estimated that 58, 50, 115 and 73% of the N added in pig slurry, fertiliser N, rye catch crop and ryegrass catch crop, respectively, were recovered in the maize crops or in the soil by the end of the experiment. The effect of the catch crops is overestimated as only the aboveground plant parts were considered (Schröder *et al.*, 1996), but anyhow, the results indicate that the utilisation of catch crop N in the longer term can be as high as that of inorganic fertiliser.

Paustian *et al.* (1992) reported yield and soil organic matter data covering a 30 year period in long-term plots covering a number of treatments among which were green manure, farm yard manure, compound fertiliser and no fertiliser treatment. Like the farmyard manure and the compound fertiliser, the green manure was added to the plots and not grown there, thus precluding pre-emptive competition effects.

A calculation indicates that losses mainly due to leaching were no different between the two treatments (Table III), and that the lower recovery of N in

Table III

Complete N Balances of a 30-year Long-term Organic Amendment and Fertiliser Experiment (Paustian *et al.*, 1992)

	Green manure (g N m^{-2})	% of total input	Compound fertiliser (g N m^{-2})	% of total input
Input				
Deposition	49		49	
Fertiliser total N	313		256	
Sum of input	362		305	
Output				
Harvested N	269	74.3	291	95.4
Measured net change in total soil N	38	10.5	−25	−8.2
Losses[a]	55	15.2	39	12.8
% Fertiliser total N harvested relative to no fertilisation treatment (nitrogen use efficiency)		39.6		57.0

[a] Losses = Sum of input N − Harvested N − Measured net change in total soil N over a 30-year period.

harvested crops in the green manure treatment (74 versus 95%) was balanced completely by a build up of soil organic matter.

The calculations of harvested N and losses both show that while the compound fertiliser treatment was most efficient in terms of transfer to the crop, the green manure treatment came quite close in efficiency, and that green manure carried on to a plot may be comparable to, e.g., pig slurry in terms of fertiliser effects. However, it is important to bear in mind that since the green manures were not grown in the amended plots themselves effects such as pre-emptive competition are not included in the overall picture in this experiment.

2. Fertiliser Replacement Value

In experiments where the effect of catch crops is compared to the effect of added fertilisers, a mineral fertiliser equivalent (FE) can be estimated. This is a rather indirect measure of catch crop N_{eff}, and will include other effects than the N effects (Janzen and Schaalje, 1992). An example of this was shown by Decker *et al.* (1994). They observed a negative N_{eff} of a wheat catch crop, and positive N_{eff} of legume catch crops, but they found little difference in the optimal N rate for the succeeding maize crop. Though the legumes increased maize yield at zero fertilisation to almost the level of optimally fertilised maize where no catch crop had been grown, they also increased the optimal yield, and thus a response to fertiliser application was observed. Though the measurements of fertiliser value are very indirect measurements of catch crop effects, they may still give our best estimate of the value of catch crops for the farmers.

When catch crops are found to have a positive effect, FE is sometimes found to be very high as compared to more direct measurements of N_{eff}. Decker *et al.* (1994) found that legumes increased the N uptake by maize with 50–70 kg N ha^{-1}, but to achieve the same N uptake without a catch crop, 135 kg N ha^{-1} had to be added. Dou *et al.* (1994) compared the effect of hairy vetch and red clover to the addition of 200 kg N ha^{-1}. The effect of the legumes on maize N uptake was around 50 and 100% of the effect of adding 200 kg N ha^{-1} in the no-till and conventional till systems, respectively. Schröder *et al.* (1996) found that an unfertilised ryegrass catch crop could not replace any N fertiliser, but when adding 100 or 200 kg N ha^{-1} to the ryegrass, fertiliser values of almost 50 and almost 100 kg N ha^{-1} was found. Red clover, which in the same experiment took up only 57 kg N ha^{-1} in aboveground plant material was found to have a FE of almost 100 kg N ha^{-1}. Stute and Posner (1995a) found fertiliser replacements of various legume crops ranging from around 20 kg N ha^{-1} to many examples of values between 100 and 200 kg N ha^{-1}. The effect of the green manures on maize N uptake was much smaller, and on average only about 20 kg ha^{-1}. During a 6-year experiment Schröder *et al.* (1996) found more moderate FE of rye and ryegrass catch crops in the order of 20–40 kg N ha^{-1}.

FE is not only a product of the catch crop itself, but also of the succeeding crop. In the experiment of Sørensen and Thorup-Kristensen (1993), catch crops of ryegrass and phacelia were found to increase the N uptake of both onion and white cabbage (Thorup-Kristensen, 1993b) with 35 kg N ha^{-1}, but as onion took up 32% of added fertiliser N and white cabbage took up 61% of added N, the estimated FE was 111 and 60 kg N ha^{-1}, respectively, for the two vegetable crops.

As maybe the best measure of agricultural value of catch crop N effects, sometimes very high FE demonstrates a high potential for using catch crops. In systems with cheap and unlimited access to fertiliser N this may not be enough to make them attractive to farmers (Stute and Posner, 1995a). In agricultural systems where access to fertiliser N is limited, such as in organic farming, water protection areas or in less intensive agriculture the potential for using catch crops and green manure is high. The strongly variable results, varying from substantially negative effects to effects equivalent to 200 kg N ha^{-1} of fertiliser N, show that it is very important to know how to manage catch crops to obtain the better effects. Catch crop management to optimise catch crop effects will be discussed in detail in Chapter 5.

3. Second Year and Longer Term Effect

As discussed in earlier sections, the immediate effects of catch crops and green manures on soil fertility are determined by a multitude of factors. As pre-emptive competition will rarely affect the N supply for the second succeeding crop, the effect of catch crops in the second year and onwards is likely to depend primarily on continued N mineralisation.

One important factor for the short-term effects on soil C and N content is the relationship between residue quality and decomposition. In the longer term, this effect of plant matter quality on soil fertility is more likely to be overshadowed by the effect of total amount of organic matter added to the soil system. Mann (1959) concluded from the first year effects of catch crops that they were unpredictable and not related to catch crop biomass production or N content, but found clear relationships between the N content of catch crops and their effect on the second succeeding crop.

Studies of the N effect of catch crops during several years after incorporation of the catch crop have indicated quite low mineralisation rates (Ladd *et al*., 1983; Mann, 1959; Thomsen, 1993). Approximately 4–10% of the catch crop N is mineralised in the second year, and very little is mineralised in the third year (Jensen, 1992). Data on N uptake in a barley crop (Andersen and Olsen, 1993) showed no second year effect of catch crops, whereas Schröder *et al*. (1996) found that barley yields in the second year were slightly increased with 0.1–0.2 Mg ha^{-1}. These studies considered the longer-term effect of one catch crop, but repeated growing of catch crops can be expected to show more clear long-term effects.

A number of contributions give evidence of an appreciable increase in labile soil organic N after relatively few years (3–7 years) with catch crops (Thomsen and Christensen, 1999; Lewan, 1994; McCracken *et al*., 1989; Schröder *et al*., 1996; Torstensson and Aronsson, 2000; Kuo and Jellum, 2000; Kuo *et al*., 1997; Sainju and Singh, 1997; Garwood *et al*., 1999; Hansen *et al*., 2000). Paustian *et al*. (1992) estimated a net change in soil organic N content equivalent to approximately 30% of the N added with green manure (average C/N ratio 16.8, average lignin content 6%). In this example a calculation shows that catch crop N was utilised almost as effectively as fertiliser N, and that the difference was due to higher soil N storage when catch crops were used (Table III).

Sainju and Singh (1997) and Garwood *et al*. (1999) reported a consistent yield reduction by winter rye used as a catch crop over 7 years, but overall positive effects on the system N balance. Suction cups yielded increasing NO_3^- concentrations under catch cropped plots, but this was countered by an estimated decrease in drainage. These experiments have been conducted in a relatively dry environment where pre-emptive competition between winter rye and the following spring crops can have a substantial yield suppressive effect.

Schröder *et al.* (1996) reported an increased dry matter production in N deficient maize systems, stating that the effect corresponded to fertiliser N rates of 105% of aboveground N in rye and 40% of aboveground N in perennial ryegrass. Averaged over 6 years 115 and 73% of the aboveground N in rye and ryegrass were recovered in the crop-soil system.

Kuo and Jellum (2000) observed that while having vetch was the only cover crop that significantly increased N deficient maize yield, both winter rye and annual ryegrass benefited soil organic N and gradually improved maize biomass production compared with the control over the longer term (8 years).

The contribution of catch crops to the long-term mineralisation rate of the soil is a contribution to the general soil fertility (Kuo and Jellum, 2000; Schröder *et al*., 1996; Hansen and Djurhuus, 1997), but it may also lead to increased nitrate leaching losses in later years. The results of Thomsen and Christensen (1999) indicate that increased leaching loss on the long-term reduced the overall catch crop effect with as much as 30% compared to the effect on nitrate leaching measured in the years when the catch crops were grown. However, the soil type and crop choice in this experiment favoured leaching, and in general such losses can be expected to be lower. The extent of such losses will depend on crop rotation and fertilisation level (Thomsen and Christensen, 1999) as well as soil type and climate. Gustafson *et al.* (2000) estimated that continued catch cropping reduced N leaching losses with an average of 50% over successive years.

The issue of long-term efficiency of systematic use of catch crops and green manures may be more affected by the managers ability to choose appropriate crops suited for the local hydrological regime, and especially the avoidance of excessive pre-emptive competition. This may be formulated as a question: is it possible to continually loose less and sustain a higher production level with the use of catch crops and green manures?

IV. OTHER EFFECTS OF CATCH CROPS

Although the major argument for incorporating catch crops and green manures into crop rotations has been to increase the N supply for succeeding crops, many other positive as well as some negative effects of catch crops and green manures have been documented (Biederbeck *et al*., 1998; Janzen and Schaalje, 1992; Sainju and Singh, 1997; Yadvinder *et al*., 1992). Some of these effects may deserve equal attention as the pure N effects, since they may not only substitute other resources, but actually enhance the yield or quality potential of the crop. As an example, there may be a positive interaction between, e.g., soil structural effects of the catch crops and the yield response of the main crop to supplied N. Furthermore, as described earlier, conventional farmers are not likely to use catch crops and green manures for their value as N source alone, due to the low price of fertilizer N. However, if other significantly positive effects exist, the sum of these may prove sufficiently profitable to encourage their use by conventional farmers, even if their positive environmental effects are disregarded.

Non-nitrogen effects may be divided into (i) effects on nutrient availability other than N, (ii) effects on soil biological activity, (iii) effects on the soil as a growth medium for the crop, (iv) effects on soil water content, and (v) effects on crop pests, pathogens and weeds.

A. EFFECTS ON OTHER NUTRIENTS THAN N

For phosphorous availability, two principal effects of catch crops and green manures may be hypothesised. Firstly, catch crops and green manures take up soil P and thus convert it from inorganic to organic form. Some species may have especially high P uptake capability, e.g., by forming particularly long root hairs (Gahoonia and Nielsen, 1997; Gahoonia *et al*., 2000), by acidifying the rhizosphere (e.g., most leguminous species), root-exudation of organic acids (Jones, 1998; e.g., in buckwheat and lupines) or high affinity for mycorrhiza. Upon incorporation of the residues into the soil the plant P is released slowly and is not as susceptible to adsorption and precipitation as inorganic P fertilisers. Moreover, as catch crop residues are typically heterogeneously distributed in the soil after incorporation, the immobilisation of released residue P is further hampered by the reduced contact with the soil matrix. This is likely to improve the crop competitive advantage, as has been shown for crop residue N with increasing heterogeneity of the incorporated residues (Wang and Bakken, 1997).

Secondly, it may be hypothesised that during decomposition, catch crop and green manure residues may mobilise some of the otherwise unavailable soil P, e.g., by release of organic acids, analogous to the release of organic exudates from roots.

However, recent attempts to verify this hypothesis have not been able to identify significant amounts of organic acids in the residue-sphere, and other studies have questioned the presumption that organic acid exudation is the reason for the high P uptake capability of some species on low P soil (Jones, 1998). Catch crops and green manure effects on phosphorous availability may thus most likely be simply due to their P uptake, and the availability to the subsequent crop determined by the residue C/P ratio and the soil P status (Thibaud *et al*., 1988).

Not many studies have quantified catch crop P uptake under temperate conditions. In a 6-year experimental period Vos and Van der Putten (2000) found that the catch crops winter rye, oil radish and forage rape catch crops in a conventional cropping system contained between 4 and 9 kg P ha^{-1} in aboveground biomass prior to incorporation in spring. However, catch crop dry matter production in this study was low and ranged between 0.4 and 0.9 mg ha^{-1}; if higher catch crop biomass production occurs, larger P uptakes must be anticipated.

For potassium, catch crops and green manures effects on K availability may be rather straightforward. Potassium taken up by the catch crop is usually very quickly released upon incorporation (e.g., Lupwayi and Haque, 1998) and thus likely to be equally available to fertiliser K. As for P, amounts of K taken up by catch crops may vary, Vos and van der Putten (2000) found between 21 and 45 kg K ha^{-1} in aboveground biomass in spring. Catch crops may also affect the content of K and other cations in the soil water directly by their uptake of these ions, or indirectly as they deplete the soil water for anions such as nitrate and sulphate (Yanai *et al*., 1996). Jäggli (1978) showed an example of how losses of K, Ca, and Mg were reduced by catch crops, and Scott *et al* (1919) showed how the soil content of a number of plant nutrients was affected by continuous use of catch cropping with vetch or rye/legume mixtures.

Sulphur deficiency has become an important feature of most North European arable cropping systems, due to the greatly reduced sulphur emissions from fossil fuels. Sulphur behaves very similar to nitrogen in the soil system, and it can easily be lost by leaching in the form of sulphate. Very few studies have focussed specifically on the effects of catch crops on sulphur retention and availability. Eriksen and Thorup-Kristensen (2002) have shown that catch crops may exert a similar influence on the distribution of soil sulphate as for soil mineral N, although the depletion of the soil profile was not as efficient for sulphate. They also showed that the uptake capability can be quite high, and that the variation among catch crop species may be substantially larger than for N. In particular cruciferous species, which usually have a high plant S concentration, showed high uptakes of 22–36 kg S ha^{-1}, compared to only 8 kg S ha^{-1} taken up Italian ryegrass. This was also manifested in the S availability effect on the subsequent crop. Spring barley after an oil radish catch crop thus contained about 50% more S than barley in the control plots where no catch crop had been grown, whereas a ryegrass catch crop actually decreased the subsequent crop S uptake compared to the control.

For micronutrients, catch crops do not constitute a significant source or sink. However, they may exert a significant influence on their availability, through their influence on redox potential of the soil or through increased chelation capacity (Hinsinger, 1998), and either may be caused by the increased biological activity and organic matter turnover (Yadvinder *et al*., 1992). However, no specific studies on catch crop and green manure effects on these properties have been conducted under temperate conditions.

B. Effects on Soil Microbiological and Faunal Activity

Effects of catch crops and green manures on soil biological activity are evident in both the short- and long-term, as also discussed in Section III.C "What Determines N Mineralisation"

Depending on the magnitude of catch crop biomass inputs, several years with frequent catch crops may increase soil microbial biomass by up to 60% and cellulytic enzyme activities by 90% (Debosz *et al*., 1999; Mendes *et al*., 1999). Effects on total soil C are small, however, Kuo *et al*. (1997) demonstrated how 7 consecutive years of cover cropping in continuous maize only increased the soil C content with 3–5% in the top 15 cm, even though the yearly biomass input from the most productive cover crops was in the order of 4 Mg ha^{-1} aboveground and 4–5 Mg ha^{-1} below ground. Catch crops will add substrate to the soil microorganisms not only at the time of their incorporation, but all through their growth period as well. Through root exudation, root turnover, symbiosis with mycorrhiza and through leaf litter loss from aboveground plant parts, substrate will be added to the soil all through the growth period of the catch crop.

Catch crops and green manures may also exert a significant effect on soil vesicular–arbuscular mycorrhiza (VAM). VAM fungal infection potential has been shown to increase in maize after cover cropping (Boswell *et al*., 1998; Kabir and Koide, 2000), whereas no effect or even slight negative effects were shown in small grain cereals (Baltruschat and Dehne, 1989).

