A review of leguminous fertility-building crops, with particular refence to nitrogen fixation and utilisation

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EXECUTIVE SUMMARY

The cornerstone of the organic philosophy is the use of legume based leys to build fertility. Indeed, the organic standards require the inclusion of legumes in the rotation. Fertility-building crops and green manures are therefore key components of organic rotations. The regulations contain no specific requirements for ley management and the paucity of research means that their management is often based on hearsay rather than empirical evidence. Management options for these crops are many, including:

- choice of species and cultivar;
- length of growing period within the rotation;
- rotational position and management of foliage (cutting and exporting, cutting and mulching, grazing or combinations of these).

These factors will affect the amount of N fixed during the fertility-building stage, i.e. influence the amount of N that has been captured. Efficient use of the captured N by the following crops relies on management practices and cropping patterns that make best use of the N released by mineralisation of the residues

The logical starting point is a synthesis of the current state of knowledge. The objective of this review is therefore to review effects of soil fertility-building crops on:

- N capture
- N use
- Pest, disease and other effects
- Available models for predicting N capture

The use of leguminous fertility-building crops represents an import of N into the system via fixation of atmospheric N. It is the most important source of N in the rotation. Therefore, the focus of this review is in managing N: fixation and the factors that affect it, and subsequent mineralisation and use of the fixed N by arable crops. However, the use of fertility-building crops should also be valuable in the conservation of other nutrients besides N, particularly K and Ca (both more mobile in soil than P). Such crops should also benefit soil structure since optimal aggregate stability requires the frequent turnover of young organic matter residues. There are indications that clover has additional benefits on soil structure.

It is important to differentiate between different N sources:

N-fixation	Refers specifically to process of symbiotic fixation of atmospheric N by legumes
Fixed-N	The amount of plant N obtained from the atmosphere
%Ndfa	Percentage of total plant N obtained from the atmosphere
Non-symbiotic fixation	Fixation of N by free living soil organisms
N input in rain and dry deposition	N deposited from the atmosphere
Plant-N or N-yield	Total amount of N in plant, derived from soil and atmosphere
Residue N	Total amount of plant N from soil and atmosphere left in soil after harvest or

cultivation of crop

As a part of the wider project, workshops were held with organic growers to discuss the challenges of managing fertility-building crops. The main areas of concern are summarised below:

- Optimum crop sequence (including length of build up and break between legumes and/or green manures)
- Management of cover crops - options/timing
- Rate of release of N from green manures/covers and crop residues
- Management of swards (i.e. cutting/mulching/removal/grazing requirements) to optimise N accumulation and minimise losses
- N fixation ability of different legume species in UK conditions (including optimum mixes for mixed swards)
- Assessment of % clover in mixed swards
- N build-up/retention - Interactions with cultivations/seed bed preparation
- N build-up/retention - Interactions with pest and disease issues
- Bi-cropping
- N build-up/retention - Interactions with other nutrients
- Management of organic manures
- Cost implications
- Grain legumes for cash crops

Soil fertility-building crops in the rotation

Fertility-building crops can be split into three types:

- ‘Nitrogen-fixers’
- ‘Nitrogen-holders’
- Those that affect other general fertility aspects such as soil structure.

As the fertility-building part of the organic rotation often occupies a large proportion of the rotation (grass/clover leys and green manures can occupy as much as 66% of the organic farming acreage), it is important to gain as much benefit from it as possible. In mixed livestock systems the grass/clover leys clearly have a role to play in forage production. However, there is some evidence that the livestock manures that are often applied to the grass would be better used on the arable crops, especially where higher protein levels are required in cereals.

For non-livestock systems it is important to have sufficient fertility-building crops to support the cash crops, as there is no opportunity to supplement the soil N with organic manure (unless imported). It is also beneficial from an economic point of view if the fertility-building crops can also provide income as they can occupy 20-40% of the rotation. Thus, clover grown for seed may be preferred over a cut/mulch system and peas/beans, which can be sold for human consumption preferred over those that are used for animal feed.

The choice of species is also important. European studies have recommended that climate is considered when choosing legumes. For example, they recommend red clover or lucerne (both of which are deep rooted) for dry conditions but point out that white clover has a very good ability to recover after drought.

Clearly, there are pest and disease implications with all farming systems. Consideration of disease interactions and implications with fertility-building crops needs to include:

1. Diseases affecting the fertility-building crops directly.
2. Diseases affecting fertility-building crops which will also affect other crops in rotation.
3. Consequences of incorporation of the fertility-building crop into soil: suppressive or antagonistic effects on soil- or air-borne pathogens.
4. Poor performance of the fertility-building crop has implications on the subsequent cash crop

The legacy of disease problems left by fertility-building crops is of major concern to growers. The extent of problems will be influenced strongly by previous cropping and its legacy of the soil pathogen population on the field or farm. Thus, farms with a history of legume cropping are likely to carry high populations of pathogens affecting legumes, whilst few legume pathogens may be present where legumes have not been grown for many years. Very intensive legume cropping may leave high soil populations of fungal pathogens, which will only decline slowly.

There are two main ways in which fertility-building crops or catch crops grown to maintain fertility can interact with invertebrate pests. Firstly, the pests may attack the fertility-building /catch crop and secondly they may carry over into the succeeding crop, resulting in poor establishment and loss of yield.

How much N is fixed?

Few studies have measured the maximum quantity of N that can be fixed under ideal conditions. The best that can be done is to estimate potential fixation from the upper range of values observed in different studies and take account of any limitations that may be present. In this respect, measurements from countries where conditions are more favourable than in the UK may be more indicative of the maximum fixation that can be achieved.

Methodological difficulties make it almost impossible to get an accurate measure of fixed N. All methods have advantages and disadvantages. The literature has used a number of methods, so that estimates are not always directly comparable. Simple measurements of N yield are an unreliable guide to the quantities of N fixed. Measurements of N-fixation must differentiate between crop N obtained from the soil and from the atmosphere. Also, much of the below-ground N can be present as fine roots or transferred to the rhizosphere, and it was concluded that standard root recovery procedures are likely to underestimate the total N accretion and turnover.

Also, the majority of estimates of N-fixation do not include fixed N in unharvested parts of the plant. Jørgensen & Ledgard (1997) suggested a correction factor of 1.65 to account for N in roots and stubble when fixation in white clover is estimated by harvesting the leaves only. This is greater than the value employed by Høgh-Jensen & Kristensen (1995), who considered that biologically fixed N was underestimated by 19-25% when only the harvested material was measured.

Where transfer of fixed N occurs, this should normally be included in any assessment of the net input from fixation, though care is required to avoid ‘double-counting’, particularly in systems that are not at equilibrium and where fixation in one year contributes to transfer in later years. Nitrogen transfer can occur through root excretion and decomposition, leaching from leaves and in leaf-fall and animal excreta.

Estimates of N fixation by **white clover** span a wide range of values and in spite of the abundant information, there is still uncertainty about the quantities fixed. Much of the variation in N-fixation can be attributed to differences in the proportion of clover in mixed swards. Almost all studies indicate that white clover obtains most of its N from the atmosphere rather than from the soil. There is evidence that the proportion of N derived from the atmosphere (%Ndfa) is less under grazing than where swards are mown.

Red clover may be more productive than white clover. As with white clover, a high proportion of N in red clover is obtained by fixation. Also, as with white clover, there is evidence of differences in the quantity of N fixed by different cultivars.

Data for **subteranean clover** are fewer, reflecting that it is not a common UK crop. However, N fixation appears to be affected in a similar way as with white and red clover. The crop obtains most of its N from fixation, and fixation is greater under a cutting than a grazing regime.

Lucerne is more persistent than red clover and has a productive life of up to 4 years. Yield is little affected by drought during British summers. Constraints on growth are poor drainage and very acid subsoils. It is therefore restricted to deep, free-draining, calcareous soils. As with the other legumes reviewed, there is a wide range of N fixation values. Lucerne seems particularly susceptible to soil nutritional status, and inoculation is essential.

There is little information about the quantities of N fixed under UK conditions by **trefoil** and by **sainfoin**. There is an indication that sanfoin is less effective at fixing N than red clover.

Peas and beans tend to be grown as a fertility boost, part way through the arable phase of a rotation. N fixation varies, partly depending on the amount of soil mineral N present. Generally, the proportion of the crop's N derived from fixation is smaller than from red or white clover. A large proportion of the fixed N is removed from the field in harvested seed, though the haulm, roots and rhizodeposits usually provide a positive N balance to the soil. Net benefits of **soybeans** to following crops are also generally small because of the removal of N in harvested grain.

Factors that limit plant growth normally also limit fixation, either through direct effects on nodule formation or function or indirectly through the host plant's ability to supply nutrients. However, some forms of stress (e.g. excess soil water, drought, cold or heat) have a greater effect on nodule function than on nitrate uptake so that plants relying on fixation may be more severely affected than plants supplied with fertiliser-N. In these situations, improvements in general growing conditions would be expected to benefit N-fixing plants more than those relying on fertiliser. Fixation can also be affected by soil structure and by disease. Where inoculation is used to introduce more effective rhizobia, the response will be influenced by the effectiveness of the native rhizobia and their competitive ability. Effectiveness can also be reduced, e.g. in soybean, where there is a temporal separation between maximum nitrate assimilation and N-fixation activity.

Regional differences and year-to-year fluctuations in weather patterns will influence legume growth and fixation activity through effects of temperature, moisture supply and radiation.

Fixation is affected by drought. There is still debate over the precise mechanism, whether it is physiological or that plants have greater and easier access to soil mineral N after a drought. Deep rooting species (red clover, lucerne) are less affected by drought than others. As would be expected, root function (including fixation) is decreased by waterlogging. Soil factors also play an important part in crop growth and subsequent N fixation. Adequate levels of nutrients and lime are required, as is good soil structure. Pests and disease can decrease fixation. A high total soil N content (and organic matter content), if it results in elevated mineralisation of N, could potentially decrease fixation.

After N, P is usually the next-limiting nutrient in temperate soils. Phosphorus has an essential role in the legume symbiosis, either by directly affecting nodule development and function or indirectly by affecting growth and metabolism of the host plant. Potassium is reported to have a role in improving the plant's resistance to environmental stress.

Soil acidity is a major factor influencing legume persistence. Generally, rhizobial growth and activity appear to be more sensitive to low soil pH than is the host plant. Soil acidity may be a particular problem in upland areas. Legume species and legume/rhizobia genotypes differ in their susceptibility to low pH.

The negative relationship between plant-available soil N and the proportion of plant N obtained by fixation could be considered to be the single most important limitation to N-fixation. It has long been known that increased availability of mineral-N in the soil has a negative effect on N-fixation. In general, legumes will obtain less of their N requirement from the atmosphere if there is an adequate supply available from the soil. Thus, soil conditions and cropping patterns that reduce the soil-N status will tend to increase the quantity of N fixed while conditions that increase soil-N will reduce fixation.

Many factors will affect the soil mineral N supply and, hence, influence N fixation by the legume. Although fertiliser N applications are not relevant in organic systems, manure applications may affect fixation. The level of soil-N in pastures also fluctuates during the year and may be high during dry summer conditions leading to a reduction in %Ndfa (percentage of total plant N obtained from the atmosphere). At other times of the year, the high potential uptake of N by ryegrass in early spring will deplete soil-N and encourage fixation later in the season when conditions are more favourable for legumes. Changes in soil-N availability affecting N-fixation can also arise as a result of agricultural operations such as cultivation that encourage N-mineralisation in the soil. As mineral N accumulates in the soil/crop system, N fixation will decline, so that legumes in second and subsequent years are likely to fix less N. However, there are indications of different species showing different responses to the presence of soil mineral N.

Growth of legumes with a companion species either as mixed cropping or intercropping will influence fixation in sometimes opposing ways. The presence of the non-legume will reduce the number of N-fixing plants per unit area and may further reduce growth of the legume through competition for light, moisture and soil nutrients. However, at the same time, a companion species can provide physical support to reduce lodging; for example, in pea crops (Karpenstein-Machan & Stuelpnagel, 2000). More generally, N uptake by the companion species may reduce the availability of mineral-N in the soil and thus encourage the legume to obtain a greater proportion of its N through fixation. The presence of weeds in the crop may have similar effects. Increasing planting density of the legume can to some extent have a similar effect to intercropping, presumably because of a greater demand for soil-N under the denser crop.

Transfer of fixed N can be substantial in grass/clover mixtures. There is a high turnover of roots and nodules of living clover and greater opportunity for transfer to occur through decomposition and mineralisation pathways than in annual crops. In contrast to grass/clover swards, evidence of N transfer between other legume species and companion crops is often conflicting.

Knowledge of relative rates of fixation at different seasons and stages of growth is important for assessing how much of this annual total is fixed by legumes that are grown for less than a full year, for example, with short-term cover crops or where a ley is cultivated during summer or early autumn. Relative rates of fixation in grass/clover swards are largely determined by temperature and moisture supply. The stage of vegetative or reproductive growth may be more important for annual grain legumes. For perennial legumes, longer-term fluctuations in factors such as soil mineral-N contents will also influence fixation.

As would be expected from the previously described relationship between the build-up of soil-N and N-fixation, fixation in grass/clover swards is also likely to decline with increasing pasture age (independently of changes in the proportion of clover).

Influence of management

Various aspects of management will influence the quantity of N provided by a legume crop. Effects can be divided between those, such as crop removal, which influence the net accumulation of N and those that influence the N-fixation process directly. Harvesting of forage or grain will remove much of the fixed N and reduce the benefit to following crops. The benefit will be further reduced if straw and other crop residues are also removed from the field. In contrast, where crops are mulched or grazed, much of the fixed N will be returned to the soil in plant debris or excreta. Nitrogen-fixation processes will be affected directly by defoliation of the legume and indirectly through effects on the mineral-N content of the soil. Other aspects of management affecting N-fixation include position of the crop in the cropping rotation, duration of cropping, methods of cultivation and applications of manures and composts.

Cutting and mulching can result in mineral N accumulation, which will reduce fixation. It may be better to remove the foliage from the field, though this then requires the foliage to be managed (presumably as forage and, ultimately, as manure). In a mixed sward, decreasing the cutting frequency could potentially decrease fixation (increased competition from the grass), but defoliation of forage legumes also causes a dramatic decrease in N-fixation activity.

Nitrogen dynamics are likely to be very different where the cut herbage is returned to the soil. However, there is little information about the direct effects of mulching on the N-fixation process.

Harvesting of forage crops or of grain legumes both remove fixed-N from the field. Although N accumulated in stubble and roots will remain, the net contribution to the soil N balance may be small or even negative, particularly with grain legumes which generally obtain a smaller proportion of their N from the atmosphere. The benefits will be even less if straw or other crop residues are removed as well as the grain.

Most estimates of N-fixation by forage legumes only include N in the above-ground parts of the plant. As the same plant parts are removed in normal agricultural harvesting operations, this will account for most of the estimated above-ground fixation. The benefit to following crops will therefore be largely dependent on the fixed-N left in the unharvested roots and stubble. With some crops this can be an important source of N.

Grazing influences N-fixation in pastures by altering the proportion of legume in mixed swards, through defoliation and through the inhibitory effects of N in dung and urine on the fixation process. The recycling of N in excreta also represents an important route for transfer of fixed-N from the legume to grass in mixed swards. This can be of a similar magnitude to 'below-ground' transfer (e.g. 3-102 kg N/ha/year or 2-26% of the N fixed). The effects of grazing on pasture composition will differ for different types of livestockand for different intensities of grazing.

There are conflicts inherent in applying manures to grass/clover swards. They supply valuable P and K but their N content may inhibit N-fixation and put clovers at a competitive disadvantage in mixed swards. Animal slurries may be expected to have a greater immediate effect on fixation than farmyard manure or well-prepared composts, which normally have a lower proportion of N in a readily-available form. However, recent Defra-funded studies indicate that slurry applications need not necessarily reduce the quantities of N fixed.

Various aspects of soil management can influence N-fixation. In many cases this will be through their effect on the soil mineral-N levels experienced by the legume, with the legume obtaining a greater proportion of its N from the atmosphere in low-N soils. Thus, more N is likely to be fixed where legumes follow crops that have previously depleted soil-N levels. This is likely to be the situation in most organic rotations, where leguminous crops normally follow a N-depleting phase.