Only few studies exist on the specific effects of catch crops and green manures on soil fauna. However, as the application of organic matter will increase the densities of most members of the detritus food web, this is likely to occur also in systems where catch crops and green manures are frequently applied. In a study of microarthropods, significantly higher abundances of collembola and mites were found after incorporation of catch crops and green manures (Axelsen and Kristensen, 2001), with fodder radish promoting densities of up 120,000 collembola and 90,000 mites m^{-2}, compared to 30,000 and 50,000 m^{-2} in the control without catch crop. Filser (1995) and Scholte and Lootsma (1998) found much higher densities of collembola in green manured compared to mineral fertilised fields, albeit at much lower total densities than (Axelsen and Kristensen, 2001).

Recently, it has also been speculated that cover crops may influence the degradation potential of the soil for pesticides. Bottomley *et al*. (1999) studied the degradation of the herbicide 2,4-D, and consistently found increased degradative capabilities of both surface and subsoil layers after a rye cover crop compared to no cover crop in a vegetable cropping system. The increased capability persisted longer than the cropping season immediately following the cover crop incorporation, and thus cover crops may possibly play a role in preventing pesticide leaching.

C. EFFECTS ON SOIL PHYSICAL PROPERTIES

Organic matter is known to improve a range of soil physical properties, including both soil structure and water retention. Catch crop and green manure effects may be divided into effects on soil tilth (soil surface strength, friability, aggregate stability) and soil porosity (air permeability, hydraulic conductivity, water retention). These may in turn affect crop establishment (seedling emergence), root development and soil losses by runoff and erosion (Meyer *et al*., 1999).

Cover crops have been shown to positively influence soil tilth by reducing the soil surface strength, created by crusting of the soil upon the impact of rainfall (Folorunso *et al*., 1992), which disrupts and slakes soil aggregates at the surface. They showed that an oat-vetch cover crop reduced soil surface strength by 24–41% depending on soil type. Winter cover crops have also been shown to increase aggregate stability, protecting against aggregate breakdown during winter and resulting in better friability and structure after spring tillage (Hermawan and Bomke, 1997).

If catch crop residues are left on the soil surface or only lightly incorporated, this may also affect the soil moisture regime dramatically by altering evaporation and soil temperature (Teasdale and Mohler, 1993). However, during active growth, catch crops and green manures deplete the available soil water and may thus impact the water supply for establishment of a subsequent crop, at least in climates with a low winter precipitation (Mitchell *et al*., 1999).

Soil porosity (Scott *et al*., 1919) and subsequent root growth have been shown to be positively influenced by a clover green manure prior to a lettuce crop (Stirzaker and White, 1995). However, effects on root development may not only be due to green manure effects on soil porosity, but also to effects on soil mineral N distribution (Thorup-Kristensen and Van den Boogaard, 1999) or possibly to allelopathic effects (Burgos *et al*., 1999; Creamer *et al*., 1996).

D. EFFECTS ON SOIL WATER CONTENT

The use of water by catch crops may be a serious problem when catch crops are grown in areas with limited rainfall (Harper *et al*., 1995). The effects on soil water content are very different from the effects on plant nutrients. Whereas catch crops do not remove nutrients from the field, and may even prevent losses, a growing catch crop will remove water from the field.

The use of water by a catch crop may occur in pre-emptive competition with the succeeding crop, as previously discussed with N. The effects on water are simpler than the effect on N though, as there is no positive effect resembling the N mineralisation from catch crop residues obscuring the observation of the pre-emptive competition. Thus only the negative effects of water use by the catch crops are observed. In California, McGuire *et al.* (1998) and Mitchell *et al.* (1999) observed reductions in spring soil water content of up to 80 mm due to catch crops. The water use by catch crops depends strongly on the growing conditions and growth period of the catch crops and under more northern conditions the water use will generally be small. However, not all water use by catch crops cause pre-emptive competition. In areas with sufficient surplus precipitation the water used by catch crops will be replaced, and only water percolation will be reduced, whereas spring soil water storage is not affected, as also McGuire *et al.* (1998) observed in one year with high winter precipitation. This is also one reason why spring water use by catch crops become a special problem; it not only increases the total water use by the catch crop, and whereas the water used in the autumn has a good chance of being replenished by subsequent precipitation this is much less likely with water used in the spring. Thus as with pre-emptive competition for N, the pre-emptive competition for water may be strongly increased by allowing active catch crop growth in the spring.

E. EFFECTS ON PESTS, PATHOGENS AND WEEDS

The majority of studies on catch crop and green manure effects on crop pests have dealt with possible effects on plant parasitic nematodes (Abawi and Widmer, 2000). On the one hand, a catch crop may increase the risk of infestation with certain parasitic nematodes that may propagate on a susceptible catch crop; on the other hand, catch crops may exert a nematicidal effect through their decomposition products. The effect seems to be largely dependant on the catch crop species. Abawi and Widmer (2000) tested the effect of a range of incorporated catch crops on infestation of bean with lesion nematodes and found effects to vary by a factor of 35, the most efficient repressors being ryegrass and rapeseed, the most promoting being Hairy vetch. McBride *et al.* (1999) demonstrated that rye catch crop foliage significantly reduced cotton root-knot nematode populations for at least 21 days. They hypothesised that the effect was due to the production of low molecular weight acids during decomposition, but they were only able to detect low concentrations of such acids in the soil solution, and found that these acids were being degraded extremely rapidly in the soil. Thus the mechanisms behind the nematicidal effects are not known.

A very common concern amongst farmers is the possibility that introducing catch crops or green manures may propagate certain soil-borne pathogens, which may render the soil inappropriate for certain crops for decades. This has been a particular concern for a number of root diseases of different crops. However, several studies have shown that catch crops and green manures can be used as break crops, actually having a suppressive effect, reducing the soil-borne pathogen intensity (Davis *et al.*, 1996; Muehlchen *et al.*, 1990; Sumner *et al.*, 1995; Theunissen and Schelling, 2000; Tu, 1988; Williams-Woodward *et al.*, 1997; Yamagishi *et al.*, 1986). Cunningham (1983) on the other hand found no effect of ryegrass or white mustard catch crops on take-all and eyespot on barley in a long-term (14 years) experiment.

The mechanisms involved in disease suppression or propagation are numerous and often unknown. Some of the mechanisms may be common with effects of organic matter amendments in general (Linderman, 1989), such as release of certain organic compounds with toxic effects or the stimulation of microbial activity resulting in increasing competitive or antagonistic suppression of pathogenic organisms. Many root disease studies indicate positive effects only of certain cover crops. Yamagishi *et al.* (1986) found that cruciferous cover crops reduced club root, Theunissen and Schelling (2000) found undersown clover to reduce cavity spot in carrots, and Davis *et al.* (1996) found sudangrass or corn green manures to reduce Verticillium wilt of potato. These studies also underline that the cover crop species greatly influences repression effectivity, Abawi and Widmer (2000) found anything from a 10% increase (after white clover) to a 40% decrease (after rapeseed) in the effect of a range of incorporated cover on root rot of beans.

A number of studies have been concerned with root rot of pea, Williams-Woodward *et al.* (1997), Tu and Findlay (1986) and Muehlchen *et al.* (1990) have found cover crops, in particular oats and crucifers (white mustard and rape), to significantly reduce pea root rot caused by *Aphanomyces eutiches*. However, Bødker and Thorup-Kristensen (1999) found the effect to be highly variable between years, with oil radish reducing incidence of *A. eutides* one year and increasing it another year.

The effects of catch crops and green manures on weeds are often more variable than those observed for pests and diseases. Again, the mechanisms may be multiple (Liebman and Dyck, 1993). On the one hand, weeds may be suppressed by either direct competition and allellopathy or by phytotoxic effects on germinating weeds upon incorporation of the green manure (Creamer *et al.*, 1996; Hoffmann *et al.*, 1996; Teasdale & Daughtry, 1993). On the other hand, catch crops may promote weed infestation by hindering chemical or mechanical weed control, or for persistent catch crops and green manures actually acting as weeds themselves later in the cropping sequence.

Based on such very different mechanisms it is not surprising that greatly variable and inconsistent results have often been found, e.g., in pea (Khatib *et al.*, 1997), in soybean (Moore *et al.*, 1994; Leiebl *et al.*, 1992) and in corn (Hoffmann *et al.*, 1993). However, Boydston and Hang (1995) found that a rapeseed catch crop was very effective in controlling weed density (73–85% reduction) in potato production, greatly enhancing the yield (17–25%). As mentioned above, decomposing cover crop material may produce phytotoxic substance that retard weed germination, but this may affect the main crop establishment and growth as well, especially in sensitive cultures as many vegetables (Stirzaker and Bunn, 1996). This underline the fact that also in this respect, correct cover crop management strategies are crucial for success.

V. MAKING THE MOST OF CATCH CROPS IN CROPPING SEQUENCES AND WHOLE CROP ROTATIONS

Before deciding on a strategy for optimal effects of catch crops, it is important to define the precise goals. It is clear that the goals may differ between farmers and the policy makers. Where the policy makers aim at reducing leaching losses and environmental problems, the farmers must try to optimise profitability through low costs of establishment and positive effects on succeeding crops (Lu *et al*., 1999). Also policy makers must try to find cost effective methods to reduce leaching losses (Hasler, 1998; Lu *et al*., 1999; Gustafson *et al*., 2000).

As the goals are different, the methods may also be different, but the strategies which can be adopted to optimise N_{eff} of a catch crop will often also improve its environmental effect. Where the farmers prioritise other goals, such as effects on soilborne diseases, soil structure, erosion control, minimising the cost of growing a catch crop, or N fixation by legumes, the choices made by the farmer may conflict with the interests of the policy makers.

To reach the goals at the farm level, the farmer has several agronomic management tools to optimise the N_{eff} of catch crops:

- The placement of the catch crops within the crop rotation, which determines both how much N will be available for the catch crops to take up, and the subsequent N_{eff} of the catch crop due to interactions with factors such as rooting depth of the succeeding crop.
- The choice of time and method of catch crop establishment, which determines cost and efficiency of catch crop establishment.
- The choice of catch crop incorporation time which may strongly affect N_{eff} through effects on mineralisation, leaching, pre-emptive competition and the depth distribution of the inorganic N in the soil.
- The choice of catch crop species, which affects practically all other factors through effects on N uptake capacity, rooting depth, kill off time and C/N ratios.

In the text below, we will discuss these main management tools available to the farmers for optimising the effects of catch crops.

The management of catch crops is complex, and tools and effects should of course not be considered in isolation but in the context of whole crop rotations.

In order to integrate the various processes and their interactive effects, we have carried out model scenario simulations, which will be presented to illustrate effects on both crop production and environmental protection.

At the policy level, the goals are different, and other management tools are available. Regulations can be made to favour catch crops on specific farm types or soil types to reduce overall leaching losses or in specific geographical regions to protect vulnerable environments or aquifers. The management of catch crops at the policy level will be discussed at the end of this chapter.

A. PLACING CATCH CROPS IN THE CROP ROTATION

One of the most important management tools which can be used to improve the results of catch crops, is choosing the right place in the crop rotation to grow the catch crops. To achieve a high N_{eff}, the farmer must consider (1) whether much leachable N is present in the field, (2) whether an efficient catch crop can be established, and (3) whether the next years crop will respond well.

The amount of N available to a catch crop depends on the previous main crop and the cropping history (Janzen and Radder, 1989; Aufhammer *et al*., 1992; Jensen, 1991; Shepherd *et al*., 1993; Kessavalou and Walters, 1999). Much N can be available in the soil after intensively fertilised crops, especially if organic fertilizer has been used (Jackson *et al*., 1993; Kessavalou and Walters, 1999; Sainju *et al*., 1999; Thorup-Kristensen and Van den Boogaard, 1999), after crops leaving high amounts of N rich residues in the field or after plough down of perennial crops (Francis *et al*., 1995; Shepherd, 1993). Much N can also be available if shallow-rooted crops have been grown, as they have only exploited the uppermost parts of the soil (Jackson and Stivers, 1993; Thorup-Kristensen and Sørensen, 1999), and much of this will then be available in deeper soil layers. Even with relatively deep-rooted crops increased fertilisation within one year may, though the fertiliser is added to upper soil layers, lead to increased subsoil nitrate content at harvest (Kessavalou and Walters, 1999; Sainju *et al*., 1999; Thorup-Kristensen, 1993b). Such deep N can only be taken up if deep-rooted catch crops are grown.

Furthermore, much N can be present in the autumn as a result of what happened in previous years. If perennial crops as a grass-clover ley have been ploughed under 1 or 2 years earlier, or if much farmyard manure has been used, mineralisation rates may still be high. Further, if much N is left in the soil in one autumn, some of this can still be available in the next autumn. This will typically be found in deeper soil layers, as there has been considerable time for downwards leaching, and a main crop have taken up what was available in upper soil layers (Fig. 9d; Dick and Christ, 1995; Izaurralde *et al*., 1995; Kessavalou and Walters, 1999; Sainju *et al*., 1999).

Another important point is to grow catch crops where they have a good chance to develop well. If the main crop is harvested late, there may be no point in growing a catch crop afterwards even if much leachable N is left in the soil after harvest. This dilemma is illustrated by the many studies made on catch crops in silage maize production in Europe (Schröder *et al.*, 1992; Ballcoelho and Roy, 1997; Schröder *et al.*, 1996; Shipley *et al.*, 1992). Silage maize is grown extensively in many parts of Europe, and is a crop which typically leaves much inorganic N in the soil after harvest. Still, the crop is harvested late, and the duration of the growing season for the catch crop after maize harvest will often be the factor limiting catch crop efficiency (Schröder *et al.*, 1996). Therefore, experiments with undersown catch crops in silage maize production have been made to secure a longer growing season for the catch crop (e.g., Ballcoelho and Roy, 1997). Generally, early harvested crops, or crops which allow effective establishment of undersown catch crops (see below) can give very good opportunities for growing catch crops.

Legume catch crops are generally not as effective as non-legumes to deplete soil inorganic N, and should therefore only be grown where little inorganic N is left in the soil (see Chapter 2), and where non-legumes would give little effect. However, the need for early establishment may be more important than with non-legume catch crops, as none of the legumes establish as rapidly as the fastest non-legumes, and it takes some time for the N_2 fixation to start. In some systems legume catch crops are expected to grow and fix N_2 mainly in the spring, e.g., before maize crops (Wagger, 1989), and then the autumn period should just allow efficient establishment, but not necessarily much growth of the legume catch crop.

Finally, the effect of a catch crop may depend strongly on crop species which are grown afterwards. As discussed in Section “Depth distribution of inorganic N” catch crops generally increase N availability in the uppermost soil layers and reduce it in the subsoil (Fig. 9c). This is advantageous to shallow rooted crops, but less so, or even disadvantageous to deeper rooted crops (Table II). As discussed in Section III.F.2 “Fertiliser Replacement Value” the estimated fertiliser replacement value of catch crops (Sørensen and Thorup-Kristensen, 1993) was 111 kg N ha^{-1} when it was followed by onions which have a very shallow root system, whereas it was 60 kg N ha^{-1} when it was followed by white cabbage. A similar result was found by Willumsen and Thorup-Kristensen (2001).

Schröder *et al.* (1997) compared catch crop effects on sugar beets and potatoes, and found less clear results. Sugar beet took up added fertiliser N more effectively than potatoes (70 versus 40%) and also took up catch crop N more effectively when the catch crop was ryegrass. Therefore, the fertiliser replacement value was not much affected by succeeding crop. However, potatoes recovered more of the N from a red clover catch crop than sugar beet, and a calculated fertiliser replacement value for the red clover catch crop was therefore approximately twice as high when it was followed by potatoes as when it was followed by sugar beet. (Shepherd, 1999) found that catch crops increased the yield and N uptake of succeeding potatoes but not that of sugar beet. However, as the potatoes were well fertilised they speculate that the effect on potato yield was not due to N effects of catch crops.

These results show that the farmer can strongly improve the effect of catch crops by choosing the optimal position in the crop rotation to grow catch crops. This includes N availability for the catch crop, the possible duration of the growing season, and the crop to be grown in the following year.

B. ESTABLISHING CATCH CROPS

Catch crops are grown in periods of the year, which are not suitable for commercial crop production. Thus the climatic conditions are often cold and the growing season short. To grow an effective catch crop, it is important to make the most of this period, and therefore it is important that the catch crop growth and N uptake starts as fast as possible after harvest of the main crop.