Cultivation practices that increase mineralisation of soil organic matter will lead to increased levels of soil-N with the result that following legume crops obtain less of their N from the atmosphere. A number of studies have demonstrated greater fixation in minimum tillage systems, presumably because this minimises the flush of mineralisation that occurs with more disruptive, conventional cultivation practices such as ploughing.

Models for predicting fixation

The challenge with any advisory model is to restrict the amount of input information and parameters that are required (so that it is usable), but to ensure that the information is sufficient to give reasonably accurate results. The advisory model should also be able to draw out the major management effects, so that it can be used to advise on best practices.

Watson *et al.* (2002) summarised the factors that prediction models tend to include - not all models take account of all factors:

- Yield of legume and grass
- Yield of grass-only reference crop (or other measure of soil-N supply)
- % legume in mixture
- Years after establishment
- N content of legumes
- N content of legumes plus grass

- N content of grass-only reference crop
- % legume N derived from fixation
- Correction for stubble/root N
- Sward management

Several studies have shown N-fixation and legume yield to be strongly correlated.

Van der Werff *et al.* (1995) estimated N-fixation in **grass/clover pastures** on mixed, organic farms on sandy soils in the Netherlands by assuming values of:

    - 40 kg N fixed per tonne of dry matter for red clover
    - 54 kg N fixed per tonne of dry matter for white clover.

Vinther & Jensen (2000), for **grazed grass/clover pasture** in a grass/arable rotation on a sandy loam in Denmark, assumed that the quantity of N fixed per tonne of clover shoot dry weight was:

- 38.6 kg N fixed per tonne of dry matter for first and second year mixtures
- 45.0 kg N fixed per tonne of dry matter for undersown grass-clover.

These were similar to other values from the literature, cited in the paper: i.e.

- 30-46 kg N fixed per tonne of dry matter for white clover
- 24-36 N fixed per tonne of dry matter for red clover.

Wheeler *et al.* (1997), in New Zealand, estimated the amount of N fixed as:

- 40 kg N fixed per tonne of dry matter for white clover on a high rainfall site
- 46 kg N fixed per tonne of dry matter for subterranean clover on a low rainfall site

It has been estimated that lucerne and subterranean clover fixed 22-25 kg N for every tonne of legume dry matter produced.

There have also been more complex, modelling approaches to estimating fixation.

Utilisation of N

Nitrogen fixation by the fertility-building crop is only the first part of the process by which atmospheric N is made available within the rotation. It then has to be released and made available to the following crops. It is necessary to consider the following pools of N in the soil-crop system at the end of the fertility-building stage:

- Soil mineral N in the soil profile, the amount depending on history and management of the fertility-building crop. Much of this may well have been derived from mineralisation of organic residues during the fertility-building stage (or from recent manure applications).
- N in the microbial biomass.
- N in roots and nodules and from rhizodeposition.
- N in leaf litter (e.g., at various stages of decay), either from natutral leaf drop or from cutting and mulching the fertility-building crop. This may also be from straw residues if the crop has been harvestsed and removed from the field (e.g. peas/beans).
- N in above ground components, such as stubble and foliage.
- N in manure residues, if manure has been applied recently or the crop has been grazed.
- N in native soil organic matter.

Therefore, the N that can be potentially be used by the subsequent crops may be in mineral or organic forms (most is likely to be in organic forms), and in a range of organic fractions that will vary in recalcitrance. Generally, the organic forms of N associated with the fertility-building crop could be termed ‘residue N’. It should also be noted that not all of the residue N will necessarily be fixed N – some will have derived from uptake of (a) N released from the native soil organic matter and (b) mineral N in the soil at the time of establishment of the fertility-building crop. The proportion of non-fixed N will depend on many factors, as described in the previous Sections.

How effectively the residue N is used by the subsequent crops in the rotation will depend on many factors, including:

- the rate of net mineralisation
- efficiency of uptake by crops
- N removal in harvested products
- N (and C) return in plant residues and
- losses of N

The rate of N depletion will be reduced if manures are applied or if the rotation includes further legumes during this phase.

Rotational Aspects

Lack of technical information and advice on management of fertility-building crops is felt to be a major problem by many farmers.

Long sequences of legumes are most common in livestock systems, usually grown in a mix with grass for forage. Conflicts can occur with respect to the management of the sward to optimise grazing potential or forage dry matter production, whilst enhancing the residue of soil N sufficiently to support the rest of the rotation. The return of animal manures contributes to the long-term fertility of these rotations. As well as clover, beans are also commonly grown as a legume that can also contribute to animal feedstock. The stockless systems are characterised by shorter (1-2 year) legume sequences, in which the legume is often grown for seed. The legume may also be grown as a ‘set-aside’ crop. A wider range of legumes seems to be grown and there is greater evidence of over-winter cover crops.

The optimum ratio of fertility crops to cash crops will depend on the nutrient retention capacity of the soil. In mixed arable/livestock systems, there are generally longer runs of grass/clover leys in the rotation, which may be to the detriment of N fixation in later years.

The calculation of nutrient balances is well recognised as technique for studying the sustainability of organic rotations and are recommended as an essential precursor to conversion. However estimating the nitrogen fixation component can be difficult.

Some crops are believed to be deep rooting and able to extract nutrients from depth, thereby enhancing the fertility of the topsoil when incorporated, but there is little documented evidence to support this claim.

As indicated above, practical considerations are also important in determining crop rotations. Crops that are harvested late do not lead well into a following crop, which requires early establishment. The benefits of stale seedbeds may need to be balanced against the disadvantages of increased N leaching. The crop-weed-nitrogen triangle is also a common dilemma.

The feeding potential of the less common forage crops is not known and some, e.g. sweet white clover, have been reported to be toxic in some circumstances.

Conclusions

Soil Fertility-building Crops

- There is a wide range [illegible]ertility-building crops available to organic farmers including both legumes (‘N fixers’) and cover/catch crops (‘N-holders’).
- Some related species are more susceptible to pests and diseases than others (eg *Trifolium spp*. and stem nematode susceptibility)
- Pest and disease carry-over may occur when similar crop types are used for fertility-building as well as a cash crop (eg mustard cover crop and brassica vegetables)
- There is often conflict between measures to maintain fertility in terms of N retention and reduction of pest and disease risk (e.g. early sowing of winter cereals after a grass/legume increases the risk of aphids/BYDV)
- Good soil management and drainage are important factors in most aspects of successful crop production including reducing the threat from soil-borne diseases and control of some pests such as slugs.
- The farmer should consider cropping history and previous diseases problems before selecting fertility-building crops.
- Some direct disease risk to fertility-building crops – foliar diseases and clubroot on crucifers, sclerotinia, foliar and root diseases on legumes.
- The ‘green bridge’ effect which enables pests and diseases to overwinter would work against rotational strategies which try to avoid overlapping crops.
- Complex biological and chemical interactions occur in soil but some benefits can occur after incorporation of green crops.
- Bi-crops can reduce disease severity.
- The feeding potential of the less common forage crops is not known and some, e.g. sweet white clover, have been reported to be toxic in some circumstances.

How much N is fixed?

- To understand the contribution of legumes to soil fertility, it is important to be able to quantify the amount of N they fix from the atmosphere, because this represents a true import onto the farm.
- Uptake of soil N is not an import onto the farm though, if the crop retains N that would have otherwise leached, then this also contributes to fertility.
- Quantifying fixation is difficult, for several reasons:
    - Several different methodological approaches with advanatages and disadvantages (and often making comparison of data difficult)
    - Whereas, the N content of the above-ground component is easily measured, that below ground is very difficult to quantify. Estimates of the below-ground contribution differ between authors, ranging 20-60% of above-ground N.
    - Due to the complex nature of N cycling, there is a risk of double counting, especially in a cut/mulch system, where N might be mineralised after cutting and be taken up by the crop again.

  - A wide range of legumes is available to the organic grower. Information on N fixation capacity and yield under UK conditions is limited for the more minor crops.
- The most commonly grown legumes for fertility-building under UK conditions are:
  - White clover/grass
  - Red clover
  - Lucerne
  - Peas and beans
- Most data is also available for white clover/grass, red clover, peas, beans and lucerne.
- Estimates of N fixed, both as kg N/ha N and as % derived from the atmosphere vary widely in the literature.
- There are reports of differences between varieties as well as differences between species.
- Many environmental factors also affect N fixation and growth of the legume:
  - Climate: particularly prone to drought and waterlogging
  - Soil factors: nutrition (especially P) and soil structure
- It is likely that the most robust advice will be able to be provided for red and white clover.

Management effects

- The literature provides considerable evidence that management factors can influence N fixation by a legume.
- Effects on fixation can be divided into those that influence the net accumulation of N and those that influence the N-fixation process directly
- Increased concentrations of soil mineral N are generally thought to reduce fixation capacity. Factors that will increase the soil mineral N pool include manure application, cutting and mulching and grazing.
- Fixation tends to decrease with legume age, mainly because the soil mineral N pool tends to increase.
- A consequence of generally increasing fertility on an organic farm (by slowly building soil organic matter levels) is that this could decrease fixation.
- Cutting and mulching is a standard practice in organic rotations, yet it may be that such a practice is decreasing fixation and the amount of N imported into the rotation from the atmosphere.
- Harvesting of forage or grain will remove much of the fixed N and reduce the benefit to following crops. The benefit will be further reduced if straw and other crop residues are also removed from the field.
- Other aspects of management affecting N-fixation include the position of the crop in the rotation, duration of cropping and methods of cultivation.
- Because of the conflicting interactions between N fixation and soil N status, management decisions often have to be a compromise.
- If growers can understand the main factors affecting fixation, then they can try to manage their crops to achieve the objectives they want.
- Unfortunately, management to maximise fixation may be conflict with the overall farm plan – e.g. cutting/mulching may be the only option in a stockless system; grazing of grass/clover swards is necessary on livestock farms.

Models

- Many factors affect N fixation. Representing all of these within models is almost impossible.

- Advisory models need to be as simple as possible, in terms of required input data.
- But the information needs to be sufficiently detailed that models can estimate N fixation and the influence of key management factors on it.
- There have been many attempts to produce models. The main factors that the models tend to use are one or more of the following:
- Grass/clover swards - % clover
- Legume dry matter yield
- Sward age
- Soil mineral N content
- A sensitivity analysis and comparison of model predictions would be a useful starting point in comparing the relative value of the respective approaches for UK conditions.
- Grass/clover is the most modelled system. Many other legume systems have not been modelled at all.
- Model output tends to be kg/ha fixed N. Clarification is sometimes needed as to whether this refers to above-ground N only.
- It is difficult to link these estimates of N fixation to utilisation models difficul as they rarely provide information on the residue quality: C:N ratio, lignin content.
- The literature provides little data on fractionation of the C and N in the fertility-building crop.

Utilisation of N

- Mineralisation of the incorporated residues is a microbially driven process, and rate of breakdown is controlled by soil temperature, soil moisture and aerobicity. Whereas the C:N ratio of the residue is also a good guide to rate of release, the physical quality of the residue also governs its availability to the microbial population, e.g. lignin content.
- Nitrogen can be lost from the organic farming system via denitrification, ammonia volatilisation and leaching of (mainly) nitrate.
  - Losses of N as ammonia can be large following manure application (but can be controlled by rapid incorporation of the manure) or during deposition of excreta during grazing. These losses represent a loss from the farming system and from the soil fertility-building crop either indirectly (if loss is from manure produced by feeding the crop as fodder) or directly (if grazing the fertility-building crop).
  - Denitrification losses can be large, particularly in warm moist soils following incorporation of N-rich residues or manure.
  - Nitrate leaching occurs predominantly during the autumn/winter. Nitrate losses can therefore be large if the fertility-building crop is ploughed in the autumn. Autumn manure applications (particularly those with a high mineral N content) also risk substantial loss after an autumn application.
- These loss processes therefore compete with crop uptake and efficient utilisation of the N fixed by fertility-building crops must include appropriate management practices to minimise losses.
- A complicating factor is the potential lack of synchrony between N mineralisation of the residues and crop uptake: a build up of soil mineral N at times of low rates of crop uptake increases the risk of N loss.
- There are numerous models for predicting mineralisation of crop residues, with variations in complexity and the levels of information required to drive the models. Soil tests as predictors have less value.

- However, because of the competition between loss processes and crop uptake following mineralisation, some account of these losses also has to be made in order to predict the N available for the crops following the soil fertility-building phase. It is not sufficient to model mineralisation alone.

Rotational Aspects

- The optimum duration and type of legume sequences in a rotation is affected differently by the economic and production constraints of livestock and stockless organic systems.
- Rotation sequences need to be chosen with due regard to weed, pest and disease considerations as well as maintenance of soil N reserves.
- Grain legumes and forage legumes grown as seed crops in stockless organic systems provide an opportunity to increase the number of cash crops within the rotation.

1. INTRODUCTION

1.1. What are 'fertility-building crops'?

Nitrogen can be imported onto organic farms by several routes (Table 1). However, the cornerstone of the organic philosophy is the use of legume based leys to build fertility. Indeed, the organic standards require the inclusion of legumes in the rotation. Fertility-building crops and green manures are therefore key components of organic rotations.

However, the regulations contain no specific requirements for ley management and the paucity of research means that their management is often based on hearsay rather than empirical evidence. Management options for these crops are many, including:

- choice of species and cultivar;
- length of growing period within the rotation;
- rotational position and management of foliage (cutting and exporting, cutting and mulching, grazing or combinations of these).

Table 1.1. Typical sources and loss pathways for nitrogen in organic farming

Sources	Losses
• Fixation of atmospheric N	• Nitrate leaching
• Purchased feed stuffs	• Ammonia volatilisation
• (Cover crops)	• N_2 and (NOx) emissions
• Imported manures/composts	• Crop/animal produce
• Rainfall	• Exported manures

Typical crops under UK conditions include red clover, white clover, vetch, lucerne, sanfoin, grass/clover leys (white clover/perennial ryegrass or red clover/Italian ryegrass), peas and beans. Lupins and soya are also being used in southern Britain. Recent work in NE England has indicated that two new legumes may also be suitable: lentil (*Lens culinaris Medik.*) and pinto bean (*Phase[illegible]s vulgaris*).

1.2. Role in rotations

Organic farming aims to be self-sufficient in nitrogen through **fixation** of atmospheric N_2, recycling of crop residues and application of internally sourced manure. As well as legume based leys, organic rotations also often include a supplementary boost of N during the fertility depleting phase by growing a leguminous crop, such as field beans or peas. However, it is the legume-based ley that is the most important element of fertility-building.

A major objective in the application of fertility-building crops (including green manures) is to provide the N required for optimal performance of the subsequent exploitative crops in the rotation (Watson *et al.*, 2002). Nitrogen is usually the limiting nutrient in organic systems, particularly in the later stages of the rotation, as the N supply from fertility-building crops declines. If organic farmers are to optimise the capture and use of this nutrient, they require a reliable estimate of the amount of N available and its pattern of release.

Supply of N to the following crops relies on **mineralisation** of the residues that have been accumulated during the fertility-building phase. Captured N can also be returned to the soil as manure, either directly by grazing animals or indirectly in manure produced by animals that have been fed on leguminous forage or grains exported from the field.

Other aspects of fertility-building crops also influence the design and performance of rotations, particularly the effect of pests and diseases during the fertility-building phase and implications for the following crops. These effects may be detrimental (e.g. clover and lucerne could increase the risks of *Sclerotinia trifoliorum* for field beans) or beneficial (e.g. green cover may reduce common scab of potatoes) to the rotation. Therefore, these issues also need to be incorporated into planning advice for organic producers.

1.3. What is 'fertility'?

'Soil fertility' can be considered to be a measure of the soil's ability to sustain satisfactory crop growth, both in the short and longer-term. Organic farming recognises the soil as being central to a sustainable farming system. It could be argued that organically managed soils require a higher level of baseline fertility because shortfalls cannot be made up by applications of soluble fertilisers.

Soil fertility is determined by a set of interactions between the physical and chemical environments of the system and by biological activity (Fig. 1.1). Organic matter is linked intrinsically to soil fertility, because it is important in maintaining good soil physical conditions (e.g. soil structure, aeration and water holding capacity) and is an important nutrient reserve. Organic matter contains most of the soil reserve of N and large proportions of other nutrients such as phosphorus and sulphur. Soil fertility is thus markedly affected by not only *quantity*, but also *quality* of the organic matter.

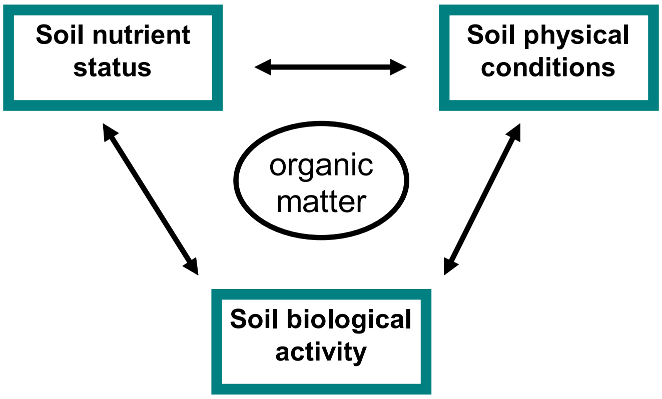


Figure 1.1. The concept of soil fertility

To maintain soil fertility, organic farming relies on sound crop rotations to include fertility-building and fertility depleting stages, returns of crop residues, N-fixation by legumes/*Rhizobium*, nutrient retention by green manures and effective use of manures/composted wastes.

Fertility-building crops clearly impact on the N status of the soil but also have effects on other nutrients. They also provide an important input of organic matter to the soil.

1.4. Nutrient supply

1.4.1. Nitrogen

Though leys are important in building soil organic matter (see later) their principle importance for fertility is their input of N. There are two aspects to fertility-building crops: 'capture' of N and 'use' of N, as shown in Figure 1.2.

Many factors will affect the amount of N fixed during the fertility-building stage and influence the amount of N that has been captured. For example, the interaction between N fixation and soil N supply (1, Fig. 1.2.). Many factors will also affect the fixation process – environmental and management practices (e.g. cutting and removal versus cutting and mulching; 2 and 3, Fig. 1.2.).

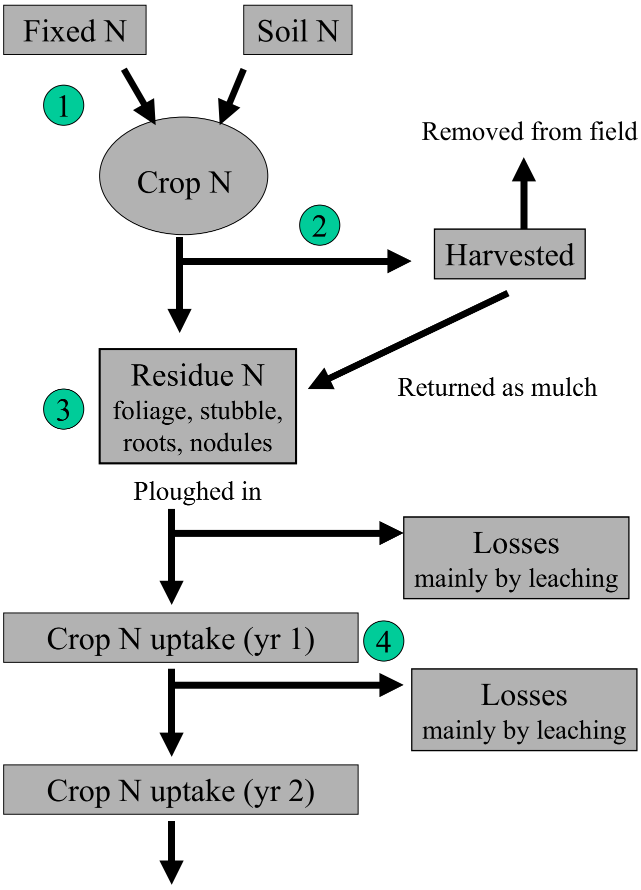


Figure 1.2. Schematic diagram of the capture of N by a leguminous fertility-building crop and its subsequent use during the arable phase of the rotation.

Efficient use of the captured N by the following crops relies on management practices and cropping patterns that make best use of the N released by mineralisation of the residues (4, Fig. 1.2.). Practices that match uptake to patterns of mineralisation will optimise crop N uptake and minimise losses of N to the wider environment.

The use of leguminous fertility-building crops represents an import of N into the system via fixation of atmospheric N. It is the most important source of N in the

rotation. Therefore, the focus of this review is in managing N: fixation and the factors that affect it, and subsequent mineralisation and use of the fixed N by arable crops.

However, other aspects of fertility-building crops need to briefly be considered.

1.4.2. Phosphorus, potassium and other nutrients

Nitrogen fixation represents a true import of N into the rotation. Effects on other nutrients are restricted to impacts on the soil's existing resource.

Fertility-building crops will take up nutrients from the soil. These, particularly P, are not as mobile as nitrate. Even so, uptake may reduce the small amounts of leaching that might have occurred, thus retaining nutrients within the rooting zone (e.g. Table 1.1).

Table 1.1. Nutrient leaching under grass leys, versus fallow (kg/ha). From Low & Armitage (1970).

	Magnesium	Calcium	Potassium	Phosphorus
Grass	41	96	5.8	2.6
Fallow	72	330	41	7.2
Input through rain	2.5	57	30	3.1

For P and other nutrients, the growth of green manure crops does not change the total content in the soil but may influence the availability. Growth and incorporation of deep-rooting crops into the soil can transfer nutrients from the subsoil to the upper layers where it will be available to other, shallower rooting crops.

Phosphorus that has been released slowly and taken up during the growth of a cover crop or green manure may provide a larger immediately available pool of P for a more demanding crop when the green manure is incorporated into the soil. Although biological N fixation by legumes does not directly benefit P budgets in the soil, there are indirect reasons why legumes may be preferred to recycle P (Atallah & Lopez-Real, 1991). Non-legumes may become N-limited, restricting the uptake of P and other nutrients. Once incorporated into the soil, the low N content of non-legume residues may inhibit their decomposition and delay the release of P. Lampkin (1992) estimated the removals of P in lucerne, red clover and white clover/grass crops to be 3.5, 3.1 and 1.3 kg P/t dry matter, respectively. If grown as green manures, ploughing in a 3 t/ha yield of each of these crops would return 10, 9 or 4 kg P/ha to the soil, respectively, plus the additional P contained in stubble and roots. Phosphorus in roots of crop residues is utilised by growing plants as rapidly as P in tops that have been incorporated into the soil (Dalal, 1979). Extractable P contents of soil in an incubation experiment were shown to be increased by incorporation of crop residues (Scagnozzi *et al.,* 1997).

A fertility-building crop will similarly accumulate the K released in the soil during the growth of the crop and will release this when it is incorporated into the soil. Exchangeable K in soil incubation experiments was increased by incorporation of crop residues (Scagnozzi *et al.,* 1997). A 3 t/ha grass/clover crop grown as a green manure would contain about 60 kg K/ha in the herbage. To this would need to be added the K present in the stubble and roots. As with P, legumes may be preferred as manure crops for recycling nutrients as growth of the legume is unlikely to become N-limited and the N-rich residues will decompose rapidly after incorporation (Atallah & Lopez-Real, 1991).

In spite of being easily leached out of dead plant material, some studies have indicated that the short-term efficiency of crop residue K is less than from mineral fertilisers but that the residual effect is greater. Other studies indicate a similar efficiency to mineral fertilisers (Spiess & Besson, 1992), and these differences in efficiency may be associated with the time of application.

On this evidence, the use of cover crops should also be valuable in the conservation of other nutrients besides N, particularly K and Ca (both more mobile in soil than P).

1.5. Organic matter

The role of soil organic matter (SOM) in the development and protection of soil structure in organic farming systems has recently been comprehensively reviewed by Shepherd *et al.* (2002). A major conclusion was that additions of fresh organic matter are critical for assisting soil structural development.

The effects of amendments on soil structural development will depend on their composition and effects on biological activity. Ekwue (1992) found that some organic materials were more effective than others, with grass leys exhibiting the greatest stability. Generally, the younger soil organic matter (i.e. fresh additions) with a larger content of polysaccharides, roots and fungal hyphae have most effect on soil structural development (Tisdall & Oades, 1982). Metzger & Yaron (1987) suggested biological and chemical agents were affecting aggregate stability in the soils they examined. Haynes & Naidu (1998) confirmed that it is fungal hyphae (the biological agent) and extracellular polysaccharides (the chemical agent) capable of linking particles together that impart aggregate stability. Mucigels are released by growing roots and rhizosphere microflora (Haynes *et al.*, 1991). Tisdall & Oades (1982) placed timescales on different SOM components. Polysaccharides act strongly for 2-3 weeks, but decline over the following 4-6 months; cellulose achieves maximum effect after 6-9 months (but is not as effective as polysaccharides); ryegrass residues increase in effect up to 3 months, persist for 4-6 months and decline thereafter (3 months approximately).

Thus, the most important SOM components exert their effect for at most a year, which matches the observations that aggregate stability is greatest under grass (continued production of these components) and decreases rapidly under arable cultivation (Loveland & Webb, 2000). The important role of young SOM in aggregate stability explains why many workers have found better correlations between components of SOM (e.g. water-soluble carbohydrates) and stability than between total SOM and stability (Loveland & Webb, 2000). This also explains why aggregate stability can change over the short-term (e.g. after ploughing a ley), although the total SOM is hardly affected (Haynes & Swift, 1990).

It is clear, therefore, that optimal aggregate stability requires the frequent turnover of young organic matter residues. There are indications that clover has additional beneficial effects on soil structure.

Mytton *et al.* (1993) evaluated the differential effects on soil structure and water infiltration of monocultural swards of white clover and perennial ryegrass and a mixture of the two. The study used undisturbed soil cores (100 mm i.d. x 180 mm length; silt loam acid brown earth) in a greenhouse. White clover stands led to greater water infiltration; 43.1 ml/4h, compared with. 32.9 ml for annual ryegrass and 39.4 ml for a mixed sward. Apparent greater soil friability in the clover cores was not reflected in soil bulk density or the % soil aggregates >2mm upon wet sieving. Total porosity was little changed, but air-filled (macroporosity) was as follows: clover > mixture > perennial ryegrass. Further work is continuing.

1.6. Objectives of review

Estimates are available of the N production from fertility-building crops. However, it is clear that numerous factors can affect N uptake and fixation, release and recovery under different circumstances. Consequently, current guidance is very broad and often of insufficient detail to provide robust advice to growers. Further research is required to produce a more comprehensive assessment of N accumulation and its subsequent release. A better understanding of N capture and release would assist organic growers and have the following advantages:

- Greater awareness of the factors affecting N accumulation and N loss, and the practical management factors affecting these processes.
- Greater ability to develop ‘sustainable rotations’, matching N supply to N requirements for the rotation.
- Increased scope for adopting novel or more innovative rotations.

The logical starting point is a synthesis of the current state of knowledge. The objective of this review is therefore to review effects of soil fertility-building crops on:

- **N capture**
- **N use**
- **Pest, disease and other effects**
- **Available models for predicting N capture and release**

The review forms part of a larger project funded by the Department for Environment, Food and Rural Affairs (OF0316 ‘The development of improved guidance on the use of fertility-building crops in organic farming’). Further details can be found at www.organicsoilfertility.co.uk

1.7. Definition of terms

Quantifying N fixation is important because this represents a net import of N into the farming system. This is important for developing a sustainable rotation, therefore. Throughout this review, we have used the terms 'N-fixation' or 'fixed-N' where we review fixation. Here, 'fixation' refers specifically to N entering the system by symbiotic biological fixation of atmospheric N. Hence, in these sections (Sections 3, 4 and 5), we are talking about the processes adding N to the soil.

However, there is a risk of confusion when dealing with the release of N to following crops (Section 6) because all of the N in the crop residues, either originating from the soil or from fixation, must be considered. Here, we refer to plant-N, residue-N, etc. Two points need to be made:

- crop uptake of soil-N and return of residues can increase the availability of native soil-N (in the short-term)
- but only fixation adds N to the total pool of soil-N.

Table 1.2. provides a summary of terms.

Table 1.2. Summary of terms

N-fixation	Refers specifically to process of symbiotic fixation of atmospheric N by legumes
Fixed-N	The amount of plant N obtained from the atmosphere
%Ndfa	Percentage of total plant N obtained from the atmosphere
Non-symbiotic fixation	Fixation of N by free living soil organisms
N input in rain and dry deposition	N deposited from the atmosphere
Plant-N or N-yield	Total amount of N in the plant, derived from soil and atmosphere
Residue N	Total amount of plant N from soil and atmosphere left in the soil after harvest or cultivation of the crop

1.8. Key issues

As a part of the wider project, workshops were held with organic growers to discuss the challenges of managing fertility-building crops. The main areas of concern are summarised below:

- Optimum crop sequence (including length of build up and break between legumes and/or green manures)
- Management of cover crops - options/timing
- Rate of release of N from green manures/covers and crop residues
- Management of swards (i.e. cutting/mulching/removal/grazing requirements) to optimise N accumulation and minimise losses
- N fixation ability of different legume species in UK conditions (including optimum mixes for mixed swards)
- Assessment of % clover in mixed swards
- N build-up/retention - Interactions with cultivations/seed bed preparation
- N build-up/retention - Interactions with pest and disease issues
- Bi-cropping
- N build-up/retention - Interactions with other nutrients
- Management of organic manures
- Cost implications
- Grain legumes for cash crops

These were used as the focus for the review.

2. FERTILITY-BUILDING CROPS IN ROTATIONS

2.1. Introduction

Fertility-building crops can be split into three types:

- 'Nitrogen-fixers'
- 'Nitrogen-holders'
- Those that affect other general fertility aspects such as soil structure.

Whilst important, the latter group are not discussed here except where they impinge directly on N availability. A list of legume species (N-fixers) suitable for UK use is shown in Table 2.1, and non-legume species used as cover crops (N-holders) in the UK are shown in Table 2.2.

Table 2.1. Legume species ('N-fixers')

Forage legumes	
Trifolium repens	White clover
Trifolium pratense	Red clover
Trifolium incarnatum	Crimson clover
Trifolium subteranneum	Subterranean clover
Trifolium hybridum	Alsike clover
Trifolium resupinatum	Persian clover
Trifolium alexandrinum	Egyptian clover
Medicago sativa	Lucerne/alfalfa
Vicia sativa	Winter vetch, common vetch
Vicia lathyroides	Summer vetch, goat
Vicia hirsuta/villosa	Hairy vetch
Anthyllis spp	Kidney vetch
Onobrychis viciifolia	Sainfoin (common & giant?)
Lotus pedunculatus (L. uliginosus)	Large birdsfoot trefoil
Lotus corniculatus	Birdsfoot trefoil
Medicago lupulina	Trefoil, black medick
Lupinus alba	White-flowering lupin
Lupinus luteus	Yellow-flowering lupin
Lupinus angustifolius	Narrow-leafed/blue lupin
Grain legumes	
Pisum sativum	Field or threshing peas
Pisum arvense	Fodder peas, grey peas
Vicia faba	Field/broad/horse beans, faba beans
Phaseolus vulgaris	Green/dwarf/French/pinto/navy beans
Glycine max	Soya beans
Lens culinaris	Lentil
Other	
Galega orientalis	Galega, Goat's rue
Lathyrus spp.	Vetchling, sweet pea, chickling vetch
Melilotus alba	White sweet clover
Cicer arietinum	Chickpea
Castanospemum australe	Black bean
Trigonella foenum graecum	Fenugreek

The first group, N-fixers, is comprised of leguminous crops, which may be grown purely for their ability to fix N (e.g. clover for mulching) or, additionally, for their cash crop value (e.g. beans). The second group, N-holders, includes cover crops (e.g. mustard), which are grown to prevent loss of N by over-winter leaching. In some instances, the cover may also act as a catch crop perhaps by providing grazing for sheep, and the covers may also be legumes.