In most catch crop experiments catch crops have been established either during main crop growth or after main crop harvest, but in some experiments both methods have been used (Stute and Posner, 1995a; Jensen, 1991; Aufhammer *et al*., 1992). Undersowing allows the catch crop to be established already before harvest, but it may cost a yield loss in the main crop due to competition (Breland, 1996b). Growth of the main crop will influence the establishment of an undersown catch crop, and a reduced seeding rate of the main crop have sometimes been recommended when establishing catch crops in small cereals. Also the N supply to the main crop can be important. Breland (1996b) found that increased N fertilisation of a barley crop increased the subsequent growth and N uptake of a ryegrass catch crop, whereas it had the opposite effect on white clover and subterranean clover.

Catch crops sown after harvest will not interfere with the main crop, but may be more expensive to establish due to the extra field operations needed, and they will have shorter time for growth and N uptake. Based on this, Karlsson-Strese *et al*. (1998) worked to identify plant species and genotypes which do not compete strongly with the main crop.

In maize, vegetables, or other row crops the competition problem with undersown catch crops is even worse (Müller-Schärer, 1996; Lotz *et al*., 1997), as the row structure tends to reduce the competitiveness of the Main crop. However, as many row crops are late harvested and leave much available N in the soil, the potential of undersowing catch crops is large. Thus, experiments have been performed to develop systems where catch crops are undersown in row crops at a later stage, where the main crop is well established and has a higher competitive ability (Müller-Schärer, 1996; Lotz *et al.*, 1997; Schröder *et al.*, 1996; Aufhammer *et al.*, 1992; Ballcoelho and Roy, 1997).

It is not possible to draw a general conclusion from these experiments, but the results do show that in many situations such systems can be developed and the potential advantages of undersowing can thus be used. The specific solutions will depend on the main crop, catch crop species and local conditions.

When catch crops are sown after main crop harvest, attempts to establish them with reduced soil tillage is one way to reduce the cost of establishment (Shepherd, 1999), but it may also reduce the effect of the catch crop. After harvest of a main crop the soil may often be too dry to allow germination of a catch crop.

Choosing catch crop species is also important, as the amount and price of seed to be used differs greatly, and some species may be more tolerant to sub optimal seedbed preparation. This is the case with some of the crucifer species, where it has even been found possible to establish a catch crop just by spreading the seeds into a cereal crop approximately 2 weeks before its harvest. Choosing species, which germinate rapidly and establish a plant cover quickly will improve the utilisation of the short growing season.

One way to reduce the cost of catch crop establishment is to reduce the seeding rate. Few results have been published on this subject, but the results of Clark *et al.* (1994) show an example where reduced seeding rate reduced catch crop N uptake and the estimated N_{eff}.

C. INCORPORATION TIME

In a number of experiments the effect of incorporation time or kill date have been studied, and sometimes quite large effects have been found, indicating that incorporation time can be an important management tool. Many of the experiments have simply compared autumn incorporation to spring incorporation (Vyn *et al.*, 2000; Hansen *et al.*, 1997), but in some experiments two or three incorporation dates in the spring (Clark *et al.*, 1994, 1997a; Garwood *et al.*, 1999; Wagger, 1989) have been compared and in a few studies two incorporation dates in the autumn (Torstensson, 1998; Wallgren and Linden, 1994) have been compared. Thorup-Kristensen (1996) compared the effect of catch crops incorporated at five dates during the winter season, two in the autumn and three in the spring.

The results from these experiments demonstrate that changing incorporation date with a few weeks during the autumn or during the spring can affect leaching losses and N_{eff} strongly (Fig. 11). Postponing incorporation during the autumn will allow catch crops to take up more N. As N mineralisation will start later, it will also reduce the risk of leaching loss of N mineralised from the catch crop residues. The results from the published experiments (Thorup-Kristensen, 1996;

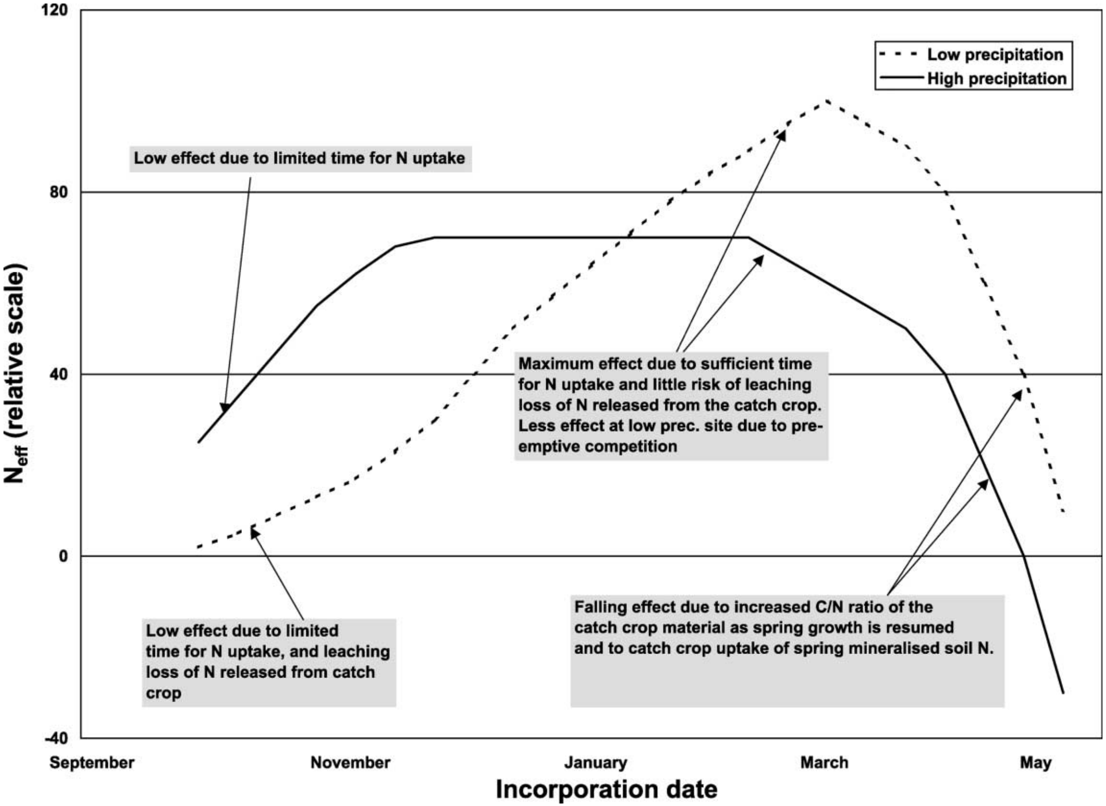


Figure 11 Effects of incorporation time on catch crops N_{eff} as dependent on precipitation regime.

Wallgren and Linden, 1994; Sanderson *et al.*, 1999) show that postponing incorporation during the autumn can significantly increase N_{eff}.

Postponing incorporation during the spring will lead to changes in plant residue quality parameters such as C/N ratio (Clark *et al.*, 1997a; Wagger, 1989) and lignification (Wagger, 1989) and thereby lead to slower N mineralisation (Wagger, 1989) or even immobilisation (Wyland *et al.*, 1995) from the incorporated residues. Postponing incorporation in the spring will also allow the catch crops to take up spring mineralised N from the soil. As this N would normally be directly available for the succeeding crop this uptake leads to a strong pre-emptive competition, and several results have shown reduced N_{eff} of non-legume catch crops when the incorporation is postponed during spring (Thorup-Kristensen, 1996).

With legume species postponing incorporation will allow more time for biological N fixation, and changes in C/N ratio will be smaller than with non-legumes, thereby making N_{eff} of legume catch crops less sensitive to incorporation time than that of non-legumes (Vyn *et al.*, 2000; Wagger, 1989; Clark *et al.*, 1994, 1997a; Wallgren and Linden, 1994). Vyn *et al.* (2000) found that a red clover catch crop increased maize yield with approximately 1.5 mg ha^{-1} irrespective of incorporation time, whereas rye reduced corn yield with 1.4 mg ha^{-1} when killed in the spring, but only 0.5 t ha^{-1} when killed in the autumn.

When legumes can be allowed to grow for a substantial period in the spring before incorporation this can actually be used to obtain increased N fixation (Clark *et al.*, 1997a) and increased mineralisation after incorporation. As an example, Clark *et al.* (1994) found that vetch increased subsequent corn yield with approximately 2 mg ha^{-1} when incorporated in April, but with approximately 3 mg ha^{-1} when incorporated in May. The effect of postponing incorporation of rye was opposite, as it had no effect on corn yield when incorporated in April, but reduced corn yield with approximately 1.5 mg ha^{-1} when incorporated in May.

After catch crops the available soil N is normally more strongly concentrated in the topsoil layers, with higher amounts of inorganic N in the uppermost soil layers and less in the deeper soil layers, an effect which becomes more marked with later incorporation (Sanderson *et al.*, 1999; Thorup-Kristensen, 1993b; Thorup-Kristensen and Van den Boogaard, 1999). It is also seen in experiments where species which survive the winter are compared to species which are naturally winter killed (Fig. 9c; Thorup-Kristensen, 1994b). This concentration of available N in the topsoil is an advantage for shallow rooted crops, but not necessarily for all crops (Table II).

Different incorporation dates of catch crops will also have other effects than effects on N_{eff} for the first succeeding crop. One example is that results from one long-term experiment indicate that repeated spring incorporation leads to higher soil C content than continued autumn incorporation (Hansen and Djurhuus, 1997).

Postponing incorporation will also allow more water use by the catch crop (Bollero and Bullock, 1994), though Clark *et al.* (1997b) found no effect. In areas where water availability is a main limitation to crop growth, increased water use can make late incorporation very disadvantageous for subsequent crop growth.

Some results show that catch crops can contain phytotoxic compounds, which may reduce the subsequent germination of other plant species, both crop and weed species (Dabney *et al.*, 1996). Incorporation of a catch crop very shortly before the establishment of the next crop will increase such effects, and can lead to problems of making an optimal seedbed preparation.

In conclusion, the highly significant effects on N_{eff} often found by changing incorporation date with a few weeks emphasise incorporation date as an important management tool in optimising catch crop effects. Incorporation time or kill date can be decided not only by choosing tillage date, but also by choosing catch crops which are winter-hardy or winter-killed as will be discussed in Section "Kill date."

The highly significant differences also emphasise the importance of the choice of incorporation date in catch crop experiments. Especially in experiments where more species are compared it should be kept in mind that the differences observed in N_{eff} may be mainly due to differences in kill date if some are winter killed and others not.

D. CHOOSING CATCH CROP SPECIES

A recurring theme in most catch crop experiments is comparison of different plant species. In most published research on catch crops several species have been included in the experiments, even where the objective of the experiments was not to study species effects but other factors such as incorporation time, mineralisation rates, etc. One reason for this continued interest in comparing species is that virtually any aspect of catch cropping is affected by the choice of species. Many results show that the effects of catch crops can depend strongly on the species choice.

Just regarding the N effects of catch crops, at least the following important factors can be controlled by the choice of catch crop species:

- Speed of establishment, growth rate and rooting depth, as well as cold tolerance. All these factors affect N uptake capacity during the autumn.
- Kill date can be controlled by choice of more or less winter hardy species.
- Nitrogen fixing capacity, by choosing legumes and choosing among legume species.
- Quality of the catch crop plant material, e.g., C/N ratio, contents of lignin, nitrate-N and other water-soluble compounds affecting subsequent N mineralisation.

Apart from all this, the non-N effects of catch crops discussed in Chapter 4 will also often depend on species choice. The fact that all these factors depend on the choice of species makes the choice of plant species a powerful management tool in catch cropping. In the following the significance of some of the specific characters which vary among catch crops will be discussed. At the end of the section, effects of different plant species or "species types" on N_{eff} and yield of the succeeding crop will be discussed.

Apart from choosing among species, many experiments with species mixtures have been made. There can be several reasons for wanting to mix different species, the most obvious is mixing non-legumes which can effectively deplete soil N with legumes with their biological N fixation (Ranells and Wagger, 1997a,b; Clark *et al*., 1997b).

1. N Uptake Capacity

As the growing season of catch crops is normally short, it is important to look for species with fast establishment, fast growth and root growth. Among the tested species several crucifer species fulfil this, and in many experiments they are found to have superior N uptake capacity compared to other non-legumes (see Section II.A "Growth and N Uptake Potential").

Though some of the crucifer species used as catch crops have fast growth and root growth they may not be the best choice when catch crops are sown very late. This is illustrated in the results of Thorup-Kristensen (2001) who found that during the early growth stages the cereals tended to have the deepest rooting, as they were faster to initiate their root growth. However, due to a clearly faster rooting depth penetration, the crucifers developed the deepest rooting at later growth stages but it took approximately 600 day degrees from sowing before the crucifers had a clearly deeper rooting than the cereals. Thus with a short growing season these data suggest that cereals were superior to crucifers, only with longer growing seasons were the advantages of crucifers realised.

One reason for the faster initial rooting of cereals may be the larger seeds and sowing rates of cereals, which will give them a head start compared to crucifers or small seeded grasses. The results of Power and Zachariassen (1993) and Ilgen and Stamp (1993) show how seed size determines the ranking of plant N uptake at early growth stages, whereas at later stages this relationship disappears as other characteristics of the plant species become more important. Differences in initial biomass due to seed weight and seeding rates can be quite dramatic. Crucifer crops are often sown at a rate of 5 or 10 kg seed ha^{-1} compared to typical rates of 100–200 kg seed ha^{-1} of cereals. Using these sowing rates, a crucifer crop will typically have to increase its weight 20-fold, just to reach the biomass a cereal catch crop has right from the time it is sown.

Cold tolerance will also become increasingly important when catch crops are sown later, as their effect then depend more on their ability to continue growth also into the colder periods. A number of studies have dealt with the response of catch crop N uptake and N metabolism to low temperatures (Laine *et al*., 1994; Macduff *et al*., 1994; Clarkson *et al*., 1992; Power and Zachariassen, 1993; Van Dam and Lantinga, 1998). Laine *et al*. (1994) found the N uptake of crucifer species to be less sensitive to low temperatures than the N uptake by monocot species. Power and Zachariassen (1993) found faba bean and especially hairy vetch to have higher N uptake than other legumes at low temperatures, also when compared to legumes normally grown in cool climates such as white clover, sweet clover and field pea.

When undersown, catch crops should preferably not grow too fast in the beginning, as this will cause competition against the main crop, but still they should be able to utilise the growing season after main crop harvest effectively (Karlsson-Strese *et al*., 1996). Karlsson-Strese *et al*. (1998) tested many species and genotypes of potential catch crops, and found that the ryegrass species, which appear to be the most commonly used species for undersown catch crops, were not optimal, as they competed too strongly with the main crop. Within each of the plant types grasses, legumes and non-legume dicots, species were identified which combined good autumn growth with less competition against the main crop.

2. N Fixing Capacity

Though large differences in N fixation among legume catch crops are observed, it is hard to draw general conclusions. With short growing periods, species such as hairy vetch, crimson clover, and red clover are often found to give good results. As an example, Stute and Posner (1995a) compared red clover, sweet clover, hairy vetch and two types of alfalfa, and found N uptake of the different legumes ranging from 42 to 128 kg N ha^{-1} on an average of 4 years. When the catch crops were undersown in oats the best results were obtained with red clover yielding 128 kg N ha^{-1}, compared to 78 kg N ha^{-1} by hairy vetch and between 47 and 56 kg N ha^{-1} for the three other crops. When the catch crops were sown after oat harvest hairy vetch showed the best result with 108 kg N ha^{-1} compared to between 42 and 67 kg N ha^{-1} for the three other crops.

However, many other species may give good results depending on the growing conditions. The conclusion seems to be that we know species which will normally give good results and which can be used in most cases, but also that much may be gained by identifying species especially suited to the relevant conditions.

Soil water content at field capacity
low=0
medium=2
high=3

Winter surplus precipitation
low=3
medium=1
high=0

Rooting depth of succeeding crop
shallow=0
medium=1
deep=3

0-2 points, or if rooting depth is shallow. *Most of the autumn pool of inorganic soil N will be leached from the root zone of the succeeding crop.*
- Grow winter hardy catch crop which is incorporated in the early spring.
- N_{eff} high. High effect on quantitative N leaching losses. Grow catch crops as often as possible.

3-5 points. *Some, but not all of the autumn N will normally be leached from the root zone of the succeeding crop.*
- Grow catch crops which are naturally winter-killed or incorporate the catch crops in the late autumn. Deep-rooted catch crops should be preferred, and catch crops with high C/N ratio (>16) should be avoided.
- N_{eff} variable. Medium effect on leaching losses and on nitrate concentration in the water leaching from the soil.

6-9 points. *Little or none of the autumn N will normally be leached from the root zone of the succeeding crop.*
- Catch crops (except legumes) are likely to reduce N supply, and should only be grown if they have other purposes. Only catch crops with low C/N ratio should be grown, and they should be incorporated in the autumn. They must not stay alive on the soil until spring.
- N_{eff} normally negative. Quantitative effect on N leaching is low, but the effect on nitrate concentration in the leaching water may be high. Grow deep-rooted catch crops, preferably at some years interval to (see section V.F).

3. Kill Date

As discussed in Section V.C "Incorporation time" the choice of incorporation date is important for optimising N_{eff}. Kill date may be controlled by mechanical incorporation of catch crops, but can also be controlled by choice of catch crop species. Species that are killed off naturally may be an advantage as the soil may often be wet and unsuited for field operations at the optimal time of catch crop incorporation. With a catch crop, which dies of during winter, incorporation may be postponed until the spring when the soil is suitable for tillage again.

Whereas winter killed species may be an advantage where catch crops should optimally be incorporated in the late autumn or during winter, they are not well suited where catch crops should be kept alive during winter and not incorporated until the spring (Figs. 11 and 12).

Thorup-Kristensen (1994b) compared the effect of winter killed and winter hardy catch crops, and showed how differences in kill date affected the timing of mineralisation and the depth distribution of inorganic N in the spring soil. Even among winter killed species, the kill date may vary significantly. In the data of Thorup-Kristensen (1994b) white mustard and fodder radish was still fully viable in mid November, whereas oats and phacelia had apparently already started to release their N content. Such differences among winter killed species may be significant, as even a few weeks delay in incorporation time of catch crops during the autumn may strongly affect N_{eff} (Section "Incorporation time").

4. Plant Material Quality and N Mineralisation

The plant matter produced by different catch crop species may have very different quality, leading to different N mineralisation rates after incorporation (Kuo *et al.*, 1996; Thorup-Kristensen, 1994a; Wagger, 1989; Wivstad, 1997).

Plant matter quality varies due to growing conditions, but systematic differences between species are also found. Some of the commonly used winter hardy cover crops (e.g., Italian ryegrass and perennial ryegrass) have been bred as fodder crops with the view to ensure a high energy delivery to ruminants, and have the ability to assimilate substantial amounts of carbon even at winter time. This in turn can result in a rather high C/N ratio (>30) in the cover crop at the time of incorporation—and thus diminish the return of N to the subsequent crop. Accordingly, ryegrass is repeatedly found to have a higher C/N ratio than winter rye (Kuo *et al.*, 1996; Thorup-Kristensen, 1994b).

Figure 12 Diagram showing a proposed practical guidance for the use of catch crops. By adding up the score from the three boxes on the left side of the diagram, an estimate of "leaching intensity from the root zone" is made. This score is used in the right side of the diagram to find the relevant advise.

Among legumes hairy vetch has repeatedly been found to have a very low C/N ratio around 10, which is lower than that of most other legume species (e.g., Kuo *et al*., 1996).

5. Species Differences in N_{eff}

As mentioned above, the different characteristics of catch crop species regarding growth, root growth, N uptake, winter hardiness, etc. leads to very different effects on the yield and N uptake of the succeeding crop. It is not surprising that legumes with their capacity for biological N fixation often have a better effect on succeeding crops than non-legumes. What may be more surprising is that systematic and sometimes quite large differences are observed among legume species as well as among non-legume species. This is found even among species which all seem to be efficient catch crops. Some of the more striking examples have been reported by Breland (1996b), Thorup-Kristensen (1994b) and Vyn *et al*. (1999, 2000).

Thorup-Kristensen (1994b) found that while barley grown without a preceding catch crop took up 45 kg N ha^{-1}, barley grown after catch crops took up anything from 58 kg N ha^{-1} after ryegrass to 112 kg N ha^{-1} after fodder radish. A similar difference is shown in Table II, though in this example the N uptake without a catch crop was intermediate to the two catch crops. On average across the results of Vyn *et al*. (1999), the yield of maize without a preceding catch crop was 8.1 Mg ha^{-1}, whereas the maize yield was 6.5, 8.6 and 10.1 Mg ha^{-1} after catch crops of ryegrass, fodder radish and red clover, respectively. Similarly, across the results of Vyn *et al*. (2000), yields of maize was reduced by approximately 1 Mg ha^{-1} after rye or oat catch crops, increased with 0.2 Mg ha^{-1} after fodder radish and increased with 2.5 Mg ha^{-1} after red clover. Schröder *et al*. (1997) found that the fertiliser N replacement value of undersown red clover was almost 100 kg N ha^{-1}, practically the same as found with ryegrass catch crops fertilised with 200 kg N ha^{-1}, whereas unfertilised ryegrass had practically no effect.

Several other examples can be found. The differences are not only dependent on the choice of "plant types," such as monocots, crucifers or legumes, but clear differences can also be found within these groups. In comparisons between rye and ryegrass catch crops, rye is found to have a better effect on the succeeding crop. When more crucifer crops are compared, fodder radish is often found to have the best effect. In experiments where legumes are compared, hairy vetch is normally superior (e.g., Stute and Posner, 1995b).

At least some of the differences observed among plant types can be understood based on the knowledge we have about root growth, N fixation, C/N ratios and other factors. However, the apparently systematic differences among species within the plant groups indicate that there are still important mechanisms we do not understand.

The comparisons mentioned above are only those which involve differences which are so obvious, that their effect can be clearly observed across a number of very different experiments. Many lesser differences, but differences, which can still be agriculturally important, could be found in experiments designed for that purpose. It should also be kept in mind, that only a small fraction of the plant species, which could be used as catch crops, has been tested as such. Generally most catch crop experiments include only species which are also grown for commercial purposes, but many other species could be used and might offer considerable advantages. As an example, Kabir and Koide (2000) performed an experiment to compare the effect of a wheat catch crop with the effect of a weed covered soil. They established dandelion as an "artificial weed," but they found dandelion to have better effects on the succeeding maize crop than the wheat catch crop, whether this was measured as yield, P uptake or mycorrhiza infection of the maize root system.

6. Research Perspectives in New Catch Crop Species

Based on the large differences observed among plant species grown as catch crops, it is obvious to continue the work in studying plant species with potential as catch crops, and to study the mechanisms behind the differences among species.

Karlsson-Strese *et al*. (1996) screened 518 accessions belonging to 134 plant species for their suitability as undersown catch crops in cereals. Based on this, Karlsson-Strese *et al*. (1998) tested 118 accessions belonging to 39 plant species, and measured their competition effect against a barley main crop, and their ability to grown and cover the soil in the autumn after barley harvest. Their results clearly show that within the groups of grasses and legumes a number of species could be used as catch crops. They also identified a number of interesting non-legume dicot species, which generally showed less competition against the main crop than the grasses or even the legumes. Among the non-legume dicots, especially chicory seemed to combine low competition against the main crop with an efficient plant cover after harvest.

Based partly on the work of Karlsson-Strese *et al*. (1998), we are currently testing a number of plant species as undersown catch crops, measuring also their root growth, soil N depletion and their N_{eff}. Initial results show that the roots of chicory reach approximately twice as deep as the roots of ryegrass, and that the N uptake by chicory is higher than that of ryegrass. As ryegrass undersown in cereals is presently the most common catch crop in Denmark, chicory may have the potential to improve catch crop effects significantly.

E. MODEL SIMULATION OF CATCH CROPS IN THE CROP ROTATION

In this section, we will try to illustrate some of the complex interactions between management tools, climatic and environmental factors described above, by presenting the results of model simulations of catch crop scenarios (Text box 1). By using a well tested and validated dynamic simulation model for this (DAISY), we can achieve realistic simulations with regard to most processes, while at the same time avoiding the experimental "noise" often caused by atypical climatic conditions.

We have set up a mixed six-course rotation, with 50% spring barley, a legume and two root crops. In this rotation we introduce 33 or 66% catch crops, either shallow-rooted (ryegrass) or deep-rooted (fodder radish). The rotation is subjected to two different N input levels (corresponding to a typical organic farm and a conventional intensive farm with animal production) and two climatic regimes (high or moderate winter precipitation). For more details on the scenarios and model, please consult Text box 1.

Overall, the catch crop scenarios reduce N leaching compared to no catch crops (Table IV). The data have been calculated as the average over the last 18 years (three rotations) of the simulated 24-year period, and the result can thus be considered the medium to long-term effect of catch crops.

Defining the correct leaching depth is very important for the estimated leaching loss. As seen in Table IV, somewhat different conclusions may be reached if the lower flux boundary is set at either 1.0 or 2.5 m. This is most prominent for the rotations including deep-rooted catch crops, but underlines the errors, which may often be made in measurements of nitrate leaching based on suction cups placed at 1.0 m depth. Actually, if deep-rooted crops are included in the rotation, N measured to be leached to below 1.0 m may be taken up again, and after mineralisation actually contribute to estimated leaching loss once again!

When looking at the leaching loss at 2.5 m, it should be noted that almost the same reduction in N leaching loss was achieved with 33% deep-rooted as with 66% mixed catch crop in the moderate precipitation regime. Table V shows that especially in this combination of deep rooted catch crops and moderate precipitation, measuring N leaching loss at 1.0 m may lead to an underestimation of the catch crop effect. This indicates that by growing deep-rooted catch crops, they need to be used less frequently under moderate or low precipitation. This may be an advantage, as strong pre-emptive competition and negative N_{eff} is found especially under moderate or low precipitation conditions, and also negative effects on the soil water balance are most likely under such conditions as indicated in Table VI.

In the low N input scenario, leaching is increased significantly (ca. 30%) by the high compared to the moderate precipitation, whereas at high N input the simulated leaching loss was comparable in the two climates.

Text box 1.

Description of model simulations of catch crop scenarios

Model

Simulations were carried out with the latest version of the Daisy model (Hansen *et al*., 1991a; Abrahamsen and Hansen, 2000), which has been extensively validated and used for crop rotation modelling and N leaching (Willigen, 1991; Diekkrüger *et al*., 1995; Hansen *et al*., 2001; Jensen *et al*., 1994, 1997, 2001; Magid and Kølster, 1995; Smith *et al*., 1997). The model was parameterised according to earlier studies (Jensen *et al*., 1999; Mueller *et al*., 1997, 1998b). Crop modules were either standard (Abrahamsen and Hansen, 2000) or in the case of Oil radish catch crop, the one developed by Jensen *et al*. (1999).

Soils and climate

Simulations were carried out with a sandy loam soil parameterised from Aarslev Experimental Station (Jensen *et al*., 1999). The climate used in the simulations was an average Danish climate (mean annual temperature of 7.8°C, warmest and coldest months 15.8 and −0.2°C, respectively), but with two different precipitation regimes, either 991 or 661 mm annual precipitation, corresponding to a simulated percolation at 2.5 m depth of 508 or 198 mm, respectively, with the chosen crop rotation. The climate file contained natural day-to-day variations in temperature and precipitation.

Crop rotation and catch crop scenarios

An overview of the crop rotation and catch crop scenarios simulated is given below. The scenarios include catch crops in 33% of the six-course rotation with either a deep (Oil radish, *Raphanus sativus*, sown after harvest of main crop) or a shallow (Ryegrass, *Lolium multiflorum*, undersown) rooted catch crop. A scenario with the maximum frequency of catch crops in the rotation (66%) was also applied with a combination of the catch crops. Finally, a control scenario without catch crops was included.

Major crops in rotation:	Green peas	Spring barley	Potatoes (late)	Spring barley	Sugar beets	Spring barley
Catch crop strategy:						
Deep-rooted (*Oil radish*)	OR	OR				
Shallow-rooted (*Ryegrass*)	RG	RG				
Combination (*both*)	OR	RG		RG		RG
No catch crops						

N input scenarios

For each of these catch crop scenarios, a low and a high N input regime were adopted. An overview of the fertilizer and manure inputs is given below for the whole crop rotation. *Low N input* corresponds to application of animal manure containing 70 kg total N ha^{-1} $year^{-1}$, but no inorganic fertilizer application. This is a typical N level for many organic farms. *High N input* corresponds to application of animal manure containing 140 kg total N ha^{-1} $year^{-1}$), supplemented with inorganic fertilizer N up to Danish statutory N norms for crop N fertilisation, corresponding to an average of 106 kg available N ha^{-1} $year^{-1}$ (176 kg total N ha^{-1} $year^{-1}$) over the crop rotation. This corresponds to a moderately intensive N input level, typical for many conventional farms in northern Europe.

Major crops in rotation:	Green peas	Spring barley	Potatoes (late)	Spring barley	Sugar beets	Spring barley	Average (kg N ha^{-1}
Low N input:							
Pig slurry (tot-N)	0	50	150	50	100	70	70
Effective-N 50%	0	25	75	25	50	35	35
Fertilizer	0	0	0	0	0	0	0
Sum available N	0	25	75	25	50	35	35
High N input:							
Pig slurry (tot-N)	0	170	120	170	210	170	140
Effective-N 50%	0	85	60	85	105	85	70
Fertilizer	0	30	110	30	20	30	36
Sum available N	0	115	170	115	125	115	106

Simulations

Scenarios were simulated by carrying out the rotation four times, i.e., for a period of 24 years. The initial rotation, the first 6 years, were considered a 'warm up' period, and all data were calculated as average figures for the last three rotations only.

In the low precipitation regime this effect continues for several years, whereas in the high precipitation regime, the effect is only observed in the first year and only when using a leaching depth of 2.5 m. In subsequent years, leaching is actually increased, e.g., after sugar beet and spring barley in years 5 and 6, due to N mineralisation from the previous catch crops. An example is seen after spring barley in the fourth year of the rotation (Table IV), where N leaching is increased from 44 to 69 kg N ha^{-1} $year^{-1}$ in the high N, high precipitation regime. As described earlier, frequent use of catch crops make years with a bare soil more vulnerable to N leaching due to the build up in soil organic matter and mineralisation capacity.

As discussed earlier nitrate concentration of the percolate, rather than total N loss may be of greater concern for groundwater quality. In this case, the conclusions are somewhat different from those on quantitative N loss (Table V). Without a catch crop, both N input levels cause the percolate to exceed the drinking water limit of 11.3 mg NO_3-N l^{-1} in the moderate precipitation regime, whereas in the high precipitation regime the limit was not exceeded at any of the scenarios. The large differences in percolation volume, where only 198 mm is lost in the low precipitation regime compared to 509 mm in the high precipitation regime (Table VI), allows much higher N leaching losses in the high precipitation regime without exceeding the limit. Catch crops may clearly improve percolate quality, but it is evident that in the long-term, the shallow-rooted catch crop will only have little effect, if only grown in 33% of the rotation. The reason for this is shown in Fig. 13, where the shallow-rooted catch crop lowers the nitrate

Table IV

Simulated N Leaching (kg N ha^{-1} $year^{-1}$, Average over Three Crop Rotations) as a Function of Precipitation Regime, N Input Level and the Effect of Catch Crop Rooting Depth, Frequency in the Rotation and Whether the Leaching Depth is Defined at 1.0 or 2.5 m. The Leaching Loss has been Cumulated in Each Crop Year until the Following Spring

		Catch crop scenario (freq.)		Leaching depth							
				100 cm				250 cm			
Climate	N input regime	Rotation	Year	Nil (0%)	Deep rooted (33%)	Shallow rooted (33%)	Combination (66%)	Nil (0%)	Deep rooted (33%)	Shallow rooted (33%)	Combination (66%)
Moderate[a] precipitation	Low[b]	Pea	1	45	2*	15*	0*	21	6*	16*	6*
		Sp. barley	2	20	0*	2*	3*	24	0*	14*	1*
		Potato	3	31	33	29	36	26	1	14	2
		Sp. barley	4	21	28	24	9*	26	10	16	9*
		Sugar beet	5	9	12	10	8	21	16	17	14
		Sp. barley	6	17	20	19	4*	22	21	20	13*
		Average		24	16	17	10	23	9	16	7
	High[b]	Pea	1	55	6*	27*	2*	39	20*	34*	11*
		Sp. barley	2	45	1*	5*	10*	39	1*	31*	0*
		Potato	3	48	43	40	50	46	2	31	4
		Sp. barley	4	48	68	53	29*	44	14	27	14*
		Sugar beet	5	23	36	26	33	39	29	31	25
		Sp. barley	6	43	76	55	37*	42	45	39	29*
		Average		43	38	34	27	41	19	32	14

(*continued on next page*)

Table IV (*continued*)

				Leaching depth							
		Catch crop scenario (freq.)		100 cm				250 cm			
Climate	N input regime	Rotation	Year	Nil (0%)	Deep rooted (33%)	Shallow rooted (33%)	Combination (66%)	Nil (0%)	Deep rooted (33%)	Shallow rooted (33%)	Combination (66%)
High[a] precipitation	Low[b]	Pea	1	60	1*	11*	1*	35	6*	22*	2*
		Sp. barley	2	26	1*	2*	2*	43	0*	11*	1*
		Potato	3	42	47	42	50	31	8	11	10
		Sp. barley	4	29	35	33	6*	37	39	35	34*
		Sugar beet	5	8	10	9	8	26	33	29	14
		Sp. barley	6	25	29	28	3*	16	21	18	9*
		Average		31	20	21	11	31	18	21	12
	High[b]	Pea	1	66	2*	17*	1*	47	14*	41*	6*
		Sp. barley	2	39	1*	3*	3*	53	0*	18*	1*
		Potato	3	56	60	56	65	44	10	15	14
		Sp. barley	4	44	69	56	16*	54	59	52	47*
		Sugar beet	5	17	21	19	26	38	55	45	25
		Sp. barley	6	49	78	66	31*	32	49	40	32*
		Average		45	38	36	24	45	31	35	21

Values given are leached N (kg N ha^{-1} year^{-1}).