Table 2.2. Non-legume species used in UK as cover crops ('N-holders')

Cover and grazing	
Sinapsis alba	White mustard
Brassica campestris	Stubble turnips
Secale cereale	Forage rye
Lolium multiflorum	Italian ryegrass
Lolium perenne	Perennial ryegrass
Raphanus sativus	Fodder radish
Brassica oleracea	Kale
Brassica napus var. napus	Forage rape
Cichorium intybus	Chicory (usually as part of a mixture)
Cover only	
Tanacetifolia	Phacelia
Helianthus annuus	Sunflower
Fagopyrum esculentum	Buckwheat
-	Assisted natural regeneration (usually barley)

In continental Europe, cover crops are usually referred to as 'green manures' and other species are commonly used, such as oil radish seed, winter rye (Reents & Möller, 2000) and turnips, which can also be sold as a cash crop (Kotnik & Köpke, 2000). Covers are often also legumes such as vetch (summer or winter) or legumes grown in mixture with cereal or brassica (Reents & Möller, 2000). Similarly, in New Zealand, lupins and tagasaste may be grown (McKenzie *et al.*, 2001)

As the fertility-building part of the organic rotation often occupies a large proportion of the rotation (grass/clover leys and green manures occupy 66% of the organic farming acreage in Denmark (Høgh-Jensen, 1996)), it is important to gain as much benefit from it as possible. In mixed livestock systems the grass/clover leys clearly have a role to play in forage production. However, there is some evidence that the livestock manures that are often applied to the grass would be better used on the arable crops (Berry *et al.,* 2000) especially where higher protein levels are required in cereals (Anon., 1997).

The choice of grass/legume mix is also important. European studies have recommended that climate is considered when choosing legumes. For example, they recommend red clover or lucerne (both of which are deep rooted) for dry conditions but point out that white clover has a very good ability to recover after drought (Anon., 1997).

Choice of grass legume mix can also alter the amount and quality of dry matter production (e.g. red clover/perennial ryegrass is better than white clover/perennial ryegrass or alfalfa/perennial ryegrass as reported by Loges *et al.*, 2000). Nutritive value may be improved by cutting more frequently as, for example, in alfalfa/red clover/cocksfoot/meadow fescue/timothy mix in Switzerland (Mosimann & Troxler, 2000). The balance of production may also be adjusted by altering the grass and legume species (Morris & Phillips, 2000), which may be important if early grass in needed.

For non-livestock systems it is important to have sufficient fertility-building crops to support the cash crops, as there is no opportunity to supplement the soil N with organic manure (unless imported). It is also beneficial from an economic point of view if the fertility-building crops can also provide income as they can occupy 20-40% of the rotation (Cormack *pers. comm.*). Thus, clover grown for seed may be preferred over a cut/mulch system and peas/beans which can be sold for human consumption preferred over those that are used for animal feed.

Recent work on less common grain legumes has indicated that these can be grown under UK conditions, even in the north. Thus, lentils (Joyce *et al*., 2001), pinto beans (Griffin & Andrews, 2001) and soy bean/navy bean/chick pea (M Andrews, pers. comm.), which have a high potential value in the health food market, may be good alternative cash legumes for organic growers. An eight-fold increase in net margin over peas and field beans has been reported (Evans *et al*., 2001). There is some information about management of lentils (Crook *et al*., 1998; Crook *et al*., 1999) but more is needed for all these health food crops, especially for the bean species. As well as giving consideration as to the best legume to grow, it may also be important to choose varieties of other crops, such as cereals, that are known to be efficient at scavenging for soil N to maximise yield from the available N supply (Foulkes *et al*., 1998).

The advantages of some of the main fertility-building crops are summarised in Tables 2.3 – 2.5 on the following pages.

Under EU legislation, from January 2004, all seed used by organic farmers must be produced organically. UK farmers are concerned about the availability of organic seed and the challenges for organic seed production are discussed by Marshall & Humphreys (2002).

Table 2.3. Advantages and disadvantages of forage legumes (including green manures).

Crop	Advantages	Disadvantages
Red clover	• Deep rooting • Vigorous growth • Large biomass for forage • High protein content forage	• Can disappear in grazed swards • Can cause bloat • Susceptible to stem nematode • Difficult to establish in autumn in north • Typical productive life of 3 years • Can be very competitive when undersown • Erect growth habit
White clover	• Viable for 5-9 years • Good regeneration after drought Resistant to stem nematode • Suitable for undersowing/bi-cropping • Prostrate growth has good ground cover • Withstands heavy grazing	• Slow establishment, best established in spring • Lower biomass productivity
Crimson clover	• Resistant to clover rot • Tolerates acid soils better than red and white clover	• Forage can be stemmy • Erect growth habit • Does not like competition in a bi-crop • Autumn establishment difficult • Does not like heavy soils
Subterranean clover **Alsike clover**	• Rhyzome regenerates below ground and survives cultivation • Deep rooting • Vigorous • Large biomass for forage • High protein content forage	• Rhyzome regenerates below ground and survives cultivation • Tolerant of wet soils • Tolerant of acid soils • Not drought resistant
Persian & Egyptian clover	• Vigorous growth • Produce nutritious fodder crops	• Not frost hardy
Lucerne/ alfalfa	• Deep rooting • drought tolerant • fodder potential (including racehorses) • Resistant to stem nematode • Can be undersown • Productive for 5+ years	• Requires inoculum to establish • Slow to establish in year 1 • Careful management to avoid over winter loss/die back • Has higher bloat risk as fresh forage • Requires pH 6+
Winter vetch, common vetch **Summer vetch**	• Late sowing possible • Highly productive biomass • Very competitive • Useful cover for brassica cash crops • High yielding as whole crop	• May be difficult to kill in spring • Viable seeds can become weeds in subsequent crops

	silage when grown in mix with cereal • Long flowering period	
Hairy vetch **Kidney vetch**	• Lower productivity than other vetches • Slower development	
Sainfoin	• High protein forage • Highly productive • Bloat free • High palatability	• Not suited to autumn sowing
Large birdsfoot trefoil	• Tolerant of anaerobic conditions and waterlogging	• Marsh trefoil (*L.uliginosus*) is intolerant of high pH
Birdsfoot trefoil	• Cold tolerant • Prostrate growth habit • Can be undersown • Tolerant of shade • Useful cover for brassica cash crops • Claimed to control black spot (*pers comm)* • Low bloat risk	• Lower biomass production
Trefoil, black medick	• Green manure • Suitable for undersowing as it tolerates shading	
White-flowering lupin	• Grain crop • Fodder potential	• Poor yield • Not very competitive • Intolerant of high pH
Yellow-flowering lupin	• Green manure	• Intolerant of high pH
Narrow-leafed/blue lupin	• Grain crop	• Intolerant of high pH • Prefers light sandy soils • Slow early development

Table 2.4. Advantages and disadvantages of grain legumes.

Crop	Advantages	Disadvantages
Peas (fresh or dried)	- Potential as cash crop, and animal feed	- Can be difficult to harvest (especially in wet conditions) as very prone to lodging - Not very competitive, susceptible to weeds - Predators – birds etc must be controlled
Field Beans	- Animal feed	- Easier harvested than peas but lower yield. - Suited to many soils
Green/dwarf/ French beans	- Potential as cash crop	-
Pinto beans	- Potential for high revenue (health food premium)	-
Soya beans	- Potential for high revenue (health food premium)	- Not very competitive - Predators – birds etc must be controlled
Navy beans	- Potential human consumption. Canning	-
Lentils	- Potential for high revenue (health food premium)	- Little known about management
Galega, Goat's rue	- Silage or cover crop	- Slow to establish
Vetchling, sweet pea, chickling vetch	- Forage crops or green manures	
White sweet clover	- Tall growing but straggly in nature - Very fast growing and competitive	- Bitter at maturity and not palatable to livestock - Too vigorous for undersowing in cereals - Possible toxic effects
Chickpea Black bean	- Potential grain crop	
Fenugreek	- Quick growing - Good forage potential - Has pharmaceutically important chemicals - Long productive season (into late autumn)	- Not totally frost hardy

Table 2.5. Advantages and disadvantages of non- legume cover crops.

Crop	Advantages	Disadvantages
Mustard	• Good potential for N uptake • Competitive • Quick growing • Large rooting system • Useful to suppress wireworm populations	• Need to establish early for good growth • Disease implications for cash brassica crops • Club root host • Not winter hardy
Stubble turnips	• Good potential for N uptake • Good winter forage	• Need to establish early for good growth • Disease implications for cash brassica crops
Ryegrass	• Non-brassica cover	• May be difficult to kill in spring
Fodder radish	• Good potential for N uptake • Competitive • Quick growing	• Need to establish early for good growth • Disease implications for cash brassica crops
Kale	• Good potential for N uptake • Competitive • Quick growing	• Need to establish early for good growth • Disease implications for cash brassica crops • Club root host
Forage rape	• Good potential for N uptake • Competitive • Quick growing • Large rooting system	• Need to establish early for good growth • Disease implications for cash brassica crops • Club root host
Chicory (usually as part of a mixture)	• Good potential for N uptake • Competitive • Quick growing • Deep rooting system • Large biomass produced • Drought resistant • Tolerant of heavy grazing	• Intolerant of high soil N conditions
Phacelia	• Deep rooting • Winter hardy • Non-brassica cover • Attractive to bees. • Pest control advantages claimed (*pers comm)*	
Buckwheat	• Tolerates poor soils • Annual • Rapid development	• Frost sensitive
Assisted natural regeneration	• Low cost	• Does not control weeds

2.2. Disease implications of fertility-building crops

Consideration of disease interactions and implications with fertility-building crops needs to include:

- Diseases affecting the fertility-building crops directly.
- Diseases affecting fertility-building crops which will also affect other crops in rotation.
- Consequences of incorporation of the fertility-building crop into soil: suppressive or antagonistic effects on soil- or air-borne pathogens.
- Poor performance of the fertility-building crop has implications on the subsequent cash crop.

Two types of cropping are considered:

- Mono-cropping where specific fertility-building crops are grown exclusively for a period of time.
- Bi-cropping or companion cropping systems where the fertility-building crop is grown with another arable or vegetable crop (but not necessarily completely synchronous with it). In these systems, fertility-building crops are grown usually as an understorey with arable or vegetable crops. Many of the principles applied to monocrops will still be valid, but there may be other direct benefits from the 'physical' presence of foliage of the companion crop, which interferes with disease activity.

2.2.1. Diseases affecting the fertility-building crops directly.

Diseases of forage and grass crops have been documented (O'Rourke, 1976) and, in some circumstances, specific problems may lead to failure or impaired productivity of fertility-building crops. However, disease resistant cultivars are often available and can be used to overcome problems or reduce risks of problems. Local knowledge of diseases in the crops selected for fertility-building is important, as is the potential for disease spread from related crop species nearby. For example, stubble turnips are very prone to dark leaf spot (*Alternaria brassicae*), which is common in other forage and vegetable brassicas and oilseed rape.

2.2.2. Diseases transfer from fertility-building crops

The legacy of disease problems left by fertility-building crops is of major concern to growers. The extent of problems will be influenced strongly by previous cropping and its legacy of the soil pathogen population on the field or farm. Thus, farms with a history of legume cropping are likely to carry high populations of pathogens affecting legumes, whilst few legume pathogens may be present where legumes have not been grown for many years. Very intensive legume cropping may leave high soil populations of fungal pathogens which will only decline slowly.

Root and foot rot pathogens (e,g *Fusarium* spp., *Pythium* spp., *Phoma medicaginis*) are economically important in arable and vegetable cropping, with field evidence indicating that there are interactions between different legume types such as *Pisum*, *Phaseolus* and *Vicia* spp.. The intensity of total legume types and the intensity of total legume cropping influences disease severity (Biddle, 1984). Ideally, there should be at least a five-year interval between legume crops (Biddle, 1984). The influence of forage legume cropping on the disease risk to subsequent legume crops requires further investigation.

It is clear that disease problems in forage legumes are aggravated by soil and nutrient stress factors and such problems must be minimised for successful cropping. Use of legume fertility-building crops may not be compatible with legume cash crops such as vining or dry harvested peas and dwarf beans if farms have a history of soil-borne disease problems (Biddle & Whalley, 1996).

The occurrence of sclerotinia rot (*Sclerotinia trifoliorum*) in winter beans in the UK appears to be linked to a history of red clover cropping in the 1950's (ADAS, unpublished data). This disease is common in winter beans but severe attacks occur only spasmodically. Clover rot is caused by the same pathogen and problems also occur in lucerne (O'Rourke, 1976). Clover varieties are now available with improved resistance to clover rot and this should reduce the risk of severe problems in future. The fungus survives for many years when buried in soil by means of large resting bodies (sclerotia). Red clover has been more susceptible than other forage legumes and it may still create problems for winter beans in the same rotation. Spring beans are affected by a related fungal pathogen, *Sclerotinia sclerotiorum,* and should be less at risk from the clover rot pathogen (though they may be more seriously affected by the foot rot pathogens). The fungus can be introduced with the seed and healthy seed is a fundamental requirement for organic systems. Some spread may occur through air-borne spores so the occurrence of the disease on the farm may necessitate a change to non-legume fertility-building crops if there is high soil-borne inoculum.

The impact of soil-borne legume diseases is strongly influenced by soil compaction and poor drainage, both of which aggravate root disease problems. Sites which are prone to such problems shopuld not be considered for legume cropping.

Fertility-building crops of legumes are likely to be a source of virus diseases to nearby legume crops and occasionally other crops (Hagendorn, 1984). For example, pea enation mosaic virus overwinters in clover and vetch and is spread by the pea aphids to a range of legume species in the spring. Similarly the occurrence of severe violet root in organic sugar beet (Gladders, *pers. comm*) is believed to be related to clover cropping within the rotation. Violet root rot is known to survive better if perennial weeds are present and clover roots may be having the same effect.

2.2.3. Suppressive or antagonistic effects on soil- or air-borne pathogens

Cruciferous fertility-building crops can be affected by clubroot disease (*Plasmodiophora brassicae*) and problems are likely to occur where there is existing soil-borne inoculum. The disease is favoured by acid soils and maintaining a neutral or slightly alkaline pH (7.0- 7.3) is an important part of its management. Wet conditions are required for infection and the disease is widespread in livestock areas, which usually have higher rainfall and a history of growing susceptible brassicas (e.g. swedes and turnips) for stockfeed. The spores of the clubroot fungus can survive passage through animals and infested manures from stock fed on affected root crops can introduce the disease.

Cruciferous crops are likely to share a range of soil-borne pathogens, which can interfere with seedling establishment and crop productivity. Rotations with five years between cruciferous crops are generally advocated though in some areas such as South Lincs, vegetable brassicas have been grown successfully in almost continuous production. If fertility-building crops are of short duration, it may be possible to use them frequently, particularly if the farm has a naturally high pH and no history of clubroot. However, use of over-wintered cruciferous crops would provide a green bridge for pests and diseases and reduce the impact of rotational strategies which try to minimise year round production.

2.2.4. Soil remediation effects

The remedial effects of fertility-building crops have received some attention and are the subject of on-going research. Literature relating to this has also been considered within the DOVE project (Defra, OF0168). Brassica crop residues can produce biofumigation effects, which reduce pests and diseases (Kirkegaard *et al*., 1996; Morra, 1999; Rosa & Rodrigues, 1999). SAC are currently investigating use of cruciferous crop residues for control of rhizoctonia diseases in potatoes.

Green manures generally stimulate soil micro-organisms and this can result in suppression of pathogens. Control of common scab (*Streptomyces* spp.) of potatoes with green manures is a well-known example, though there are concerns that green material could increase the risk of slug damage. One mechanism involved is antibiotic production by the bacterium *Bacillus subtilis*, which inhibits *Steptomyces scabies (*Cook & Baker, 1996).

Addition of plant residues or organic matter may favour increased activity of pathogens with strong saprophytic activity. Pot experiments in the DOVE project (OF0168) indicated that interactions between pathogens and soil micro-organisms were complex, involving not only N (e.g. straw locked up N and reduced crop growth), pH changes, effects on plant growth as well as pathogen development. Most studies have examined effects on single pathogens and further work is required at the field scale to establish net benefits against a range of pests and pathogens.

Bi-cropping may produce benefits through the interaction between plant species. Fertility crops that cover the lower diseased leaves of crop plants may reduce the upward splash dispersal of fungal spores such as those of *Septoria tritici.* There have also been effects on leek rust (Theunissen & Schelling, 1996). Soil borne diseases such as carrot cavity spot (*Pythium violae*) have been reduced by clover intercropping (Theunissen & Schelling, 2000). The mechanisms involved have not been established (Deadman *et al*., 1996), but it is possible that the intercrop modified available soil N and thereby reduced activity of the fungal pathogen.

2.2.5. Nitrogen release

The amount and rate of release of N from fertility-building crops is also likely to influence disease severity. Nitrogen is often the limiting factor for microbial growth in soil and it is likely to influence both beneficial and pathogenic organisms. The N content of foliage has a strong effect in disease severity as demonstrated for yellow rust (Bryson *et al*., 1995) and the uptake of large quantities of N is likely to predispose plants to fungal diseases. The interaction of N with disease merits further investigation, so that the appropriate balance between crop productivity and disease risk can be established.

2.3. The interaction of fertility-building crops and invertebrate pests

2.3.1. Introduction

There are two main ways in which fertility-building crops or catch crops grown to maintain fertility can interact with invertebrate pests. Firstly, the pests may attack the fertility-building/catch crop and secondly they may carry over into the succeeding crop, resulting in poor establishment and loss of yield.

In this section, the pests of fertility builders/catch crops and their potential to attack subsequent crops will be covered separately. In reviewing pests of fertility builders/catch crops, detail will be provided on basic biology and factors that should be taken into account when attempting to predict the likely risk of attack. The interaction between fertility builders/catch crops and the subsequent crop will concentrate on the risks posed by carry over of pests together with details on biology and crop husbandry, which may minimise yield loss.

Gratwick (1992) provides a useful summary of crop pests in the UK and much of the information in this section is taken from that source. Control of pests and diseases of grass and forage crops (Anon., 1985) is also a useful reference.

2.3.2. Pests of fertility-building crops

Clover

Red and white clovers are probably the most common legumes grown as fertility-building crops, either as a crop in their own right or as part of a grass/clover ley. Pests probably play a minor role in the decline of clover in the long-term but can prevent good establishment of the crop.

Aphids - Several species of aphid occur on clover. Of these the most commonly found in large numbers are the pelargonium aphid (*Acysthsiphon molvae*), the pea aphid (*Acyrthosiphon pisum*), the leaf-curling plum aphid (*Brachycaudus helichrysi*) and the vetch aphid (*Megoura viciae*). Damage due to these pests will tend to be greatest during periods of warm, humid weather.

Leatherjackets and wireworms - As with grass seedlings, leatherjackets and wireworms may damage clover seedlings at establishment. The most serious damage is during spring and early summer.

Pea, bean and clover weevils - The pea and bean weevil (*Sitona lineatus*) and the other *Sitona* species, are common on clover crops where both adults and larvae may be important. Adults of the narrower, pear-shaped, clover seed weevils (*Apion* spp.) may also be found, although they cause little damage. Adult pea and bean weevils overwinter on leguminous crops and become active in the spring and feed on the leaves causing the distinctive notching. Eggs are laid in the soil and larvae feed on the root nodules. Damage to the nodules may also allow pathogenic fungi such as *Sclerotinia trifoliorum* (severe clover rot) to invade the plants.

Stem nematode -_Stem nematode (*Ditylenchus dipsaci*) can be responsible for serious losses in red clover where it is known as “clover sickness”. Races or strains of the nematode exist. The red clover race damages red clover, vetch, lucerne, strawberries and onion, the white clover race damages white clover and alsike but not red clover, and the lucerne race severely damages alsike clover but not red or white clovers. The oat-onion race is the most commonly found race and attacks oats and rye as well as beans, peas, clovers, onions and many common species of weed.

Slugs - As with grass on heavy soils in wet seasons, slugs can severely thin newly germinated crops. Young seedlings are attacked underground and at soil level in the spring and autumn. Leaves of established plants may be grazed, but this is not usually of economic importance.

Grass/clover leys
Grass crops are at risk from a number of so called ley pests. Susceptibility to pest attack is greatest during the establishment phase when slugs, leatherjackets, frit fly and wireworms can significantly reduce plant stand. Established swards can still be attacked by pests and, although the crop is usually able to tolerate some damage, the pests could pose a threat to the subsequent crop. Information on the potential pests of the clover component of a grass/clover ley is given in the section on clover.

Slugs - The greatest risk from slugs (e.g. the field slug, *Derocerus reticulatum*) will occur in heavy soil types, although some loams can also be favourable for this pest. Farmers should be guided by past experience since certain fields tend to be particularly "sluggy". Previous cropping can be some guide to risk of slug damage. Grass is often damaged when grown after crops that provide good shelter for slugs or leave a lot of residue. Ultimately the likelihood of slug damage will be most dependent upon weather and soil and seedbed conditions near the time of drilling.

Leatherjackets - Leatherjackets (e.g. *Tipula paludosa*) are the larvae of crane flies or daddy long legs. Adult crane flies lay their eggs in the autumn and larvae hatch within 10 days to feed on plant tissue or decaying vegetable matter in the soil. Feeding increases during the spring, and larval survival is improved by wet conditions so attacks tend to be worse in wet years or in low lying, poorly drained fields. Crane flies are weak fliers and populations could increase locally in the presence of suitable grass-based organic rotations. Leatherjackets can also be a problem in established grass where first signs of damage are either dry-looking areas of grass debris or "clod pulling" by birds.

Frit fly - There are normally three generations of frit fly (*Oscinella frit*) each year. Adult frit flies can disperse widely, often being carried for several miles by wind currents in the upper air. Therefore, in a particular field, the incidence of one generation may have no great effect on the abundance of the next. However, the general prevalance of the pest is likely to be favoured in districts with large areas of grass. Adult frit flies of the autumn generation lay their eggs on grasses and volunteer cereals in August and September. Frit fly populations tend to be highest in short term leys, especially those based on ryegrass and, in particular, Italian ryegrass. In established grass, frit fly attack can result in the decline of the proportion of ryegrass in the sward.

Wireworms - These are the larvae of click beetles and the majority of attacks are due to Agriotes spp. They live in the soil, feeding on underground parts of the plants and spend four or five years in the larval stage before becoming adult beetles. Adult beetles are active from April until July and do not move far from their emergence sites, so there is no rapid spread from field to field. There are two main periods of feeding activity each year, from early March until the end of May, and during September and October. The risk of wireworm attack increases with increasing age of the grass ley.

Aphids - Many species of aphids can be found in established grass, but only the fescue or grass aphid (*Metopolophium festucae*) is usually responsible for damage. Populations often increase after mild, open winters. Symptoms of feeding by this aphid are brown grass which assumes a scorched appearance. Ryegrass is most commonly affected but damage is sporadic. Wild and cultivated grasses are a natural reservoir of barley yellow dwarf virus (BYDV). This virus is a widespread threat to cereal crops and is capable of causing significant losses in yield in autumn- and spring-sown cereals. BYDV is carried by and spread in grasses and cereals by cereal aphids, the most important virus-vector species of which are the bird-cherry aphid (*Rhopalosiphum padi*) and the grain aphid (*Sitobion avenae*).

Chafers - The most troublesome and widespread chafer in grassland is the garden chafer (*Phyllopertha horticola*). Adult beetles swarm in June and July and eggs are laid in the soil, usually in the same fields where the beetles emerged. Therefore, infested grass is regularly re-infested each year. Damage usually occurs in September and October. Poorly growing patches of grass become obvious and turn brown in dry weather. Frequently, birds cause further damage as they rip up the grass searching for the larvae.

Ley pests - Frit fly, leatherjackets and wireworms may be regarded as important “ley pests”, but the term is mainly reserved for other minor pests which are encountered less regularly. These pests can infest grasses but generally do not cause noticeable damage until they move into a cereal crop. In most cases they are more important in the cereals than grass. Pests that come into this category are wheat flea beetle (*Crepidodera ferugginea*), wheat shoot beetle (*Helophorus nubilis*), grass and cereal flies (*Opomyza* spp.), grass or crambid moths (e.g. garden grass veneer moth, *Chrysoteuchia culmella*) and common rustic moth (*Mesapamea secalis*).

Peas and beans

Peas and winter and spring beans are used as fertility-building crops and are at risk from a wide range of pests.

Aphids - Black bean aphid (*Aphis fabae*) is a common and widespread pest of field beans. The aphid overwinters on spindle (*Euonymus europaeus*) and snowball tree (*Viburnum opulus roseum*), and these hatch from late February to early April. In May or June, winged female aphids migrate to their herbaceous summer host. In autumn, winged females fly back to the woody host. Damage on beans is primarily due to direct feeding. Pea aphids (*Acyrthosiphon pisum*) migrate into peas in the spring and cause direct feeding damage as well as transmitting virus.

Thrips - Pea thrips (*Kakothrips pisivorus*) is found throughout England and Wales but damage is usually recorded in south and east England, particularly in hot dry seasons. The main attacks are in June and July with the most notable feature being silvery mottled patches on the young pods. Field thrips (*Thrips angusticeps*) is a localised pest on peas in parts of Essex and Cambridgeshire, on the wolds of Lincolnshire and East Yorkshire and occasionally elsewhere. Damage starts as soon as the seedlings emerge.

Pea moth - Pea moth (*Cydia nigricana*) is one of the most important pests of field peas. Its caterpillars feed in the pod and are responsible for serious losses in some seasons. Other leguminous plants are also known to be attacked, and pea moths have been bred from meadow vetchling (*Lathyrus pratentsis*) and tufted vetch (*Vicia cracca*). Early and late sown crops of peas suffer least damage. Crops sown mid-June will, to a large extent, escape attack. Early maturing varieties should be sown where possible for picking before the second week of July.

Pea and bean weevil - Pea and bean weevil (*S. lineatus*) has already been discussed under pests of clover but will also attack both peas and beans. The new generation of adults emerge in July and often find that peas have been cut and that beans are drying out and are unpalatable. These weevils may migrate and attack young clover in undersown leys. The risk of this will be greatest in undersown clovers bordering pea or bean fields.

Bean seed fly - Two species of bean seed fly occur in Britain, *Delia platura* and *Delia florilega*. Their maggots can cause damage to peas. Although flies are common and widespread, damage is localised and sporadic, often worse in soil with a high organic matter content. Maggots mine the cotyledons, stems, underground shoots and, occasionally, roots. Adults lay eggs in the soil during May and prefer freshly disturbed soil. There may be three or four overlapping generations during the summer, but it is usually only the first generation arising from overwintered pupae which causes most damage.

Pea midge - Pea midge is a localised pest in Britain with large populations in east Yorkshire, Lincolnshire, north Cambridgeshire and parts of Norfolk. Elsewhere its incidence is slight and seldom important. The longer growing period of dry harvested peas frequently allows them to escape, or compensate for, midge damage. Serious damage and loss of yield occurs only when the flower trusses contributing to harvested yield are affected.

Bryobia mites - The clover bryobia mite (*Bryobia praetiosa*) feeds on grass and other low herbage, particularly plants belonging to the pea family (*Leguminosae*). They are rarely of commercial importance but occasionally cause nuisance by invading dwelling houses.

Pea cyst nematodes - Pea cyst nematode (*Heterodera goettingiana*) can be a serious pest of peas but generally appears in widely scattered localities. It is a potential risk in the intensive pea growing areas of eastern England. Both peas and field beans can be attacked. The nematode can also multiply on wild vetches. If peas are continually grown on infested land, then it may be 10 years or more before a good crop can be again grown in that field.

Stem nematode - Both the oat-onion race and the so-called “giant bean” race infest winter and spring varieties of field beans. Infested seed is sometimes produced. Peas can also be attacked and vetches are occasionally found to be infested.

Trefoil, vetches and other legumes

There is little information available on the pest problems associated with these less common leguminous crops. Some information has been provided in the section on peas and beans. For example, pea moth has been bred from meadow vetchling (*L. pratensis*) and tufted vetch (*V. cracca*). Bryobia mites will feed on plants belonging to the family leguminosae, and pea cyst nematode will multiply on wild vetches. Some races of stem nematode will undoubtedly infest different legumes.

Catch/cover crops
Although not strictly fertility-building, some crops are planted in order to maintain soil fertility (N-holders). These include stubble turnips, mustard and phacelia.

Stubble turnips
Stubble turnips may be attacked by a wide range of pests of cruciferous crops. Flea beetles (*Phyllotreta* spp.) can cause serious damage to young turnip plants. Loss is usually greatest in dry springs, but considerable damage can occur in the summer when large numbers of beetles migrate downwind after brassica seed crops have been cut. Cabbage stem flea beetle (*Psylliodes chrysocephala*) is also a potential pest of stubble turnips. The adults will feed on the cotyledons and leaves and cause damage or destroy young crops in dry weather when growth is slow. Eggs are also laid in the soil and newly hatched larvae invade the plants. Turnip gall weevil (*Ceutorynchus pleurostigma*) lays most of its eggs in August and September and so could infest stubble turnips. Once hatched the young grub feeds on the root which reacts by forming a gall. However, usually the crop is not seriously affected and the effect on yield is slight or negligible. Cabbage root fly (*Delia radicum*) is probably the major pest of brassicas and can also infest stubble turnips, particularly the third generation of flies which emerges from about mid-August onwards. However, the third generation does not always occur every year. Beet cyst nematode (*Heterodera schachtii*) will also multiply on stubble turnips and the crop may be infested by peach potato aphid (*Myzus persicae*).

Mustard
There is little detailed information available on the pests of mustard. The crop can be attacked by turnip gall weevil (*C. pleurostigma*) and will also support beet cyst nematodes (*H. schachtii*). Mustard beetle (*Phaedon cochleariae*) is a sporadic pest of mustard. However, adult beetles invade crops in the spring so it is unlikely to be a major problem in autumn sown crops.

Phacelia
There is little if any detailed information on the pests of phacelia.

2.3.3. Pests and bi-cropping

Cereal bi-cropping, growing a cereal crop through a permanent understorey of white clover, is a system particularly suited to growing winter wheat for whole crop silage (Clements *et al.,* 2002). One of the major pests of cereals is the aphid, which spreads BYDV and also causes direct feeding damage. However, the need for insecticides in a bi-cropping system is greatly reduced as aphid numbers usually remain low. This is thought to happen for four main reasons:

1. aphids migrating in the autumn are believed to rely on the contrast between cereal seedlings and bare soil to be able to detect the crop. The clover crop provides a green backdrop and probably camouflages the emerging cereal.
2. the permanent, undisturbed nature of the clover understorey allows large populations of predatory beetles and spiders to develop during the periods of the year when aphids could be causing damage. The predators not only consume any aphids in their path, but some of them also climb cereal plants to search out prey.
3. aphids fall from plants frequently – up to 90% of the aphid population fall to the ground each day and the clover understorey makes it physically more difficult for them to re-locate their host plant. Also, while they are searching, they are vulnerable to attack by predators.

4. the relatively low N status at which the bi-cropping system operates deprives aphids of a rich source of nutrients and slows both their development time and rate of reproduction.

Slug damage to cereal seedlings was recorded in some instances but was controlled by using slug pellets. It is suggested that using a seed drill with a press wheel that closes the slot would help make the seed less vulnerable to slugs.

Much of the published work on bi-cropping has been on the cereal clover system, although many of the suggested means of preventing pest damage are likely to be applicable to other systems. White cabbage has been grown in association with white clover and there were reduced infestations by thrips and cabbage root fly, although there were detrimental effects on yield. Theunissen & Ouden (1980) showed that damage to Brussels sprouts by garden pebble moth caterpillars (*Evergestis forficalis*) was reduced by intercropping with spurry (*Spergula arvensis*).