[*] A catch crop was grown after this main crop in the rotation.

[a] Moderate and high precipitation was 661 and 991 mm year^{-1} respectively.

[b] With low and high N input regime 35 and 106 kg N ha^{-1} year^{-1} was added respectively.

Table V

Simulated Average Soil Solution Nitrate-N Concentration (mg NO_3-N l^{-1}) Over Time at 1.0 and 2.5 m Depth (Average Over Three Rotations) as a Function of Catch Crop Rooting Depth and Frequency in the Rotation, Climate and N Input. The Recommended Limit for Nitrate in Drinking Water is 11.3 mg Nitrate-N l^{-1} (50 mg nitrate l^{-1}), Figures Exceeding This has been Marked in Bold in the Table

		Leaching depth							
Catch crop scenario (freq.)		100 cm				250 cm			
Precipitation	N input	Nil (0%)	Deep rooted (33%)	Shallow rooted (33%)	Combination (66%)	Nil (0%)	Deep rooted (33%)	Shallow rooted (33%)	Combination (66%)
Moderate	Low	**13**	8	9	5	**13**	5	9	4
	High	**23**	**18**	**23**	10	**24**	**12**	**23**	6
High	Low	6	4	4	2	6	4	4	2
	High	9	7	8	4	9	7	9	4

Values given are soil solution nitrate N concentration (average mg NO_3-N l^{-1}).

Table VI

Simulated Differences in Water Balance Components (Actual Evapotranspiration and Percolation at 2.5 m) as Affected by Catch Crop Rooting Depth, Frequency in the Rotation, N Input and Precipitation Regime. Figures are Averages Over High and Low N Input (Only Small Differences)

		Water balance							
		Actual evapotranspiration (mm year^{-1})				Percolation (at 250 cm; mm year^{-1})			
Precipitation	Catch crop scenario (freq.)	Nil (0%)	Deep rooted (33%)	Shallow rooted (33%)	Combination (66%)	Nil (0%)	Deep rooted (33%)	Shallow rooted (33%)	Combination (66%)
Moderate		461	471	476	493	197	186	182	159
	Diff.[a]		2%	3%	7%		−6%	−8%	−20%
High		481	488	497	515	509	502	493	476
	Diff.[a]		2%	3%	7%		−1%	−3%	−7%

[a] Difference to Nil treatment in %.

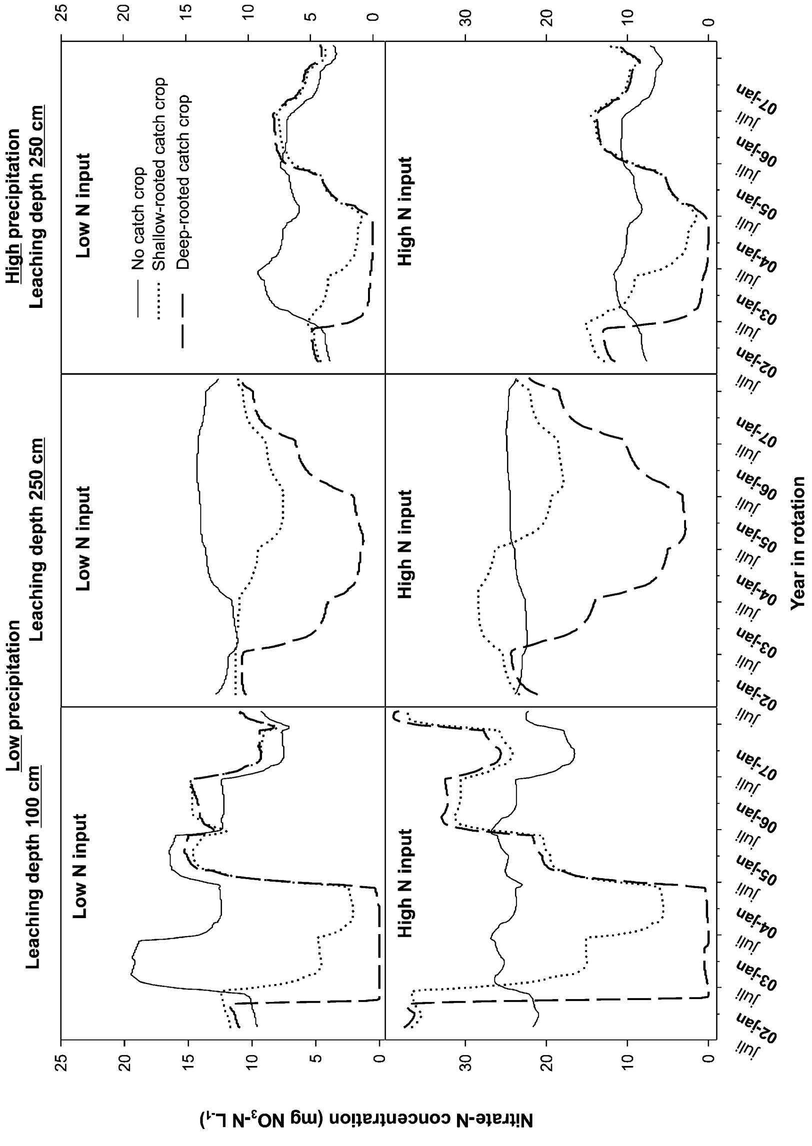
concentration in half the years, but increases the concentration in the subsequent years, where no catch crop is grown. This again underlines that by incorporating catch crops in rotations, years without catch crops can become more vulnerable. In the high precipitation regime increased leaching is often seen already in the next year, whereas in the moderate precipitation regime the effect of catch crops continue for two or more years. Together these results indicate that different catch crop strategies should be used depending on precipitation regime.

Furthermore, the inclusion of catch crops affects the water balance by increasing evapotranspiration and thereby decreasing the percolation. The relative effect on percolate quantity is more dramatic in moderate precipitation regime, where percolate volume is reduced by up to 20% compared with 7% in the high precipitation regime (Table VI). This means, that in order to decrease percolate nitrate concentrations, the catch crop has to be even more efficient.

An important question can then be raised concerning the N retained from leaching by the catch crops: How efficiently is it then used for increased crop production? The results from the simulations show that the catch crops reduce annual N leaching by 7–19 kg N ha^{-1} in the low input and 9–27 kg N ha^{-1} in the high N input scenarios (Table IV). The increase in harvested N was as little as 0–7 kg N ha^{-1} (data not shown) and thus the utilisation of the retained N is low, ranging from 0 to 50%, with the highest utilisation generally found in the low N scenarios, confirming the conclusions in the literature reported in Section III.F.3 “Second year and longer term effect.”

What happens to the remainder? The only important component of the N balance remaining is the change in soil organic N stocks. Figure 14 shows a clear relationship between the amount of N accumulated by the catch crops and the increase in soil organic matter N over the nil treatment (which has a continuous annual decrease in soil organic N of 0.14 and 0.09% in the low and high N input scenarios, respectively). From Fig. 14 it seems that a steady state in soil organic matter is not approaching within this 24 year period, more likely it will take many decades or even a century before a new near equilibrium is reached. In this example catch crops are grown in 33 or 66% of the years. These scenarios in most cases exceed what is common practice with respect to fraction of catch crops in the rotation. In Denmark, farmers are only required by legislation to grow catch crops on 6% of the arable area; from the above it is evident that such a low proportion is very unlikely to have any significant effect on soil C and N storage in the medium to long-term.

The output from the simulations illustrate how catch crops can contribute to solving problems with N leaching losses from agriculture, by reducing the amount of N lost as well as the nitrate concentration in the water lost from the soil. The simulations also illustrate how different catch crop strategies may be optimal depending on the soil and climate conditions, as illustrated by the differences between the climate scenarios.


Low precipitation
Leaching depth 100 cm
Leaching depth 250 cm
High precipitation
Leaching depth 250 cm
Low N input
High N input
No catch crop
Shallow-rooted catch crop
Deep-rooted catch crop
Nitrate-N concentration (mg NO_3-N L^{-1})
Year in rotation
0
5
10
15
20
25
30
Juli
02-Jan
03-Jan
04-Jan
05-Jan
06-Jan
07-Jan

F. Placing Catch Crops at the “Policy Scale”

Catch crops should be encouraged in areas where nitrate leaching affects sensitive aquifers. The use of catch crops is just one of several possible ways to try to reduce the nitrate load of the environment, and it should be compared to other methods to find the most cost effective way of reducing losses (Gustafson *et al*., 2000; Hasler, 1998; Lu *et al*., 1999). Few studies have attempted to compare the effectiveness of different available methods, but Gustafson *et al.* (2000) compared reduced fertilisation with catch crops as methods to reduce leaching losses. In their comparison catch crops were clearly the most effective method. Catch crops reduced nitrate leaching slightly more than when no fertiliser N was added to the crops, but with much less effect on main crop yield.

Catch crops can also be the part of a more complex approach to reduction of nitrate leaching losses. Hasler (1998) suggested levies on chemical N fertiliser use, combined with a demand for using catch crops if the farmers shift to certain crops such as grain legumes, which have a lower N demand but which can still lead to relatively high N leaching losses.

The problems can be nitrate contamination of drinking water resources or eutrofication of streams, lakes or coastal waters. It is often assumed that the worst problems are found where the highest amounts of nitrate is leached, but that is not always so. Especially when considering water resources for human use, the nitrate concentration rather than the amount of nitrate is important. This means that in dry areas where water percolation is limited, even low amounts of nitrate lost can lead to unacceptably high nitrate concentrations in the aquifers. As discussed below, such situations may require different catch crop strategies compared to situations where larger absolute amounts of nitrate leaching is to be handled.

Apart from placing catch crops in areas affecting sensitive aquifers, it can be relevant to try to place the catch crops at specific types of farms. Typically, the largest nitrate leaching losses occur from farms with intensive animal husbandry (Hall *et al*., 2001) or intensive horticulture (Jackson *et al*., 1993). Catch crops grown at such farms will prevent much more leaching loss than catch crops grown at arable farms with cereal rotations.

Also within the farm it is important where the catch crops are grown. Depending on previous crop and cropping history, and on the type of crop that is to be grown in the next season, the effect will be very different as discussed in chapter III “Catch Crop Effect on N Supply for Succeeding Crops.” It may be difficult to make regulations that go into this sort of detail on within-farm management of catch cropping. Still, regulations on factors as latest time of

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Figure 13 Simulated nitrate-N conc. (mg NO_3-N l^{-1}) over time at 1.0 and 2.5 m depth (average over three crop rotations) as a function of catch crop rooting depth, climate and N input. The recommended limit for nitrate in drinking water is 11.3 mg nitrate-N l^{-1} (50 mg nitrate l^{-1}).

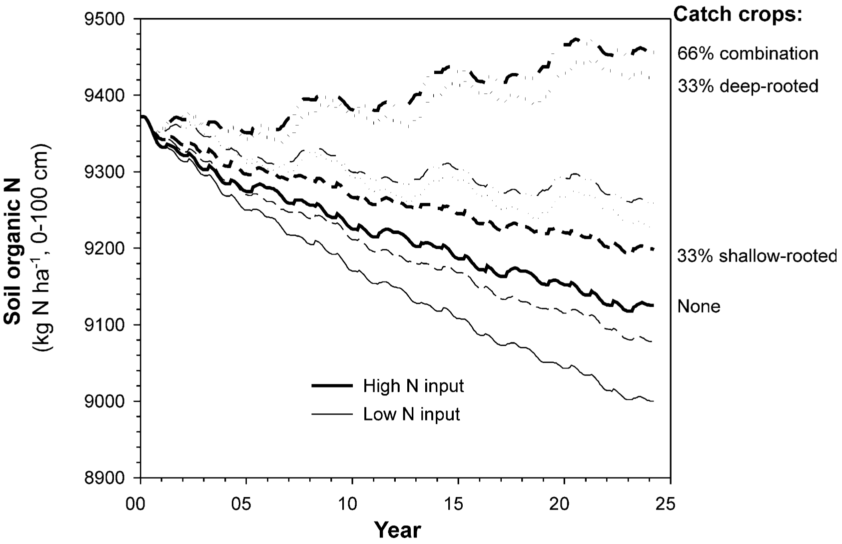

Figure 14 Simulated change in soil organic matter N content to 1 m depth over the four rotations (4 × 6 = 24y), as affected by catch crop rooting depth, frequency and N input regime. Data from the low precipitation regime (see Text box 1).

establishment, earliest date of incorporation and of species choice can be made as it is already the case with, e.g., Danish regulations on catch cropping.

A special case is the drier areas where nitrate leaching becomes a problem because of a low volume of drainage water rather than because of high amounts of nitrate lost by leaching. Low precipitation areas are exactly the areas where catch crops will normally cause strong pre-emptive competition, as much of the N they take up would not otherwise have been lost by leaching. This will often lead to a negative N_{eff}. If this further leads to depressed crop yields catch crops may become a very expensive way to control the nitrate problem. If the negative N_{eff} leads to increased N fertiliser use, it is uncertain whether any environmental effect is achieved in the long-term.

Still, catch crops may be a valuable part of the solution also under such conditions, if used correctly. With low water percolation, the nitrate will only move slowly downwards in the soil profile, thus there is longer time to catch it before it leaves the root zone, especially if deep rooted catch crops are grown. This offers the possibility of growing catch crops at some year's interval to take up the N left by the crops during the previous years. Such a possibility is also indicated by the model simulations presented in Section "Model simulation of catch crops in the crop rotation," where deep rooted catch crops in 33% of the years had almost the same effect on N leaching loss as 66% catch crops in the low precipitation scenario.

Using deep rooted catch crops grown at some years interval to "clean up" after the previous years nitrate loss will induce much less pre-emptive competition and negative agricultural effects over the rotation over the rotation than if they are grown more often. Further, if the catch crops can then take up substantial amounts of nitrate from deeper soil layers, this will involve little pre-emptive competition and the catch crops may lead to positive N_{eff} even under such relatively dry conditions.

VI. PERSPECTIVES

Catch crops can be one of the important tools in trying to reduce nitrate leaching losses from agriculture. They also have the potential to supply significant amounts of available N to the main crops, which can be valuable especially in low input agriculture such as organic farming. Placing catch crops in the crop rotation, selection of species or species mixtures and other aspects of catch crop management will have large effects on both environmental and agronomic effects of catch crops. A main conclusion is that the solution is not just "grow catch crops" but that catch cropping should be adapted to the relevant soil, climate and cropping situation to make sure that the desired effects are achieved.