*Table 2.6. The relative importance of invertebrate pests in fertility-building and catch crops. (*** Major pest frequently capable of causing yield loss; ** Often present but only occasionally affects yield; * Sporadic, only rarely affects yield)*

Crop	Pest	Importance	Comments
Clover	Stem nematode	**	Damage dependent on race present
	Slugs	**	Worst in heavy soil types and in damp conditions
	Leatherjackets and wireworms	*	Risk is greater if grass/clover mix
	Pea and bean and clover weevils	**	Both adults and larvae are damaging
	Clover cyst nematode	*	
	Aphids	*	
Grass/clover leys	Slugs	***	As per clover
	Leatherjackets	***	Worst in wet years which improves larval survival
	Frit fly	**	Risk increases with increasing ryegrass content of the sward (especially Italian ryegrass)
	Wireworms	**	Greatest risk after long term grass
	Aphids	*	Also vectors of BYDV
	Chafers	*	Sporadic
	Wheat flea beetle	*	Sporadic
	Wheat shoot beetle	*	
	Grass and cereal flies	*	
	Crambid moth	*	
	Common rustic moth	*	
Peas and beans	Black bean aphid	**	Potential to predict risk from eggs laid on weedy host
	Pea aphid	**	
	Thrips	*	
	Pea moth		Early and late sown crops suffer least damage
	Pea and bean weevil	**	Threat also to undersown clover bordering peas
	Bean seed fly	*	Sporadic pest, risk greater in soil with high organic matter content
	Pea midge	*	Localised in east Yorkshire, Lincolnshire, north Cambridgeshire and parts of Norfolk

*Table 2.7. The relative importance of invertebrate pests in fertility-building and catch crops. (*** Major pest frequently capable of causing yield loss; ** Often present but only occasionally affects yield; * Sporadic, only rarely affects yield)*

Crop	Pest	Importance	Comments
Peas and beans (continued)	Bryobia mites	*	Rarely of commercial importance
	Pea cyst nematode	**	Localised, particularly east of England
	Stem nematode	**	Both oat-onion and giant bean race important
Trefoils, vetches and other legumes	Pea moth	*	Has been bred on meadow vetchling and tufted vetch
	Bryobia mites	*	Will feed on a range of legumes
	Pea cyst nematodes	*	Will multiply on wild vetches
	Stem nematodes	*	Risk dependent on race present
Stubble turnips	Flea beetles (*Phyllotreta* spp.)	***	Potential damage in dry springs and summer
	Cabbage stem flea beetle	**	
	Turnip gall weevil	*	Negligible affect on yield
	Cabbage root fly	**	Primarily risk from third generation flies
	Beet cyst nematode	*	
	Peach potato aphid	*	Potential virus transmission
Mustard	Turnip gall weevil	*	
	Beet cyst nematode	*	
	Mustard beetle	*	Sporadic pest, invades crops in spring

2.3.4. The potential for pest attack in crops following fertility-building crops

The risk of carry over of pests from a fertility-building crop to subsequent cereal or other arable and horticultural crops is summarised in Tables 2.8 and 2.9, respectively. Further detail on specific interactions between the fertility-building crop and subsequent crop are provided in the following paragraphs.

Carry over of pests from clover
Slugs, leather jackets and wireworms and are the major pests which could pose a threat to any subsequent crop following a clover ley. Slug damage is reduced in well-consolidated seedbeds with a fine tilth, where there are fewer air spaces in the soil structure in which the slugs can move and feed. Consequently, avoidance of slug damage often depends on what success the farmer has in preparing a fine and firm seedbed.

Cereal crops sown in the early autumn are generally less vulnerable to slug attack than later sowings. Early sowing results in rapid germination, less exposure to the risk of grain hollowing and the establishment of plants that are better able to outgrow slug damage than smaller and slower growing plants of later sowings (Port & Port, 1986). However, early sowing can result in increased risk of BYDV infection so the relative importance and risk from each pest must be assessed on a local basis.

The depth of sowing can also influence the amount of slug damage (Glen *et al.,* 1990 & 1992). Seed sown at 2̃2.5 cm was more vulnerable to attack than seed at 4̃5 cm depth as slug activity is usually greatest near the soil surface. Deeper sowing thus made the seed less accessible to slugs feeding on or near the soil surface. However, excessively deep sowing (more than 5 cm) may have a detrimental effect by slowing crop emergence and establishment.

Consolidation of the seed bed by rolling can reduce slug damage by causing larger soil aggregates to break down into finer particles, or by reducing the size of air spaces between soil particles (Stephenson, 1975; Davis, 1989). Provided that consolidation does not result in the seeds being made more accessible to slugs by decreasing the depth of burial, evidence suggests that consolidation can considerably reduce slug damage to wheat seeds (Glen, 1993).

To minimise the risk of carry over of leatherjackets, early ploughing of the sward, before crane flies lay their eggs during August and September, is recommended. Ploughing will also tend to kill leatherjackets by mechanical damage and by increasing their chance of exposure to predators such as birds and small mammals. However, ploughing could increase the risk from wheat bulb fly if undertaken in July or early August. Improving the drainage of wet, low lying fields, which favour the survival of leatherjackets, would assist in reducing attack from this pest. Also, as with slugs, early sown crops are likely to withstand damage better than backward, late sown crops.

There is little that can be done, by cultural means, to reduce the number of wireworms in old swards. Ploughing will help expose wireworms to predation by birds and small mammals. The time of ploughing is also important. Autumn ploughing for winter cereals does little to reduce the wireworm populations (Gair, 1982). However February or March ploughing, followed by a full fallow, causes a greater reduction in numbers than June or July ploughing followed by a partial (bastard) fallow. However, fallowing in July and August may increase the risk of wheat bulb attack in districts where this pest is established. If soil conditions allow, rolling is useful in cases of wireworm attack as it restricts the movement of the pests and encourages plants to grow away from damage. Peas and beans tend to be less susceptible to wireworm damage than most other crops.

Both clover and oats can be attacked by stem nematode. The red clover race of stem nematode can attack kidney vetch, and strawberry and the white clover race only attacks alsike to any significant effect. The oat-onion race, if present, will potentially infest oats and alliaeceous vegetables such as onions and leeks.

Carry over of pests from grass/legume leys
The potential for carry over of slugs, leather jackets, wireworms and stem nematodes from mixed swards is very similar to that from clover and is described above. Additional pests are chafers, aphids and frit fly.

Pests such as aphids and frit fly are a particular risk to cereal crops that follow a grass/clover ley. A natural reservoir of barley yellow dwarf virus (BYDV) exists in wild and cultivated grasses. Infestation of cereals following grass/clover leys can occur via the “green bridge” route in which aphids transfer from the grass to the subsequent cereal crop. This green bridge can be destroyed by ploughing well in advance (at least five weeks) before drilling to allow time for the aphids to die within the soil.

The impact of frit fly on organic cereals following grass/legume leys can be minimised by leaving a long interval between the ploughing of sward and sowing of the cereal crop. This reduces survival of frit fly larvae and the infestation of cereal seedlings by transfer of larvae from buried grass.

Length of leys and pest build up

The duration of a grass ley can influence the build up of some pest species, particularly those with a life cycle longer than one year. This includes wireworms (*Agriotes* spp.) summer chafers (*Amphimallon solstitialis*), brown chafers (*Serica brunnea*) and ghost swiftmoths (*Hepialus humuli*). The life cycle of a wireworm is 4-5 years, 2 years for the summer and brown chafers, and 2 years and occasionally 3 years for the ghost swiftmoth. Consequently the longer a ley is left undisturbed the greater the risk of these pests completing their life cycle. The duration of the ley will have little influence on other pest species.

Carry over of pests from peas and beans

Pests of peas and beans are generally specific to leguminous crops. It is highly unlikely that successive pea and bean crops will be grown so there is limited risk to other non-legumes. The oat-onion race of stem nematode will attack field beans and does pose a threat to any following oat, alliaceous or strawberry crop. Also, if pea crops are harvested early, this may encourage egg laying by wheat bulb fly which could damage winter wheat and, very occasionally, winter barley.

Carry over of pests from catch crops

Although a number of pests that attack stubble turnips could potentially carry over into vegetable brassicas, it is very unlikely that two cruciferous crops would be grown consecutively in an organic rotation. However, peach-potato aphid, which will infest stubble turnips, could potentially transfer into potato and sugar beet crops with the risk of virus transmission. Thorough cultivation to ensure remnants of the stubble turnips are well buried should help to minimise the risk.

2.3.5. Maximising conditions for natural predators

Numbers of natural predators are likely to increase where there is limited disturbance to a system. Therefore minimal cultivations as opposed to ploughing and rotary cultivations is likely to benefit natural predators. For example, the success of beetle banks is dependent upon providing an undisturbed refuge for predatory beetles. One of the reasons that bi-cropped cereals and clover have reduced aphid numbers in comparison with a conventional system, is that the pests are consumed by predators that reside in the undisturbed understorey. A diverse plant population is also likely to attract more natural predators than a monoculture.

2.4. Interactions between pests and diseases

2.4.1. Aphids and sooty moulds (-ve)

Aphid honeydew is full of sugars so provides an ideal substrate for sooty moulds that, if very severe, can reduce photosynthetic efficiency.

2.4.2. Insect/nemateode wounding increases susceptibility to fungal attack (-ve)

If an insect/nematode feeds on plant tissue then the wound it creates will increase the susceptibility of that plant to fungal attack. For example, feeding by syphylid on potato roots provide an entry point for soil fungi. In general, insect or nematode feeding on the roots is likely to increae the risk of attack by soil fungi. The risk of potatoes being infected by *Verticillium dahliae* is thought to be increased by the presence of root feeding nematodes.

2.4.3. Aphids/nematodes as virus vectors (-ve)

Although not strictly an interaction with a fungal disease both aphids and nematodes can act as virus vectors. The obvious examples are aphids and BYDV, virus yellows and potato viruses. A nematode example would be stubby root nematodes and tobacco rattle virus that causes spraing.

2.4.4. Insect parasitic fungi (+ve)

Insects can be parasitised by a range of fungi. Aphids are often seen to be 'fungosed' in the field. Some fungi eg *Verticillium spp.* have been produced commercially as biological control agents. In organic systems the potential for parasitic fungi to have a beneficial effect on pests could be greater than in conventional systems due to the absence of most fungicides, which kill 'friendly' as well as ‘enemy’ fungi.

2.4.5. Early drilling conflicts (+ve/-ve)

Where early drilling is favoured for canker control (eg oilseed rape) this can increase pest problems such as cabbage root fly and aphids/virus.

Table 2.8. The risk of invertebrate pest attack in organic cereals following a range of fertility-building/catch crops

Fertility builder/ catch crop	**Pest**	**Cereal crop** **Wheat**	**Barley**	**Oats**	**Rye**	**Triticale**	**Maize**
Grass/clover ley	Slugs	✓	✓	✓	✓	✓	✓
	Leatherjackets	✓	✓	✓	✓	✓	✓
	Frit fly (autumn gen)	✓	✓	✓	✓	✓	
	Frit fly (spring gen)	-	-	✓oat grains	-	-	✓
	Wireworms	✓	✓	✓	✓	✓	✓
	Aphids (BYDV)	✓	✓	✓	✓	✓	✓
	Aphids (direct feeding)	✓	✓	✓	✓	✓	?
	Chafers	✓	✓	✓	✓	✓	✓
	Wheat flea beetle	✓	-	-	-	-	-
	Wheat shoot beetle	✓	-	-	-	-	-
	Opomyza spp.	✓	-	-	-	-	-
	Crambid moths	✓	✓	✓	?	?	?
	Common rustic moth	✓	-	✓	-	-	-
Clover	Leatherjackets	✓	✓	✓	✓	✓	✓
	Wireworms	✓	✓	✓	✓	✓	✓
	Slugs	✓	✓	✓	✓	✓	✓
	Stem nematode	-	-	✓oat-onion race	-	-	-
Peas and beans	Stem nematode	-	-	✓oat-onion race	-	-	-
	Wheat bulb fly	✓	✓rarely	-	-	-	-

Table 2.9. The risk of invertebrate pest attack in arable crops other than cereals and vegetable crops following a range of fertility-building/catch crops

Fertility builder /catch crop	Pest	Arable crops				Vegetable crops			
		Potatoes	**Peas & beans**	**Sugar beet**	**Brassicas**	**Alliaceous**	**Salads**	**Umbeliferous**	**Strawberry**
Grass/clover ley	Slugs	✓	✓	✓	✓	✓	✓	✓	✓
	Leatherjackets	✓	✓	✓	✓	✓	✓	✓	✓
	Wireworms	✓	✓rarely	✓	✓	✓	✓	✓	✓
	Chafers	✓	✓	✓	✓	✓	✓	✓	✓
Clover	Leatherjackets	✓	✓	✓	✓	✓	✓	✓	✓
	Wireworms	✓	✓	✓	✓	✓	✓	✓	✓
	Stem nematode	✓	✓	✓	-	✓	-	✓	✓
	Slugs	✓	✓	✓	✓	✓	✓	✓	✓
Peas & beans	Stem nematode	✓	✓	✓	-	✓ e	-	✓	✓
Stubble turnips	Peach potato aphid	✓	-	✓	✓	-	-	-	-

2.5. Conclusions

- There are a wide range of fertility-building crops available to organic farmers including both legumes (‘N fixers’) and cover/catch crops (‘N-holders’).
- Some related species are more susceptible to pests and diseases than others (eg *Trifolium spp*. and stem nematode susceptibility)
- Pest and diseases carry over may occur when similar crop types are used for fertility-building as well as a cash crop (eg mustard cover crop and brassica vegetables)
- There is often conflict between measures to maintain fertility in terms of nitrogen retention and reduction of pest and disease risk (eg early sowing of winter cereals after a grass/legume increases the risk of aphids/BYDV)
- Good soil management and drainage are important factors in most aspects of successful crop production including reducing the threat from soil-borne diseases and control of some pests such as slugs.
- Consider cropping history and previous diseases problems before selecting fertility-building crops.
- Some direct disease risk to fertility-building crops – foliar diseases and clubroot on crucifers, sclerotinia, foliar and root diseases on legumes.
- ‘Green bridge’ effect which enables pests and diseases to overwinter would work against rotational strategies which try to avoid overlapping crops.
- Complex biological and chemical interactions occur in soil but some benefits can occur after incorporation of green crops.
- Bi-crops can reduce disease severity.

3. HOW MUCH N IS CAPTURED?

3.1. Fixation potential of different crops

The quantity of N fixed by different legumes is determined by the inherent capacity of the crop/rhyzobium symbiosis to fix N, modified by the crop growing conditions (e.g. soil, climate, disease), management and length of time for which the crop is grown. It should therefore be possible to predict the quantity of N fixed from knowledge of the potential fixation and how this is affected by the particular conditions of the crop.

Unfortunately, few studies have measured the maximum quantity of N that can be fixed under ideal conditions and the conditions under which the crop has been grown are often poorly defined. The best that can be done is to estimate potential fixation from the upper range of values observed in different studies and take account of any limitations that may be present. In this respect, measurements from countries where conditions are more favourable than in the UK may be more indicative of the maximum fixation that can be achieved.

In general, crops that accumulate a greater biomass with a higher N content will accumulate most N. However, this can be a poor indicator of the actual input from fixation, as legumes differ in the proportion of N they derive from the atmosphere (%Ndfa) and take up from the existing mineral N pool in the soil. Nor is the proportion derived from the atmosphere constant for a particular species, being dependent on soil and environmental conditions.

Simple measurements of N yield are therefore an unreliable guide to the quantities of N fixed. Measurements of N-fixation must differentiate between crop N obtained from the soil and from the atmosphere.

Most estimates of fixation have been obtained using the N-difference method or by the ^{15}N isotope dilution method. In the former, fixation is determined as the difference between the total N yield of the legume and that of a non-fixing reference crop grown on the same soil. In the isotope dilution method, the soil is labelled with ^{15}N and the proportion of labelled N in the legume is compared with that in a non-fixing reference crop. The proportion of ^{15}N in the reference crop will reflect the proportions of label in the soil mineral-N pool. There will be a lower proportion of ^{15}N in the legume, depending on how much of the plant N has been obtained from the unlabelled atmospheric N pool. Studies have also used differences in the natural abundance of ^{15}N to estimate fixation (e.g. Shearer & Kohl, 1986; Wanek & Arndt, 2002). Reviews by Ledgard & Steele (1992) and Wood (1996) have considered the limitations of these methods and the uncertainties inherent in all estimates of N-fixation. In particular, it is important that the non-fixing reference crop used in both the N difference and isotope dilution methods should exploit the same mineral N pool in the soil and have similar uptake characteristics as the legume under examination. These requirements may be difficult to satisfy in practice. Measurements of N-fixation in peas using either natural ^{15}N abundance or artificially enriched soils only produced similar results when barley was used as the reference crop, rather than flax or even a non-fixing pea cultivar (Bremer *et al.,* 1993). However, Kilian *et al.* (2001) found that for estimating fixation in *Vicia faba,* a non-fixing bean cultivar was a better reference crop than cabbage or ryegrass. In a study of N-fixation by a number of leguminous green manure plants, Italian ryegrass was found to be a more suitable control plant than either winter rape or winter rye (Mueller & Thorup-Kristensen, 2001).

As in the example above, estimates may also be influenced by the method used to measure fixation. McNeill & Wood (1990) reported that values obtained using the N-difference method were approximately 25% lower than those estimated using the ^{15}N isotope dilution method. Similarly, under a high N regime, the N-difference method was found to underestimate the amount of fixed N in harvested clover material by up to 33% (Høgh-Jensen & Kristensen, 1995). Boller & Nösberger (1987), however, found that, on average, the difference method gave a 10% higher estimate of fixation than the isotope dilution method for mixtures of grass with either red or white clover. A study by Loges *et al.* (2000a) compared estimates of fixation by the N-difference, isotope dilution and natural abundance methods for pure legume and grass/legume mixtures. Estimates using the isotope dilution method were between 89 and 104% of those obtained with the N-difference method, whereas estimates using the natural abundance method were only 52-61% those with the difference method. These values were based on sampling of the above-ground herbage. Differences between the methods were less marked (67-97%) when the calculations included below-ground plant components and changes in soil mineral-N. Nevertheless, it is clear that there are large uncertainties in any measurments of N-fixation.

An additional limitation of these methods is that they are most suited to determining the accumulation of N in the above-ground parts of the plant. Few measurements include the N in roots and in stubble below sampling height. These components may be particularly important in providing N to following crops. In the study by Loges *et al.* (2000a), estimates using the N difference, isotope dilution and natural abundance methods were on average 33, 46 and 75% greater when based on total plant material + soil mineral N than when based on just the above-ground, harvested material. McNeill *et al.* (1997) estimated that the total below-ground N for subterranean clover plants was equivalent to 73% of that in the shoots.

Thus, much of the below-ground N can be present as fine roots and rhizosphere soil. It was concluded that standard root recovery procedures are likely to underestimate the total N accretion and turnover.

Nitrogen-fixation has also been determined from the rate at which acetylene is reduced by the nodules when the gas is injected into the soil around the legume roots. The acetylene is reduced by nitrogenase in the nodules, the same enzyme responsible for the N-fixation reaction. However, this method is generally considered to be unsuitable for estimating the amount of N fixed during the season because of uncertainties about the exact equivalence between the N-fixation and acetylene reduction processes and the need to interpolate from a limited number of short-term measurements. It is of greater value for comparative, short-term measurements of relative rates of fixation: in these circumstances, results are more satisfactorily reported in terms of rates of nitrogenase activity.

Methodological difficulties make it almost impossible to get an accurate measure of fixed N. All methods have advantages and disadvantages. The literature has used a number of methods, so that estimates are not always directly comparable.

The majority of N-fixation values in the following sections were obtained using the N-difference and isotope dilution methods. Where the less-reliable acetylene reduction method was used, this is stated in the text. Most estimates refer to fixation in the above-ground herbage.

Estimates of the quantities of N fixed by legumes that can be grown under UK conditions are considered below. Results are included from non-UK studies where they provide an indication of the fixation that can be achieved under conditions that are more (or less) favourable than those in this country. In particular, much of the information about fixation by white clover originates from studies in New Zealand where the temperate climate and longer growing season particularly favours clover. Legumes grown in studies in southern Australia and in the dryland cereal areas of North America are more likely to be affected by summer drought unless irrigated. Data from other countries in north Western Europe are more directly comparable with UK conditions but, further east, are likely to have a more continental climate with warmer summers and colder winters.

For the purposes of modelling the potential for legumes in European dairy farming, Topp *et al.* (2002) proposed eight agro-climatic zones for Northern Europe. The north of the UK was grouped with Ireland and the southern UK grouped with France, the Netherlands and Belgium. Highest yields of fertilised grass and of monocultures of red clover and lucerne were allocated to this latter zone. Mixtures of grass with white clover, red clover or lucerne also performed best in this zone.

White clover is by far the most important legume for use in grazed pastures. Both white and red clover are important as silage crops. Red clover is the most common leguminous green manure grown on organic farms in the UK (Phillips *et al.,* 2002; Watson, 2002). Other forage legumes and green manures include lucerne, vetches, trefoil and lupins. The range of grain legumes includes winter and spring varieties of field beans, peas, lupins and specialised crops such as lentils and soybeans. Peas and beans are the most commonly grown, mainly for use as animal feed (Taylor & Cormack, 2002). The potential of each of these crops to fix atmospheric N is reviewed in the following sections.

3.1.1. White clover (Trifolium repens)

There have been many studies of the amount of N fixed by white clover, reflecting its importance in pastures in this country and more especially in New Zealand. White clover is generally grown as a mixture with grass and differences in the proportions of grass and clover undoubtedly contribute to the wide range of fixation values observed. Factors affecting the growth of white clover/grass mixtures have been reviewed by Kessler & Nösberger (1994). Typical estimates of annual fixation are listed in Table 3.1. White clover monocultures are relatively drought resistant but less so when grown in mixtures with grass (Thomas & Bowling 1981).

Estimates of N fixation by white clover span a wide range of values and in spite of the abundant information, there is still uncertainty about the quantities fixed.

Estimates of the amounts of biological N-fixation by grass/clover pastures in the UK have been reviewed by Wood (1996). It was concluded that white clover had the potential to fix 100-200 kg

N/ha annually under UK conditions, though individual values were as high as 445 kg/ha/year. These estimates do not take account of N in unharvested parts of the plant such as stubble, roots and stolons.

Table 3.1. Estimates of the quantity of N fixed annually by unfertilised white clover/grass mixtures: range (mean) in above-ground plant parts.

Fixation (kg N/ha/year)	**Comments**	**Reference**
100-200	Typical values for UK pastures	Wood (1996)
0-255 (152)	22 sites, UK	Whitehead (1995)
150-200	Adapted from Kahnt (1983)	Lampkin (1990)
1-260	Lowland and hill soils, Wales (including roots)	Goodman (1998 & 1991)
74-280 (158)	UK, various studies	Cowling (1982)
128-305	Organic farms, Denmark	Høgh-Jensen (1996)
100-235	Mixed organic farms, Denmark	Vinther & Jensen (2000)
268-373 (308)	First production year, no N fertiliser; Switzerland	Boller & Nösberger (1987)
55-296	Grazed pastures, New Zealand	Ledgard & Steele (1992)
79-212	New Zealand	Ledgard *et al.* (2001)
112-143	Organic & conventional orchards, New Zealand	Goh *et al.* (1995); Goh & Ridgen (1997)
11-135	Grazed dairy pastures, Australia	Riffkin *et al.* (1999a)
	Mown pasture	Ledgard (2001)
28-187 (136)	- recently sown	
45-315 (152)	- permanent	
	Grazed pasture	
11-159 (59)	- permanent	

Ledgard & Steele (1992) quoted a range of 55-296 kg/ha for fixation in grazed white clover pastures in New Zealand. Fixation of up to 673 kg/ha has been reported for clover grown under extreme conditions particularly favourable to clover growth and N-fixation (Sears *et al.,* 1965). Measurements of the amount of N fixed on organic farms in Denmark were between 128 and 305 kg/ha/year (Høgh-Jensen, 1996). Above-ground fixation in grazed grass/clover mixtures during an organic, grass-arable rotation in Denmark supplied 29 and 15 kg/ha in the seeding year for grass/clover undersown into spring barley and 100-235 kg/ha in following years (Vinther & Jensen, 2000). Less N was fixed in a three-year study by Høgh-Jensen & Schjoerring (1997b) on a sandy loam, possibly because of water-limited growth conditions. Fixation in plots receiving 3 kg fertiliser-N/ha averaged 83 kg N/ha. During the course of the study, the proportion of clover varied between 20 and 80% of total harvested dry matter. In Switzerland, Boller & Nösberger (1987) measured N-fixation of 49-227 kg/ha (mean 131 kg/ha) by perennial ryegrass/clover mixtures in the seeding year and 268-273 kg/ha (mean 308 kg/ha) in the first production year. Where swards received 30 kg fertiliser N/ha at each cut, the corresponding means in the two years were 83 and 232 kg N/ha.

Measurements on an organic farm in the UK indicated that white clover grown as a green manure accumulated 592 kg N/ha in above-ground herbage over a 25-month period (Stopes *et al.,* 1996). In comparison, a ryegrass control, reliant on soil-N, accumulated 346 kg N/ha, indicating that the clover fixed about 120 kg N/ha/year. Nitrogen-fixation was measured as 112-143 kg/ha in a white clover/perennial ryegrass understorey of a conventional apple orchard in New Zealand (Goh & Ridgen, 1997) and as 118-126 kg/ha in an organically farmed orchard (Goh *et al.,* 1995).

Much of the variation in N-fixation can be attributed to differences in the proportion of clover in mixed swards.

Much less N is fixed in swards that contain relatively little clover. For example, Hansen & Vinther (2001) attributed differences between annual N-fixation of 59 and 125 kg/ha in ungrazed grass/clover plots in Denmark to differences in growth rates and the proportion of clover. In the Netherlands, N-fixation in grass/clover fields with a relatively low clover content (6-15% clover) contributed only 40 kg N/ha with a further 25 kg/ha transferred from clover to grass (Ennik, 1983). Similarly, estimates of 11-18 kg N fixed/ha per year in grazed dairy pastures in south western Victoria, Australia (compared with 44-135 kg N/ha elsewhere in Australia) were attributed to low pasture yields and poor legume content in the swards (average 8%) (Riffkin *et al*., 1999a). In New Zealand, N-fixation in unfertilised grass/clover farmlets ranged from 79 to 212 kg N/ha/year for clover contents between 9 and 20% (Ledgard *et al.,* 2001). Boller & Nösberger (1987) stressed the importance of maintaining a high clover content ($\geq$ 50%) for achieving high rates of N-fixation (>200 kg/ha/year). A recent review by Ledgard (2001) summarised estimates obtained from ^{15}N dilution measurements during the past 20 years. The much lower fixation in long-term pastures under grazing than under cuting was attributed to the lower clover content in grazed pastures, which contained 8-28% clover (mean 16%) compared with 20-46% (mean 26%) under cutting.

Pure stands of clover in Denmark fixed 262 and 211 kg N/ha in the first and second production year; compared with 187 and 177 kg/ha when grown as a mixture with perennial ryegrass (Jørgensen *et al.,* 1999). Over a three-year period, Høgh-Jensen & Schjoerring (1997b) measured an average annual fixation of 109 kg N/ha for pure clover compared with 83 kg/ha for a grass/clover mixture. Percentage Ndfa was 78-83% for the monoculture and 93-95% for the mixture. White clover grown for seed in SE Australia fixed 327 kg N/ha (Kumar & Goh, 2000).

Almost all studies indicate that white clover obtains most of its N from the atmosphere rather than from the soil (Table 3.2). There is evidence that the proportion of N derived from the atmosphere (%Ndfa) is less under grazing than where swards are mown (see Section 4.3).

Estimates generally refer to the proportion of fixed N contributing to the overall annual N yield. The proportion derived from the atmosphere may be less at particular times of the year (see Section 3.2.1).

The majority of estimates of N-fixation do not include fixed N in unharvested parts of the plant. Jørgensen & Ledgard (1997) suggested a correction factor of 1.65 to account for N in roots and stubble when fixation in white clover is estimated by harvesting the leaves only. This is greater than the value employed by Høgh-Jensen & Kristensen (1995), who considered that biologically fixed N was underestimated by 19-25% when only the harvested material was measured.

Table 3.2. Estimates of percentage of N derived from fixation (%Ndfa) in white clover: season/annual mean.

%Ndfa	Comments	Reference
90	Monoculture grown for seed; SE Australia	Kumar & Goh (2000)
	Clover monoculture	Høgh-Jensen (2000)
75-94	Clover monoculture	Jørgensen *et al.* (1999)
85-97	Grass/clover mixture	
90-97	Grass/clover mixture: controlled environment with ^{15}N-enriched atmosphere	McNeill *et al.* (1994)
80	Grass/clover mixture; New Zealand	Wheeler *et al.* (1997)
89-95	Ungrazed grass/clover; Denmark	Hansen & Vinther (2001)
70-87	Grazed dairy farms; Denmark	
70-99	Grazed pasture following barley; Denmark	Vinther & Jensen (2000)
74-83	Clover/perennial ryegrass (unfertilised/cut); Switzerland	Boller & Nösberger (1987)
65	Grazed dairy pastures: SE Australia	Riffkin *et al.* (1999a)
	Mown pasture	
89-98 (95)	- recently sown	Ledgard (2001)
80-89 (86)	- permanent	
	Grazed pasture	
44-82 (70)	- permanent	

Breeding has had a significant impact on the yield and agronomic performance of different clover varieties (Frame & Boyd, 1987). The effect of clover variety on N-fixation was studied in a cutting trial with perennial ryegrass/white clover mixtures in the Netherlands (Elgersma & Hassink, 1997). Nitrogen yield and apparent N-fixation were higher with the large-leaved clover cv. Alice than for mixtures with the small/medium-leaved cvs. Gwenda and Retor. This was largely a result of the higher clover yield, which was sufficient to offset a slightly lower input of N per tonne clover dry matter for this variety (51-54 kg N/t clover dry matter compared with 56-65 kg/t for Gwenda and Retor). Over the three years of the study, apparent N-fixation averaged 438, 360 and 291 kg N/ha/year for the varieties Alice, Gwenda and Retor, respectively

(Elgersma & Schlepers, 1997). Choice of cultivar of the companion grass did not consistently affect yield or botanical composition. In an earlier study, Laidlaw (1988) found that differences between cultivars did not have a significant effect on the amount of N fixed.

3.1.2. Red clover (Trifolium pratense)

Red clover is normally grown as a 1 or 2-year ley for silage or for mulching as a green manure, either grown alone or with ryegrass (Watson 2002). Because of its deep taproot it is relatively drought resistant. There are fewer estimates of the quantity of N fixed than for white clover (Table 3.3).

Red clover may be more productive than white clover. As with white clover, a high proportion of the plant N is obtained by fixation and there is evidence of differences in the quantity of N fixed by different cultivars.

In a trial on an organic farm in the UK, red clover grown as a green manure accumulated more N in above-ground herbage than a corresponding white clover treatment, even though the white clover accumulated more dry matter. Red clover accumulated 371 kg N/ha over 13 months, compared with 328 kg N/ha by white clover. Corresponding values after 25 months were 741 and 592 kg/ha (Stopes *et al.*, 1996). Subtracting the N uptake by the ryegrass control indicates that red clover fixed 277 and 395 kg N/ha over 13 and 25 months, respectively. Similarly, cut red clover was more productive than grass/white clover in a trial in the Netherlands (Wijnands & Kroonen-Backbier, 1991). Loges *et al.* (2000b) measured fixation of 343 kg N/ha by red clover/grass mixtures when cut for forage but only 154 kg/ha when cut and mulched as a green manure.

Table 3.3. Estimates of the quantity of N fixed annually by unfertilised red clover (in above-ground plant parts).