Considering the large differences in N_{eff} and other characteristics found among the relatively few plant species which have been tested, it is highly likely that some of the many other species which could be used will offer important advantages as catch crops. Thus, looking for new species may be one of the most important lines of research in order to improve their practical applicability both agronomically and environmentally. At the same time, studying the different effects of catch crop species, and the mechanisms behind them, may be one of the most promising ways to improve our understanding of the basic effects of catch crops, and thereby to improve the results of catch cropping on the long-term.

Apart from the knowledge we have about catch crop effects on N losses and N_{eff}, there is still a number of other effects of which we presently know little, and which may differ strongly among catch crop species. Factors such as the degree and timing of winter dormancy, and plant growth reactions to N limitations may be important. N limitation may affect plant production, plant quality, or both, and thereby determine N_{eff}. These and many other factors may affect catch crop N_{eff} and may be the reasons for the differences observed among catch crop species, but many other "non-N" effects may also vary strongly among plant species.

A central conclusion must also be that it is important that the N effect of catch crops is utilised by subsequent crops. In low input systems where the crops are more or less N limited this may not be a problem. In high input systems where the crops are already optimally supplied with fertiliser N, the effect of a catch crop may lead to excessive supply and thereby to increased losses at a later time. This will to some extent reduce the overall effect of the catch crops on N leaching loss compared to the reduced leaching during the period when the catch crop was actually grown. Methods to predict how much the fertiliser application to the main crops can be reduced will therefore be important.

Apart from the effects on N losses and N availability, catch crops can have a number of other effects both beneficial and potentially negative effects. Catch crops may lead to increased problems with weeds, pests and diseases. However, it seems that most of these problems can be handled relatively easily; as an example, disease problems can probably be handled through the choice of catch crop species. Beneficial effects can be achieved on many areas, regarding weeds, pests and diseases, but also on soil structure, erosion control, soil organic matter content, mycorrhiza and effects on other plant nutrients. The scientific literature on these subjects is still scattered, and few conclusions can be drawn, but generally the results indicate that catch crops can be used actively to handle several problems apart from the desired effects on N.

The new understanding of catch crop effects gained through recent research lead to a more detailed understanding of when catch crops can be a useful tool for environmental protection and farm N management. It has also increased our understanding of the mechanisms of catch crop effects, and to manage catch crops to achieve the optimal results. Continued research on the mechanisms of catch crop effects, and on the reasons for the variable results are likely to lead to further progress, as several of the new but important topics have only been subjected to a limited research effort.

REFERENCES

Abawi, G. S., and Widmer, T. L. (2000). Impact of soil health management practices on soilborne pathogens, nematodes and root diseases of vegetable crops. *Appl. Soil Ecol.* **15**, 37–47.

Abrahamsen, P., and Hansen, S. (2000). Daisy: an open soil–crop–atmosphere system model. *Environ. Modell. Soft.* **15**, 313–330.

Al-Khatib, K., Libbey, C., and Boydston, R. (1997). Weed suppression with Brassica green manure crops in green pea. *Weed Sci.* **45**, 439–445.

Andersen, A., and Olsen, C. C. (1993). Rye grass as a catch crop in spring barley. *Acta Agric. Scand., Sect. B—Soil Plant Sci.* **43**, 218–230.

Andersen, M. K., and Jensen, L. S. (2001). Low soil temperature effects on short-term gross N mineralisation–immobilisation turnover after incorporation of a green manure. *Soil Biol. Biochem.* **33**, 511–521.

Aufhammer, W., Stützel, H., Kübler, E., and Figenbaum, A. (1992). Interplanting of non-legumes into faba bean (*Vicia faba* L.) to reduce the risk of nitrate contamination of the ground water. *Eur. J. Agron.* **1**, 59–69.

Aulakh, M. S., Doran, J. W., Walters, D. T., and Power, J. F. (1991). Legume residue and soil water effects on denitrification in soils of different textures. *Soil Biol. Biochem.* **23**, 1161–1167.

Axelsen, J. A., and Kristensen, K. T. (2001). Collembola and mites in plots fertilised with different types if green manure. *Pedobiologia* **44**, 556–566.

Baggs, E. M., Watson, C. A., and Rees, R. M. (2000). The fate of nitrogen from incorporated cover crop and green manure residues. *Nutr. Cycl. Agroecosyst.* **56**, 153–163.

Ballcoelho, B. R., and Roy, R. C. (1997). Overseeding rye into corn reduces NO_3 leaching and increases yields. *Can. J. Soil Sci.* **77**, 443–451.

Baltruschat, H., and Dehne, H. W. (1989). The occurrence of vesicular–arbuscular mycorrhiza in agro-ecosystems. II. Influence of nitrogen fertilization and green manure in continuous monoculture and in crop rotation on the inoculum potential of winter barley. *Plant Soil* **113**, 251–256.

Biederbeck, V. O., Campbell, C. A., Rasiah, V., Zentner, R. P., and Wen, G. (1998). Soil quality attributes as influenced by annual legumes used as green manure. *Soil Biol. Biochem.* **30**, 1177–1185.

Bollero, G. A., and Bullock, D. G. (1994). Cover cropping systems for the central corn belt. *J. Prod. Agric.* **7**, 55–58.

Boswell, E. P., Koide, R. T., Shumway, D. L., and Addy, H. D. (1998). Winter wheat cover cropping, VA mycorrhizal fungi and maize growth and yield. *Agric. Ecosyst. Environ.* **67**, 55–65.

Bottomley, P. J., Sawyer, T. E., Boersma, L., Dick, R. P., and Hemphill, D. D. (1999). Winter cover crop enhances 2,4-D mineralization potential of surface and subsurface soil. *Soil Biol. Biochem.* **31**, 849–857.

Boydston, R. A., and Hang, A. (1995). Rapeseed (*brassica napus*) green manure crop suppresses weeds in potato (*solanum tuberosum*), *Weed Technology* **9**, 669–675.

Bødker, L., and Thorup-Kristensen, K. (1999). Effect of green manure crops on root rot and arbuscular mycorrhizal fungi in pea roots. *DARCORF Report no. 1. In* "Designing and testing crop rotations for organic farming". (J. E. Olesen, R. Eltun, M. J. Goulding, E. S. Jensen and U. Köpke, Eds.), pp. 337–345.

Breland, T. A. (1994a). Enhanced mineralization and denitrification as a result of heterogeneous distribution of clover residues in soil. *Plant Soil* **166**, 1–12.

Breland, T. A. (1994b). Measured and predicted mineralization of clover green manure at low temperatures at different depths in two soils. *Plant Soil* **166**, 13–20.

Breland, T. A. (1996a). Green manuring with clover and ryegrass catch crops undersown in small grains—effects on soil mineral nitrogen in field and laboratory experiments. *Acta Agric. Scand., Sect. B–Soil Plant Sci.* **46**, 178–185.

Breland, T. A. (1996b). Green manuring with clover and ryegrass catch crops undersown in small grains: crop development and yields. *Acta Agric. Scand., Sect. B—Soil Plant Sci.* **46**, 30–40.

Bulson, H. A. J., Welsh, J. P., Stopes, C. E., and Woodward, L. (1996). *In* "Stockless organic farming in the UK: potential and limits, New Research in Organic Agriculture [Proceedings from the 11th International Scientific IFOAM Conference]", (N. H. Kristensen and H. Høeg-Jensen, Eds.), pp. 17–22.

Burgos, N. R., Talbert, R. E., and Mattice, J. D. (1999). Cultivar and age differences in the production of allelochemicals by *Secale cereale*. *Weed Sci.* **47**, 481–485.

Burns, I. G. (1984). Estimation of annual variations in leaching of residual nitrate under deep-rooted crops during winter. *In* "The Nitrogen Requirements of Cereals, MAFF/ADAS Reference book 385", pp. 95–101. Her Majesty's Stationary Office, London.

Clark, A. J., Decker, A. M., and Meisinger, J. J. (1994). Seeding rate and kill date effects on hairy vetch–cereal rye cover crop mixtures for corn production. *Agron. J.* **86**, 1065–1070.

Clark, A. J., Decker, A. M., Meisinger, J. J., and Mcintosh, M. S. (1997a). Kill date of vetch, rye, and a vetch–rye mixture. 1. Cover crop and corn nitrogen. *Agron. J.* **89**, 427–434.

Clark, A. J., Decker, A. M., Meisinger, J. J., and Mcintosh, M. S. (1997b). Kill date of vetch, rye, and a vetch–rye mixture. II. Soil moisture and corn yield. *Agron. J.* **89**, 434–441.

Clarkson, D. T., Jones, L. H. P., and Purves, J. V. (1992). Absorption of nitrate and ammonium ions by *Lolium perenne* from flowing solution cultures at low root temperatures. *Plant Cell Environ.* **15**, 99–106.

Creamer, N. G., Bennett, M. A., Stinner, B. R., Cardina, J., and Regnier, E. E. (1996). Mechanisms of weed suppression in cover crop-based production systems. *HortScience* **31**, 410–413.

Cunningham, P. C. (1985). Characteristics of Trends in Disease Caused by Soilborne Pathogens with Spring Barely Monoculture. (C.A. Parker, A.D. Rovira, K. J. Moore, P.T.W. Wong, editors, *In* "Ecol. Manage. Soilborne Plant Pathogens" St. Paul, Minnesota, USA pp. 9–13.

Dabney, S. M., Schreiber, J. D., Rothrock, C. S., and Johnson, J. R. (1996). Cover crops affect sorghum seedling growth. *Agron. J.* **88**, 961–970.

Davis, J. R., Huisman, O. C., Westermann, D. T., Hafez, S. L., Everson, D. O., Sorensen, L. H., and Schneider, A. T. (1996). Effects of green manures on verticillium wilt of potato. *Phytopathology* **86**, 444–453.

Debosz, K., Rasmussen, P. H., and Pedersen, A. R. (1999). Temporal variations in microbial biomass C and cellulolytic enzyme activity in arable soils: effects of organic matter input. *Appl. Soil Ecol.* **13**, 209–218.

Decker, A. M., Clark, A. J., Meisinger, J. J., Mulford, F. R., and Mcintosh, M. S. (1994). Legume cover crop contributions to no-tillage corn production. *Agron. J.* **86**, 126–135.

Dick, R. P., and Christ, R. A. (1995). Effects of long-term residue management and nitrogen fertilization on availability and profile distribution of nitrogen. *Soil Sci.* **159**, 402–408.

Diekkrüger, B., Söndergarth, D., Kersebaum, K. C., and McVoy, C. W. (1995). Validity of agroecosystem models: a comparison of results of different models applied to the same data set. *Ecol. Model.* **81**, 3–29.

Ditsch, D. C., and Alley, M. M. (1991). Nonleguminous cover crop management for residual N recovery and subsequent crop yields. *J. Fert. Effects* **8**, 6–13.

Dou, Z., Fox, R. H., and Toth, J. D. (1994). Tillage effect on seasonal nitrogen availability in corn supplied with legume green manures. *Plant Soil* **162**, 203–210.

Elers, B., and Hartmann, H. D. (1987). Biologische Konservierung von Nitrat. *Gemüse* **4**, 210–214.

Eriksen, J., and Thorup-Kristensen, K. (2002). The effect of catch crops on sulphate leaching and availability of S in the succeeding crop. *Agric. Ecosyst. Environ.* **90**, 247–254.

Esala, M. J. (1995). Changes in the extractable ammonium- and nitrate-nitrogen contents of soil samples during freezing and thawing. *Commun. Soil Sci. Plant Anal.* **26**, 61–68.

Filser, J. (1995). The effect of green manure on the distribution of collembola in a permanent row crop. *Biol. Fert. Soil.* **19**, 303–308.

Folorunso, O. A., Rolston, D. E., Prichard, T., and Louie, D. T. (1992). Soil surface strength and infiltration rate as affected by winter cover crops. *Soil Technol.* **5**, 189–197.

Fox, R. H., Myers, R. J. K., and Vallis, I. (1990). The nitrogen mineralization rate of legume residues in soil as influenced by their polyphenol, lignin, and nitrogen contents. *Plant Soil* **129**, 251–259.

Francis, G. S. (1995). Management practices for minimising nitrate leaching after ploughing temporary leguminous pastures in Canterbury, New Zealand. *J. Contam. Hydrol.* **20**, 313–327.

Francis, G. S., Bartley, K. M., and Tabley, F. J. (1998). The effect of winter cover crop management on nitrate leaching losses and crop growth. *J. Agric. Sci.,* Cambridge **131**, 299–308.

Francis, G. S., Haynes, R. J., and Williams, P. H. (1995). Effects of the timing of ploughing-in temporary leguminous pastures and two winter cover crops on nitrogen mineralization, nitrate leaching and spring wheat growth. *J. Agric. Sci.* **124**, 1–9.

Frankenberger, W. T., and Abdelmagid, H. M. (1985). Kinetic parameters of nitrogen mineralization rates of leguminous crops incorporated into soil. *Plant Soil* **87**, 257–271.

Franzleubbers, K., Weaver, A. S., Juo, A. S. R., and Franzleubbers, A. J. (1994a). Carbon and nitrogen mineralization from cowpea plant parts decomposing in moist and repeatedly dried and wetted soil. *Soil Biol. Biochem.* **26**, 1379–1387.

Franzleubbers, K., Weaver, A. S., Juo, A. S. R., and Franzleubbers, A. J. (1994b). Carbon and nitrogen mineralization from cowpea plant parts decomposing in moist and repeatedly dried and wetted soil. *Soil Biol. Biochem.* **26**, 1379–1387.

Gahoonia, T. S., Asmar, F., Gise, H., Gissel-Nielsen, G., and Nielsen, N. E. (2000). Root-released organic acids and phosphorus uptake of two barley cultivars in laboratory and field experiments. *Eur. J. Agron.* **12**, 281–289.

Gahoonia, T. S., and Nielsen, N. E. (1997). Variation in root hairs of barley cultivars doubled soil phosphorus uptake. *Euphytica* **98**, 177–182.

Garwood, T. W. D., Davies, D. B., and Hartley, A. R. (1999). The effect of winter cover crops on yield of the following spring crops and nitrogen balance in a calcareous loam. *J. Agric. Sci.,* Cambridge **132**, 1–11.

Grindlay, D. J. C (1995). Rooting depth in cover crops and its relation to shoot size. From PhD thesis: Principles governing the ability of cover crop species to trap nitrate. 230–278, University of Nottingham.

Gustafson, A., Fleischer, S., and Joelsson, A. (2000). A catchment-oriented and cost-effective policy for water protection. *Ecol. Engng.* **14**, 419–427.

Hall, M. D., Shaffer, M. J., Waskom, R. M., and Delgado, J. A. (2001). Regional nitrate leaching variability: What makes a difference in northeastern Colorado. *J. Am. Water Resour. Assoc.* **37**, 139–150.

Hansen, E. M., and Djurhuus, J. (1997). Yield and N uptake as affected by soil tillage and catch crop. *Soil Till. Res.* **42**, 241–252.

Hansen, E. M., Djurhuus, J., and Dick, W. A. (1997). Nitrate leaching as influenced by soil tillage and catch crop. *Soil Biol. Till.* **41**, 203–219.

Hansen, E. M., Djurhuus, J., and Kristensen, K. (2000). Nitrate leaching as affected by introduction or discontinuation of cover crop use. *J. Environ. Qual.* **29**, 1110–1116.

Hansen, S., Jensen, H. E., Nielsen, N. E., and Svendsen, H. (1991). Simulation of nitrogen dynamics and biomass production in winter wheat using the Danish simulation model DAISY. *Fert. Res.* **27**, 245–259.

Hansen, S., Thirup, C., Refsgaard, J. C., and Jensen, L. S. (2001). Modelling of nitrate leaching at different scales—application of the Daisy model. *In* "Modeling Carbon and Nitrogen Dynamics for Soil Management". (M. Shaffer, M. Liwang and S. Hansen, Eds.), pp. 511–547. Lewis Publishers, Boca Raton.

Harper, L. A., Hendrix, P. F., Langdale, G. W., and Coleman, D. C. (1995). Clover management to provide optimum nitrogen and soil water conservation. *Crop Sci.* **35**, 176–182.

Hasler, B. (1998). Analysis of environmental policy measures aimed at reducing nitrogen leaching at the farm level. *Environ. Pollut.* **102**, 749–754.

Hendrix, P. F., Coleman, D. C., and Crossley, D. A. (1992). Using Knowledge of Soil Nutrient Cycling Processes to Design Sustainable agriculture. *In* "Integrating sustainable agriculture, ecology, and environmental policy". (Olson R.K.,), 63–82..

Hermawan, B., and Bomke, A. A. (1997). Effects of winter cover crops and successive spring tillage on soil aggregation. *Soil Till. Res.* **44**, 109–120.

Hinsinger, P. (1998). How do plant roots acquire mineral nutrients? Chemical processes involved in the rhizosphere. *Adv. Soil Sci.* **64**, 225–265.

Hoffman, M. L., Regnier, E.E., and Cardina, J., (1993). Weed and Corn (*Zea mays*) Responses to a Hairy Vetch (*Vicia villosa*) Cover Crop, *Weed Technology* **7**, 594–599.

Hoffman, M. L., Weston, L.A., Snyder, J. C., and Regnier, E.E. (1996). Allelopathic influence of germinating seeds and seedlings of cover crops on weed species, *Weed Science* **44**, 579–584.

Ilgen, B., and Stamp, P. (1993). Root development in seedlings of oilradish, white mustard and pea. *J. Agron. Crop Sci.* **169**, 122–127.

Izaurralde, R. C., Feng, Y., Robertson, J. A., McGill, W. B., Juma, N. G., and Olson, B. M. (1995). Long-term influence of cropping systems, tillage methods, and N sources on nitrate leaching. *Can. J. Soil Sci.* **75**, 497–505.

Jackson, L. E. (2000). Fates and losses of nitrogen from a nitrogen-15-labeled cover crop in an intensively managed vegetable system. *Soil Sci. Soc. Am. J.* **64**, 1404–1412.

Jackson, L. E., and Stivers, L. J. (1993). Root distribution of lettuce under commercial production: Implications for crop uptake of nitrogen. *Biol. Agric. Hort.* **9**, 273–293.

Jackson, L. E., Wyland, L. J., and Stivers, L. J. (1993). Winter cover crops to minimize nitrate losses in intensive lettuce production. *J. Agric. Sci.* **121**, 55–62.

Janzen, H. H., and Radder, G. D. (1989). Nitrogen mineralization in a green manure-amended soil as influenced by cropping history and subsequent crop. *Plant Soil* **120**, 125–131.

Janzen, H. H., and Schaalje, G. B. (1992). Barley response to nitrogen and non-nutritional benefits of legume green manure. *Plant Soil* **142**, 19–30.

Jäggli, F. (1978). Sickerverluste an mineralstoffen. *Mitteilungen für die Schweizerische Landwirtschaft* **26**, 130–136.

Jensen, E. S. (1991). Nitrogen accumulation and residual effects of nitrogen catch crops. *Acta Agric. Scand.* **41**, 333–344.

Jensen, E. S. (1992). The release and fate of nitrogen from catch-crop materials decomposing under field conditions. *J. Soil Sci.* **43**, 335–345.

Jensen, E. S. (1994). Mineralization immobilization of nitrogen in soil amended with low C:N ratio plant residues with different particle sizes. *Soil Biol. Biochem.* **26**, 519–521.

Jensen, L. S., Mueller, T., Bruun, S., and Hansen, S. (2001). Application of the Daisy model for short and long-term simulation of soil carbon and nitrogen dynamics. *In* "Modeling carbon and nitrogen dynamics for soil management". (M. Shaffer, M. Liwang and S. Hansen, Eds.), Lewis Publishers, Boca Raton.

Jensen, L. S., Mueller, T., Eriksen, J., Thorup-Kristensen, K., and Magid, J. (1999). Simulation of plant production and N fluxes in organic farming systems with the soil–plant–atmosphere model DAISY. *In* "Designing and Testing Crop Rotations for Organic Farming. Proceedings from an International Workshop". (J. E. Olesen, R. Eltun, M. J. Gooding, E. S. Jensen and U. Köpke, Eds.), pp. 235–247. Danish Research Centre for Organic Farming, Tjele, Denmark.

Jensen, L. S., Mueller, T., Nielsen, N. E., Hansen, S., Crocker, G. J., Grace, P. R., Klir, J., Korschens, M., and Poulton, P. R. (1997). Simulating trends in soil organic carbon in long-term experiments using the soil–plant–atmosphere model DAISY. *Geoderma* **81**, 5–28.

Jensen, L. S., Stougaard, B., and Olsen, P. (1994). Simulation of nitrogen dynamics at three Danish locations by use of the DAISY model. *Acta Agric. Scand., Sect. B—Soil Plant Sci.* **44**, 75–83.

Jones, D. L. (1998). Organic acids in the rhizosphere–a critical review. *Plant Soil* **205**, 25–44.

Kabir, Z., and Koide, R. T. (2000). The effect of dandelion or a cover crop on mycorrhiza inoculum potential, soil aggregation and yield of maize. *Agric. Ecosyst. Environ.* **78**, 167–174.

Karlsson-Strese, E. M., Rydberg, I., Becker, H. C., and Umaerus, M. (1998). Strategy for catch crop development. II. Screening of species undersown in spring barley (*Hordeum vulgare* L.) with respect to catch crop growth and grain yield. *Acta Agric. Scand.* **48**, 26–33.

Karlsson-Strese, E. M., Umaerus, M., and Rydberg, I. (1996). Strategy for catch crop development. I. Hypothetical ideotype and screening of species. *Acta Agric. Scand., Sect. B—Soil Plant Sci.* **46**, 106–111.

Katterer, T., Reichstein, M., Andrén, O., and Lomander, A. (1998). Temperature dependence of organic matter decomposition: a critical review using literature data analyzed with different models. *Biol. Fert. Soil* **27**, 258–262.

Kessavalou, A., and Walters, D. T. (1999). Winter rye cover crop following soybean under conservation tillage: Residual soil nitrate. *Agron. J.* **91**, 643–649.

Kuo, S., and Jellum, E. J. (2000). Long-term winter cover cropping effects on corn (*Zea mays* L.) production and soil nitrogen availability. *Biol. Fert. Soil* **31**, 470–477.

Kuo, S., Sainju, U. M., and Jellum, E. (1996). Winter cover cropping influence on nitrogen mineralization, presidedress soil nitrate test, and corn yields. *Biol. Fert. Soil* **22**, 310–317.

Kuo, S., Sainju, U. M., and Jellum, E. J. (1997). Winter cover crop effects on soil organic carbon and carbohydrate in soil. *Soil Sci. Soc. Am. J.* **61**, 145–152.

Ladd, J. N., Amato, M., Jackson, R. B., and Butler, H. A. (1983). Utilization by wheat crops of nitrogen from legume residues decomposing in soils in the field. *Soil Biol. Biochem.* **15**, 231–238.

Ladd, J. N., Oades, J. M., and Amato, M. (1981). Distribution and recovery of nitrogen from legume residues decomposing in soils sown to wheat in the field. *Soil Biol. Biochem.* **13**, 251–256.

Laine, P., Bigot, J., Ourry, A., and Boucaud, J. (1994). Effects of low temperature on nitrate uptake, and xylem and phloem flows of nitrogen, in *Secale cereale* L. and *Brassica napus* L. *New Phytol.* **127**, 675–683.

Lainé, P., Ourry, A., Macduff, J., Boucaud, J., and Salette, J. (1993). Kinetic parameters of nitrate uptake by different catch crop species: Effects of low temperatures or previous nitrate starvation. *Physiol. Plant.* **88**, 85–92.

Larsson, L., Ferm, M., Kasimirklemedtsson, A., and Klemedtsson, L. (1998). Ammonia and nitrous oxide emissions from grass and alfalfa mulches. *Nutr. Cycl. Agroecosyst.* **51**, 41–46.

Lewan, E. (1994). Effects of a catch crop on leaching of nitrogen from a sandy soil: Simulations and measurements. *Plant Soil* **166**, 137–152.

Liebl, R., Simmons, F.W., Wax, L.M., and Stoller, E.W., (1992). Effect of Rye (*Secale cereale*) Mulch on Weed Control and Soil Moisture in Soybean (*Glycine max*), *Weed Tech* **6**, 838–846.

Liebman, M., and Dyck, E., (1993). Crop rotation and intercropping strategies for weed management, *Ecol. Appl.* **3**, 92–122.

Linderman, R. G. (1989). Organic amendments and soil-borne diseases. *Can. J. Plant Phatol.* **11**, 180–183.

Lotz, L. A. P., Groeneveld, R. M. W., Theunissen, J., and Vandenbroek, R. C. F. M. (1997). Yield losses of white cabbage caused by competition with clovers grown as cover crop. *Neth. J. Agric. Sci.* **45**, 393–405.

Lu, Y. C., Watkins, B., and Teasdale, J. (1999). Economic analysis of sustainable agricultural cropping systems for mid-Atlantic states. *J. Sust. Agric.* **15**, 77–93.

Lupwayi, N. Z., and Haque, I. (1998). Mineralization of N, P, K, Ca and Mg from Sesbania and Leucaena leaves varying in chemical composition. *Soil Biol. Biochem.* **30**, 337–343.

Macduff, J. H., Jarvis, S. C., and Cockburn, J. E. (1994). Acclimation of NO_3—fluxes to low root temperature by brassica napus in relation to NO_3—supply. *J. Expl. Bot.* **45**, 1045–1056.

Magid, J., Henriksen, O., Thorup-Kristensen, K., and Mueller, T. (2001). Decoupled C and N cycling at low temperatures—implications for green manure efficiency in temperate agro-ecosytems. *Plant Soil* **228**, 73–82.

Magid, J., and Kølster, P. (1995). Modelling nitrogen cycling in an ecological crop rotation—an explorative trial. *Biol. Agric. Hort.* **11**, 77–87.

Magid, J., Mueller, T., Jensen, L. S., and Nielsen, N. E. (1997). Modelling the measurable—interpretation of field-scale CO_2 and N-mineralization, soil microbial biomass and light fractions as indicators of oilseed rape, maize and barley straw decomposition. *In* "Plant Litter Quality and Decomposition". (G. Cadisch and K. E. Giller, Eds.), pp. 349–632. CAB International, Wallington, UK.

Mann, H. H. (1959). Field studies in green manuring. II. *Empire J. Expp. Agric.* **27**, 243–251.

Marstorp, H., and Kirchmann, H. (1991). Carbon and nitrogen mineralization and crop uptake of nitrogen from six green manure legumes decomposing in soil. *Acta Agric. Scand.* **41**, 243–252.

Martinez, J., and Guiraud, G. (1990). A lysimeter study of the effects of a ryegrass catch crop, during a winter wheat/maize rotation, on nitrate leaching and on the following crop. *J. Soil Sci.* **41**, 5–16.

McBride, R. G., Mikkelsen, R. L., and Barker, K. R. (1999). Survival and infection of root-knot nematodes added to soil amended with rye at different stages of decomposition and cropped with cotton. *Appl. Soil Ecol.* **13**, 231–235.

McCracken, D. V., Corak, S. J., Frye, W. W., and Blevins, R. L. (1989). Residual effects of nitrogen fertilization and winter cover cropping on nitrogen availability. *Soil. Sci. Soc. Am. J.* **53**, 1459–1464.

McGuire, A. M., Bryant, D. C., and Denison, R. F. (1998). Wheat yields nitrogen uptake, and soil moisture following winter legume cover crop vs. fallow. *Agron. J.* **90**, 404–410.

Mendes, I. C., Bandick, A. K., Dick, R. P., and Bottomley, P. J. (1999). Microbial biomass and activities in soil aggregates affected by winter cover crops. *Soil Sci. Soc. Am. J.* **63**, 873–881.

Meyer, L. D., Dabney, S. M., Murphree, C. E., Harmon, W. C., and Grissinger, E. H. (1999). Crop production systems to control erosion and reduce runoff from upland silty soils. *Trans. ASAE* **42**, 1645–1652.

Mitchell, J. P., Peters, D. W., and Shennan, C. (1999). Changes in soil water storage in winter fallowed and cover cropped soils. *J. Sust. Agric.* **15**, 19–31.

Moore, M.J., Gillespie, T.J., and Swanton, C.J., (1994). Effect of cover crop mulches on weed emergence, weed biomass, and soybean (*glycine max*) development, *Weed Tech.* **8**, 512–518.

Muehlchen, A. M., Rand, R. E., and Parke, J. L. (1990). Evaluation of crucifer green manures for controlling aphanomyces root rot of peas. *Plant Dis.* **74**, 651–654.

Mueller, T., Jensen, L. S., Magid, J., and Nielsen, N. E. (1997). Temporal variation of C and N turnover in soil after oilseed rape straw incorporation in the field: Simulations with the soil–plant–atmosphere model DAISY. *Ecol. Model.* **99**, 247–262.

Mueller, T., Jensen, L. S., Magid, J., and Nielsen, N. E. (1998). Turnover of carbon and nitrogen in a sandy loam soil after incorporation of chopped maize, barley straw and blue grass in the field. *Soil Biol. Biochem.* **30**, 561–571.

Mueller, T., Magid, J., Jensen, L. S., and Nielsen, N. E. (1998). Soil C and N turnover after the incorporation of chopped maize, barley straw and blue grass in the field: Evaluation of the DAISY soil-organic-matter submodule. *Ecol. Model.* **111**, 1–15.

Mueller, T., and Thorup-Kristensen, K. (2001). N-fixation of selected green manure plants in an organic crop rotation. *Biol. Agric. Hort.* **18**, 345–363.

Muller, J. C.D., Denys, D., Morlet, G., and Mariotti, A. (1989). Influence of catch crops on mineral nitrogen leaching and its subsequent plant use, pp. 85–98. Elsevier, London, New York.

Müller-Schärer, H. (1996). Interplanting ryegrass in winter leek: Effect on weed control, crop yield and allocation of N-fertilizer. *Crop Prot.* **15**, 641–648.

Müller, M. M., and Sundman, V. (1988). The fate of nitrogen (^{15}N) released from different plant materials during decomposition under field conditions. *Plant Soil* **105**, 133–139.

Neergaard, T. A. F. D., Nielsen, H. H., Jensen, L. S., and Magid, J. (2002). Decomposition of white clover (*Trifolium repens*) and ryegrass (*Lolium perenne*) components: C and N dynamics simulated with the DAISY soil organic mattter submodule. *Eur. J. Agron.* **16**, 43–55.

Nicolardot, B., Fauvet, G., and Cheneby, D. (1994). Carbon and nitrogen cycling through soil microbial biomass at various temperatures. *Soil Biol. Biochem.* **26**, 253–261.

Olesen, J. E., Askegaard, M., and Rasmussen, I. (2000). Design of an organic farming crop rotation experiment. *Acta Agric. Scand., Sect. B—Soil Plant Sci.* **50**, 13–21.

Parton, W. J., Stewart, J. W.B., and Cole, C. V. (1988). Dynamics of C, N, P and S in grassland soils—a model. *Biogeochemistry* **5**, 109–131.

Paustian, K., Parton, W. J., and Persson, J. (1992). Modeling soil organic matter in organic-amended and nitrogen-fertilized long-term plots. *Soil Sci. Soc. Am. J.* **56**, 476–488.

Pound, B., Anderson, S., and Gundel, S. (1999). Species for niches: When and for whom are cover crops appropriate? *Mount. Res. Developp.* **19**, 307–312.

Power, J. F., and Zachariassen, J. A. (1993). Relative nitrogen utilization by legume cover crop species at three soil temperatures. *Agron. J.* **85**, 134–140.

Quemada, M., and Cabrera, M. L. (1995). Carbon and nitrogen mineralized from leaves and stems of four cover crops. *Soil Sci. Soc. Am. J.* **59**, 471–477.

Quemada, M., and Cabrera, M. L. (1996). Temperature and moisture effects on C and N mineralization from surface applied clover residue. *Plant Soil* **189**, 127–137.

Ranells, N. N., and Wagger, M. G. (1996). Nitrogen release from grass and legume cover crop monocultures and bicultures. *Agron. J.* **88**, 777–782.

Ranells, N. N., and Wagger, M. G. (1997). Grass–legume bicultures as winter annual cover crops. *Agron. J.* **89**, 659–665.

Ranells, N. N., and Wagger, M. G. (1997). Nitrogen-15 recovery and release by rye and crimson clover cover crops. *Soil Sci. Soc. Am. J.* **61**, 943–948.

Ranells, N. N., and Wagger, M. G. (1997). Winter annual grass–legume bicultures for efficient nitrogen management in no-till corn. *Agric. Ecosyst. Environ.* **65**, 23–32.

Rask, N., Pedersen, S. E., and Jensen, M. H. (2002). Response to lowered nutrient discharges in the coastal waters around the island of Funen. *Hydrobiologia* **393**, 69–81.

Richards, I.R., Wallace, P.A., and Turner, I.D.S., (1996). A comparison of six cover crop types in terms of nitrogen uptake and effect on response to nitrogen by a subsequent spring barley crop. J. Agric Sci **127**, 441–449.

Renius, W., and Entrup, E. L. (2002). *In* "Zwischenfruchtbau Zur Futtergewinnung und Gründüngung", pp. 206. DLF Verlag, Frankfurt/Main.

Robinson, D., Linehan, D. J., and Caul, S. (1991). What limits nitrate uptake from soil? *Plant, Cell Environ.* **14**, 77–85.

Robinson, D., Linehan, D. J., and Gordon, D. C. (1994). Capture of nitrate from soil by wheat in relation to root length, nitrogen inflow and availability. *New Phytol.* **128**, 297–305.

Rosecrance, R. C., McCarty, G. W., Shelton, D. R., and Teasdale, J. R. (2000). Denitrification and N mineralization from hairy vetch (*Vicia villosa* Roth) and rye (*Secale cereale* L.) cover crop monocultures and bicultures. *Plant Soil* **227**, 283–290.

Sainju, U. M., and Singh, B. P. (1997). Winter cover crops for sustainable agricultural systems—influence on soil properties, water quality, and crop yields [review]. *HortScience* **32**, 21–28.

Sainju, U. M., Singh, B. P., Rahman, S., and Reddy, V. R. (1999). Soil nitrate-nitrogen under tomato following tillage, cover cropping, and nitrogen fertilization. *J. Environ. Qual.* **28**, 1837–1844.

Sainju, U. M., Singh, B. P., and Whitehead, W. F. (1998). Cover crop root distribution and its effects on soil nitrogen cycling. *Agron. J.* **90**, 511–518.

Sanderson, J. B., MacLeod, J. A., and Kimpinski, J. (1999). Glyphosate application and timing of tillage of red clover affects potato response to N, soil N profile, and root and soil nematodes. *Can. J. Soil Sci.* **79**, 65–72.

Scholte, K., and Lootsma, M. (1998). Effect of farmyard manure and green manure crops on populations of mychophagous soil fauna and Rhizoctonia stem cracker of potato, Pedobiologia. **42**, 223–231.

Schröder, J. J., Groot, W. M., and Dijk, W. (1992). Nitrogen losses from continuous maize as affected by cover crops. *Aspects Appl. Biol.* **30**, 317–326.

Schröder, J. J., Holte, L. T., Janssen, B. H., and Ten-Holte, L. (1997). Non-overwintering cover crops: a significant source of N. *Neth. J. Agric. Sci.* **45**, 231–248.

Schröder, J. J., Vandijk, W., and Degroot, W. J.M. (1996). Effects of cover crops on the nitrogen fluxes in a silage maize production system. *Neth. J. Agric. Sci.* **44**, 293–315.

Scott, H. D., Keisling, T. C., Waddle, B. A., Williams, R. W., and Frans, R. E. (1919). Effects of winter cover crops on yield of cotton and soil properties. *Arkansas Expp. Station Bull.* **924**, 1–21.

Shepherd, M. A. (1993). Measurement of soil mineral nitrogen to predict the response of winter wheat to fertilizer nitrogen after applications of organic manures or after ploughed-out grass. *J. Agric. Sci. Camb.* **121**, 223–231.

Shepherd, M. A. (1999). The effectiveness of cover crops during eight years of a UK sandland rotation. *Soil Use Manag.* **15**, 41–48.

Shepherd, M. A., Davies, D. B., and Johnson, P. A. (1993). Minimizing nitrate losses from arable soils. *Soil Use Manag.* **9**, 94–99.

Shipley, P. R., Meisinger, J. J., and Decker, A. M. (1992). Conserving residual corn fertilizer nitrogen with winter cover crops. *Agron. J.* **84**, 869–876.

Smith, P., Smith, J. U., Powlson, D. S., McGill, W. B., Arah, J. R.M., Chertov, O. G., Coleman, K., Franco, U., Frolking, S., Jenkinson, D. S., Jensen, L. S., Kelly, R. H., KleinGunneweik, H., Komarov, A. S., Li, C., Molina, J. A.E., Mueller, T., Parton, W. J., Thornley, J. H.M., and Whitmore, A. J. (1997). A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. *Geoderma* **81**, 153–225.

Sørensen, J. N. (1992). Effects of catch crops on the content of soil mineral nitrogen before and after winter leaching. *Z. Pflanzenernähr. Bodenk.* **155**, 61–66.

Sørensen, J. N., and Thorup-Kristensen, K. (1993). Nitrogen effects of non-legume catch crops. *Z. Pflanzenernähr. Bodenk.* **156**, 55–59.

Sørensen, P., and Jensen, E. S. (1996). ^{15}N-labelling of animal manure: problems, solutions and use. *In* "Trans. 9th Nitrogen Workshop", pp. 67–70. Technische Universitet Braunschweig, Braunschweig, Germany.

Sørensen, P., and Jensen, E. S. (1998). The use of N-15 labelling to study the turnover and utilization of ruminant manure N. *Biol. Fert. Soil* **28**, 56–63.

Sørensen, P., Jensen, E. S., and Nielsen, N. E. (1994). The fate of N-15 labeled organic nitrogen in sheep manure applied to soils of different texture under field conditions. *Plant Soil* **162**, 39–47.

Strizaker, R.J., and Bunn, D.G. (1996). Phytotoxicity of ryegrass and clover cover crops, and a lucerne alley crop for no-till vegetable production, Biol. Agric. Hort. **13**, 83–101.

Stirzaker, R. J., and White, I. (1995). Amelioration of soil compaction by a cover-crop for no-tillage lettuce production. *Aust. J. Agric. Res.* **46**, 553–568.

Stute, J. K., and Posner, J. L. (1995). Legume cover crops as a nitrogen source for corn in an oat corn rotation. *J. Prod. Agric.* **8**, 385–390.

Stute, J. K., and Posner, J. L. (1995). Synchrony between legume nitrogen release and corn demand in the upper midwest. *Agron. J.* **87**, 1063–1069.

Sumner, D. R., Phatak, S. C., Gay, J. D., Chalfant, R. B., Brunson, K. E., and Bugg, R. L. (1995). Soilborne pathogens in a vegetable double-crop with conservation tillage following winter cover crops. *Crop Prot.* **14**, 495–500.

Teasdale, J.R., and Daughtry, G.S.T. (1993). Weed suppression by live and desiccated hairy vetch (*Vicia villosa*), Weed Sci. **41**, 207–212.

Teasdale, J. R., and Mohler, C. L. (1993). Light transmittance, soil temperature, and soil moisture under residue of hairy vetch and rye. *Agron. J.* **85**, 673–680.

Theunissen, J. (1995). Application of intercropping in organic agriculture. Entomological research in organic agriculture Austrian Federal Ministry of Science and Research, Vienna, March 1995. *Biol. Agric. Hortic.* **15**, 251–259.

Theunissen, J., and Schelling, G. (2000). Undersowing carrots with clover: suppression of carrot rust fly (*Psila rosae*) and cavity spot (*Pythium* spp.) infestation. *Biol. Agric. Hort.* **18**, 67–76.

Thibaud, M., Morel, C., and Fardeau, J.-C. (1988). Contribution of phosphorus issued from crop residues to plant nutrition. *Soil Sci. Plant Nutr.* **34**, 481–491.

Thomsen, I. K. (1993). Nitrogen uptake in barley after spring incorporation of ^{15}N labelled Italian ryegrass into sandy soils. *Plant Soil* **150**, 193–201.

Thomsen, I. K., and Christensen, B. T. (1999). Nitrogen conserving potential of successive ryegrass catch crops in continuous spring barley. *Soil Use Manag.* **15**, 195–200.

Thomsen, I. K., Kjellerup, V., and Jensen, B. (1997). Crop uptake and leaching of N-15 applied in ruminant slurry with selectively labelled faeces and urine fractions. *Plant Soil* **197**, 233–239.

Thorup-Kristensen, K. (1993a). Root development of nitrogen catch crops and of a succeeding crop of broccoli. *Acta Agric. Scand., Sect. B—Soil Plant Sci.* **43**, 58–64.

Thorup-Kristensen, K. (1993b). The effect of nitrogen catch crops on the nitrogen nutrition of a succeeding crop I. Effects through mineralization and pre-emptive competition. *Acta Agric. Scand., Sect. B—Soil Plant Sci.* **43**, 74–81.

Thorup-Kristensen, K. (1994). An easy pot incubation method for measuring nitrogen mineralization from easily decomposable organic material under well defined conditions. *Fert. Res.* **38**, 239–247.

Thorup-Kristensen, K. (1994). The effect of nitrogen catch crop species on the nitrogen nutrition of succeeding crops. *Fert. Res.* **37**, 227–234.

Thorup-Kristensen, K. (1996). Effect of catch crop incorporation time on N availability for a succeeding crop. *In* "Long Term Reduction of Nitrate Leaching by Cover Crops, First progress report of EU concerted action (AIR3) 2108". (J. J. Schröder, Ed.), pp. 49–54.

Thorup-Kristensen, K. (2001). Are differences in root growth of nitrogen catch crops important for their ability to reduce soil nitrate-N content, and how can this be measured? *Plant Soil* **230**, 185–195.

Thorup-Kristensen, K., and Nielsen, N. E. (1998). Modelling and measuring the effect of nitrogen catch crops on the nitrogen supply for succeeding crops. *Plant Soil* **203**, 79–89.

Thorup-Kristensen, K., and Sørensen, J. N. (1999). Soil nitrogen depletion by vegetable crops with variable root growth. *Acta Agric. Scand., Sect. B—Soil Plant Sci.* **49**, 92–97.

Thorup-Kristensen, K., and Van den Boogaard, R. (1999). Vertical and horizontal development of the root system of carrots following green manure. *Plant Soil* **212**, 145–153.

Torbert, H. A., Reeves, D. W., and Mulvaney, R. L. (1996). Winter legume cover crop benefits to corn: rotation vs fixed-nitrogen effects. *Agron. J.* **88**, 527–535.

Torstensson, G. (1998). Nitrogen delivery and utilization by subsequent crops after incorporation of leys with different plant composition. *Biol. Agric. Hort.* **16**, 129–143.

Torstensson, G., and Aronsson, H. (2000). Nitrogen leaching and crop availability in manured catch crop systems in Sweden. *Nutr. Cycl. Agroecosyst.* **56**, 139–152.

Tu, J. C. (1988). The impact of interseason green manuring on root diseases and soil environments. *Med. Fac. Landbouww. Rijksuniv. Gent* **53**, 2–321.

Tu, J. C., and Findlay, W. I. (1986). The effect of different green manure crops and tillage practices on pea root rots. *Br. Crop Protect. Conf.—Pest Dis.* **3C-1**, 229–236.

Van Dam, A. M., and Lantinga, E. A. (1998). Leaf CO_2 assimilation and leaf dynamics in catch crops during autumn and winter at two levels of nitrogen supply. *Neth. J. Agric. Sci.* **46**, 249–265.

Van Dam, A. M., and Leffelaar, P. A. (1998). Root, soil water and nitrogen dynamics in a catch crop—soil system in the Wageningen Rhizolab. *Neth. J. Agric. Sci.* **46**, 267–284.

Van Gestel, M., Merckx, R., and Vlassak, K. (1993). Soil drying and rewetting and the turnover of 14C-labelled plant residues: First order decay rates of biomass and non-biomass 14C. *Soil Biol. Biochem.* **25**, 125–134.

Van schöll, L., Van Dam, A. M., and Leffelaar, P. A. (1997). Mineralisation of nitrogen from an incorporated catch crop at low temperatures: experiment and simulation. *Plant Soil* **188**, 211–219.

Vigil, M. F., and Kissel, D. E. (1995). Rate of nitrogen mineralized from incorporated crop residues as influenced by temperature. *Soil. Sci. Soc. Am. J.* **59**, 1636–1644.

Vos, J., van der Putten, P. E. L., Hussein, M. H., Van Dam, A. M., and Leffelaar, P. A. (1998). Field observations on nitrogen catch crops. II. Root length and root length distribution in relation to species and nitrogen supply. *Plant Soil* **201**, 149–155.

Vos, J., and van der Putten, P. E. L. (2000). Nutrient cycling in a cropping system with potato, spring wheat, sugar beet, oats and nitrogen catch crops. I. Input and offtake of nitrogen, phosphorus and potassium. *Nutr. Cycl. Agroecosyst.* **56**, 87–97.

Vos, J., and van der Putten, P. E. L. (1997). Field observations on nitrogen catch crops. 1. Potential and actual growth and nitrogen accumulation in relation to sewing date and crop species. *Plant Soil* **195**, 299–309.

Vyn, T. J., Faber, J. G., Janovicek, K. J., and Beauchamp, E. G. (2000). Cover crop effects on nitrogen availability to corn following wheat. *Agron. J.* **92**, 915–924.

Vyn, T. J., Janovicek, K. J., Miller, M. H., and Beauchamp, E. G. (1999). Soil nitrate accumulation and corn response to preceding small-grain fertilization and cover crops. *Agron. J.* **91**, 17–24.

Wagger, M. G. (1989). Time of desiccation effects on plant composition and subsequent nitrogen release from several winter annual cover crops. *Agron. J.* **81**, 236–241.

Wallgren, B., and Linden, B. (1994). Effects of catch crops and ploughing times on soil mineral nitrogen. *Sweed. J. Agric. Res.* **24**, 67–75.

Wander, M. M., Traina, S. J., Stinner, B. R., and Peters, S. E. (1994). Organic and conventional management effects on biologically active soil organic matter pools. *Soil Sci. Soc. Am. J.* **58**, 1130–1139.

Wang, J., and Bakken, L. R. (1997). Competition for nitrogen during decomposition of plant residues in soil: Effect of spatial placement of N-rich and N-poor plant residues. *Soil Biol. Biochem.* **29**, 153–162.

Whitehead, D. C., Lockyer, D. R., and Raistrick, N. (1988). The volatilization of ammonia from perennial ryegrass during decomposition, drying and induced senescence. *Ann. Bot.* **61**, 567–571.

Williams-Woodward, J. L., Pfleger, F. L., Fritz, V. A., and Allmaras, R. R. (1997). Green manures of oat, rape and sweet corn for reducing common root rot in pea (*Pisum sativum*) caused by *Aphanomyced euteiches*. *Plant Soil* **188**, 43–48.

Willigen, P. D. (1991). Nitrogen turnover in the soil–crop system; comparison of fourteen simulation models. *Fert. Res.* **27**, 141–149.

Willumsen, J., and Thorup-Kristensen, K. (2001). Effects of green manure crops on soil mineral nitrogen available for organic production of onion and white cabbage in two contrasting years. *Biol. Agric. Hort.* **18**, 365–384.

Wivstad, M. (1997). Plant morphology and content of nitrogen, cell wall and lignin at different phenological stages of red clover and yellow sweetclover. *Sweed J. Agric. Res.* **27**, 3–14.

Wyland, L. J., Jackson, L. E., and Schulbach, K. F. (1995). Soil–plant nitrogen dynamics following incorporation of a mature rye cover crop in a lettuce production system. *J. Agric. Sci.* **124**, 17–25.

Yadvinder, S., Bijay, S., and Khind, C. S. (1992). Nutrient transformations in soils amended with green manures. *Adv. Soil Sci.* **20**, 237–309.

Yamagishi, H., Yoshikawa, H., and Ashizawa, M. (1986). Effects of resistant plants as a catch crop on the reduction of resting spores of clubroot (*Plasmodiophora brassicae* Worn.) in soil. *J. Jpn Soc. Hortic. Sci.* **54**, 460–466.

Yanai, J., Linehan, D. J., Robinson, D., Young, I. M., Hackett, C. A., Kyuma, K., and Kosaki, T. (1996). Effects of inorganic nitrogen application on the dynamics of the soil solution composition in the root zone of maize. *Plant Soil* **180**, 1–9.