Fixation (kg N/ha/year)	Comments	Reference
240	Cut	Schmidt *et al.* (1999)
245	Cut (part year)	Lampkin (1990)
105	Grazed (part year)	
230-460	Red clover/grass - adapted from Kahnt, 1983	
219	Herbage crop, Saxmundham, UK	Williams & Cooke (1972)
>200	Monoculture, Terrington, UK	Cormack (*pers. comm*)
307 & 373	Grass/clover, Switzerland	Boller & Nösberger (1987)
154-343	Grass/clover, N Germany	Loges *et al.* (2000b)
128 & 210	Grass/clover, Norway	Nesheim & Oyen (1994)
73-159	Grass/clover, Iowa, USA	Farnham & George (1993)

Two unfertilised red clover/perennial ryegrass swards in Switzerland fixed 165 and 49 kg N/ha in the seeding year and 373 and 307 kg/ha in the first production year (Boller & Nösberger, 1987). Red clover grown in a mixture with timothy fixed 210 kg N/ha at a site in SW Norway, compared with 128 kg/ha at a site in the north of the country (Nesheim & Oyen, 1994).

Estimates of fixation and N transfer in long-term stands of red clover with orchardgrass in Iowa indicated annual fixation in herbage of 73-159 kg/ha with 17 kg N/ha transferred to grass herbage and 58 kg/ha transferred in the following year (Farnham & George, 1993).

Typical values of %Ndfa are shown in Table 3.4 showing that, as with white clover, a high proportion of N in red clover is obtained by fixation. The estimates from Reiter *et al.* (2002) were obtained from a long-term tillage study in Germany comparing continuous conventional ploughing with a continuous minimum tillage system. Although clover showed no significant differences in dry matter and N accumulation between the tillage systems, slightly less of the N was obtained from the atmosphere in the conventional system. This reflected the greater mineralisation of soil N following ploughing. Percentage Ndfa values for the conventional tillage system were 55 and 62% in 1998 and 1999, respectively, compared with 64 and 71% for the minimum tillage system.

Table 3.4. Estimates of percentage of N derived from fixation (%Ndfa) in red clover: season/annual mean.

%Ndfa	**Comments**	**Reference**
85-93	Red clover/Italian ryegrass (unfertilised/cut); Switzerland	Boller & Nösberger (1987)
96-97	Red clover/orchardgrass mixture; Iowa, USA	Farnham & George (1993)
80-93	Red clover/ryegrass, lysimeters; Germany	Russow *et al.* (1997)
55-71	Monoculture, seeding year; Germany	Reiter *et al.* (2002)

Annual fixation in 4-year stands of a red clover/birdsfoot trefoil mixture grown as a hay crop in Minnesota ranged from 69 to 133 kg N/ha, including roots (average 91 kg/ha) (Heichel *et al.,* 1985). Percentage Ndfa ranged from 35 to 68% (average 54%). Of the total plant dry matter, 10% or less was in root and crown which usually had a N concentration 0.5-0.6 that of herbage. There was therefore relatively little return of fixed N to a following crop unless herbage was also ploughed into the soil.

As with white clover, there is evidence of differences in the quantity of N fixed by different cultivars. In a Swiss study, N-fixation varied from 148 to 443 mg/plant for red clover strains grown with grass (Boller & Nösberger, 1994). Although there were significant and consistent strain differences in %Ndfa, differences were relatively small (range 77-81%) and differences in dry matter yield were responsible for most of the variation in fixation. In contrast, the study by Farnham & George (1993) in Iowa concluded that under the conditions of the trial the red clover cultivars tested did not differ in their abilities to fix N (or to transfer fixed-N to the associated grass).

3.1.3. Subterranean clover (Trifolium subterraneum)

Most estimates of fixation by subterranean clover are from studies in Australia, where it is most commonly grown as an annual pasture. Its ecology and use as a pasture legume in Australasia has recently been reviewed by Smetham (2003). Lilley *et al.* (2001) measured 320 kg fixed-N/ha in sampled herbage from an irrigated clover monoculture and 250 kg/ha when the clover was grown with grass. The %Ndfa in herbage was approximately 59% for pure clover and 71% for the mixture. Fixation was equivalent to 18–24 kg N fixed per tonne of above-ground clover dry matter. Stem bases (below 7-cm cutting height) contained 23% of the total plant-N in the clover monoculture. Roots contained a further 5%, though it was considered that this was probably an underestimate. The data in the paper indicate that the total quantity of N-fixed in cut herbage, plant bases and roots was about 450 and 320 kg/ha for the monoculture and mixture, respectively. Other estimates of above-ground fixation cited in the paper ranged from 20 to 238 kg N/ha, with 20-30 kg N fixed per tonne of clover dry matter. Dear *et al.* (1999) reported that subterranean clover fixed 23-34 kg N per tonne clover dry matter. Percentage Ndfa was between 73 and 95%. The range of recent measurements on subterranean clover swards, summarised by Ledgard (2001), indicate less fixation in longer-term pastures under grazing than cutting. As with white clover, this was attributed to the lower clover content of grazed pastures, which contained 12-84% clover (mean 32%), compared with 10-100% (mean 45%) for mown pastures.

In a study by Anderson *et al.* (1998), subterranean clover in a mixed pasture in western Australia fixed between 29 and 162 kg N/ha. Other estimates of fixed N in clover shoot biomass in annual pastures in the region ranged from 50 to 125 kg N/ha. Quantities fixed paralleled trends in clover production (Bolger *et al.,* 1995). Unkovich *et al.* (1995) reported that %Ndfa for subterranean clover in grazed pastures averaged 72% (range 0 – 100%). In grazed annual pastures in ley-arable rotations %Ndfa was greater than 65% and fixation between 5 and 238 kg/ha/year (above-ground) (Bowman *et al.,* 2002). Bergersen & Turner (1983) reported %Ndfa of 96-99% for herbage sampled 175-191 days after sowing. Maximum fixation rates were about 4 kg N/ha/day.

Data for subterranean clover are fewer, reflecting that it is not a common UK crop. However, N fixation appears to be affected in a similar way as with white and red clover. The crop obtains most of its N from fixation, and fixation is greater under a cutting than a grazing regime.

Table 3.5. Estimates of the quantity of N fixed from the atmosphere by unfertilised subterranean clover (in above-ground plant parts).

Fixation (kg N/ha/year)	Comments	Reference
320	Monoculture (irrigated), Australia	Lilley *et al.* (2001)
250	Grass/clover (irrigated), Australia	
29-162	Grass/clover, Australia	Anderson *et al.* (1998)
5-238	Grazed grass/clover, Australia	Bowman *et al.* (2002)
	Mown pasture	Ledgard (2001)
26-206 (104)	- recently sown	
18-126 (66)	- permanent	
	Grazed pasture	
29-188 (101)	- recently sown	
4-97 (48)	- permanent	

Table 3.6. Estimates of percentage of N in subterranean clover derived from fixation (%Ndfa): season/annual mean.

%Ndfa	Comments	Reference
	Mown pasture	Ledgard (2001)
70-91 (78)	- recently sown	
79-85 (83)	- permanent	
	Grazed pasture	
64-91 (80)	- recently sown	
60-90 (74)	- permanent	
59	Monoculture (irrigated), Australia	Lilley *et al*. (2001)
71	Grass/clover (irrigated), Australia	

3.1.4. Crimson clover (Trifolium incarnatum)

Crimson clover is normally sown in spring or by mid-September and grown for 2-3 months as a summer green manure. When sown in autumn it may overwinter in favourable regions. Crimson clover grown as an autumn-sown green manure fixed about 111 and 77 kg N/ha in the two years of a trial in Denmark reported by Mueller & Thorup-Kristensen (2001). In a trial in Germany, crimson clover had fixed 178 kg N/ha by maturity (Karpenstein-Machan & Stuelpnagel, 2000).

Other clovers that are used in agriculture include Alsike clover (*Trifolium hybridum*), Persian clover (*T. resupinatum*) and Egyptian clover or berseem (*T. alexandrinum*). There is relatively little information about fixation by these species; however, in Denmark Mueller & Thorup-Kristensen (2001) found that Persian clover and Egyptian clover fixed 100 and 32-69 kg N/ha/year, respectively. Crops were grown as green manures after barley. White sweetclover or white melilot (*Melilotus alba)* and yellow sweetclover or yellow melilot (*M. officinalis*) are also possible forage legume crops. Yellow sweetclover fixed up to 109 kg N/ha in a trial in subarctic Alaska, compared with up to 121 kg/ha for red clover (Sparrow *et al.,* 1995).

3.1.5. Lucerne (Medicago sativa)

Lucerne or alfalfa is a drought resistant and high yielding legume, which is grown mainly for silage, typically with three or more cuts per year.

Lucerne is more persistent than red clover and has a productive life of up to 4 years. The majority is grown pure or with a small inclusion of a non-aggressive grass as it has little tolerance of competitive species such as ryegrass. It can also be made into hay. Yield is little affected by drought during British summers. Constraints on growth are poor drainage and very acid subsoils. It is therefore restricted to deep, free-draining, calcareous soils (Doyle & Thomson, 1985). Inoculation of the seed is considered essential.

Experience from New Zealand indicates that the introduced rhizobia generally do not persist in the soil in the absence of the host plant and inoculation is therefore necessary at each sowing. Lucerne is sensitive to Mo deficiency and is more sensitive to B deficiency than is white clover (Douglas, 1986).

Table 3.7. Estimates of the quantity of N fixed by lucerne.

Fixation (kg N/ha/year)	**Comments**	**Reference**
300	Various studies	Royal Society (1983)
47-342 (152)	5 sites in UK, inoculated crops only	Bell & Nutman (1971)
300-550	Various studies	Lampkin (1990)
230	Monoculture, UK	Davies (1964)
221	With grass, UK	
263	Saxmundham, UK	Williams & Cooke (1972)
4	Green manure, Canada	Townley-Smith *et al.* (1993)
2-79	Australia	Bowman *et al*. (2002)
47-167	Grazed pasture, Australia	Peoples *et al.* (1998)
160-224	Hay cropping, Minnesota	Heichel *et al*. (1984)
Up to 58	Alaska	Sparrow *et al*. (1995)
Up to 500	Netherlands	Spiertz & Sibma (1986)

Experiments at 5 sites in the UK in 1967-70 showed wide variation in the amount of N fixed by lucerne, ranging from 0 to greater than 300 kg N/ha (Bell & Nutman, 1971). Most of the variation could be explained by whether effective rhizobia were present and by soil nutritional factors. If only those sites that had been inoculated and received adequate lime, P and K are included, fixation was 47-230 kg N/ha for first-year crops (mean 142 kg/ha) and 40-342 kg/ha for second-year crops (mean 161 kg/ha). The paper cited an average of 125 kg N/ha from other published studies.

Lucerne/grass mixtures in northern Germany fixed 320 kg N/ha/year when harvested as a forage crop but only 136 kg/ha when cut and mulched as a green manure (Loges *et al*., 2000b). Lucerne sown in spring in Canada as a green manure contained 36 kg N/ha after 12 weeks growth. Nitrogen-fixation (measured by acetylene reduction) averaged only 4 kg/ha compared with fixation of 15-40 kg/ha by other legumes in the trial (Townley-Smith *et al*., 1993).

Lucerne grown as a hay crop over 4 years in Minnesota fixed 160-177 kg/ha in the seeding year and up to 224 kg/ha in the final (best) year (including roots). Percentage Ndfa ranged from 33 to 78%. Most of the fixed N was removed in harvested material (Heichel *et al.* 1984). Fixation under different climatic conditions in Australia (New South Wales) ranged from 2 to 79 kg/ha/year. Under these conditions, biomass production was highest in summer but most fixation occurred in winter and autumn (possibly because of moisture stress and high temperatures in summer) (Bowman *et al*., 2002). In perennial lucerne-based grazed pastures in ley-arable rotations in SW Australia, lucerne fixed 47-167 kg/ha/year (above ground). More than 65% of the plant N was derived from fixation (Peoples *et al.,* 1998). Dear *et al*. (1999) reported %Ndfa values of 39-61% with 17-29 kg N fixed per tonne shoot biomass (dry matter). Also in Australia, annual inputs of fixed N by a lucerne and annual medic mixture during a pasture ley were 40-95 kg N/ha/year in herbage or 80-190 kg/ha/year in the total plant (McCallum *et al.,* 1999).

Lucerne was included in a recent multi-site study examining the potential of forage legumes in northern Europe (Halling *et al.*, 2002). Nitrogen yields of the grass/legume mixtures in the first and second years of the ley are shown in Table 3.8. Although the values refer to total N-yield rather than fixed-N, an indication of the N supplied by the soil is provided by the zero-N grass treatment. Apart from a higher N-yield from red clover in the first year, all the legume mixtures contained broadly similar amounts of N under UK conditions.

Table 3.8. Total yield of N (kg/ha) in legume-grass mixtures and from grass receiving 0 and 200 kg fertiliser-N/ha/year (Halling et al.*, 2002)*

	First year ley				**Second year ley**			
Species	**DE**	**FI**	**SE**	**GB**	**DE**	**FI**	**SE**	**GB**
Red clover+grass	343	185	259	259	240	218	196	170
Lucerne+grass	261	116	248	203	264	151	173	163
White clover+grass	228	152	249	207	91	182	220	143
Galega+grass	260	94	162	211	218	163	126	158
Lotus+grass	239	84	176	229	104	129	96	162
Grass 0N	46	52	73	150	29	63	66	93
Grass 200N	153	163	143	226	131	183	146	181
sem	34	34	34	38	37	34	34	34

DE = Germany, FI = Finland, SE = Sweden, GB = Great Britain
sem = standard error of mean

As with the other legumes reviewed, there is a wide range of N fixation values. Lucerne seems particularly susceptible to soil nutritional status and inoculation is essential.

3.1.6. Trefoil or black medick (Medicago lupulina)

Yellow trefoil is an annual which tolerates shade and can be undersown to a cash crop in the spring to provide a vigorous green manure once the main crop has been harvested.

There is little information about the quantities of N fixed by trefoil under UK conditions.

However, trefoil was included in the trial referred to above, in which a number of green manures were compared (Stopes *et al.,* 1996). Trefoil accumulated significantly less dry matter and N than either white or red clover. Values for *total* N accumulation (not fixation) by red clover, trefoil and the unfertilised ryegrass control were 371, 211 and 94 kg N/ha, respectively after 13 months growth and 741, 459 and 346 kg/ha after 25 months. Subtracting the N-yield of the ryegrass control indicates that trefoil may have fixed about 117 kg N/ha in the first 13 months.

Sickle medick (*Medicago sativa*) has also been grown as an agricultural crop.

3.1.7. Sainfoin (Onobrychis viciifolia)

Sainfoin can be grown for grazing or conservation. When grown as a mixture, it is usually sown with non-competitive grasses such as meadow fescue or timothy. Although it has desirable nutritional characteristics (including high protein) and does not cause bloat, Doyle *et al.* (1984) reported that there was limited data about its use as a grazing crop. They commented that sainfoin did not winter well in the UK north of the Humber. Waterlogging was more likely to be detrimental to growth than frosts. Sainfoin requires alkaline or calcareous soils but is less sensitive to drought than red clover.

In 1984, when reviewing the potential of sainfoin in the UK, Doyle *et al.* (1984) quoted a dry matter yield of 8.4 t/ha and concluded that the crop was unsuitable for UK conditions unless higher yields could be achieved. More recent studies in the UK, examining 4 cultivars of sainfoin, obtained yields of 9.0-16.6 t/ha, excluding one cultivar that failed to nodulate (Koivisto *et al.* 2002). Crude protein contents were between 13.4 and 17.9%. Assuming a protein factor of 6.25, these values are equivalent to 2.1-2.9% N or a *total* N content in the crop of about 340-410 kg N/ha. Whitehead & Jones (1969) reported a mean N content of 2.87% N for sainfoin, compared with 2.94, 3.40 and 4.42% for lucerne, red clover and white clover, respectively.

There is little information about the quantities of N fixed by sainfoin. There is an indication that it is less effective at fixing N than red clover.

A glasshouse study in New Zealand showed that sainfoin plants dependent on N-fixation grew less well than those receiving nitrate and it was concluded that fixation was unable to satisfy the plants' N requirements (Hume *et al.,* 1985; Hume & Withers, 1985; Hume, 1985). Sainfoin appeared to have a low specific nodule activity but fixation (as assessed by acetylene reduction) on a whole-plant basis compared favourably with other legumes (lucerne, birdsfoot trefoil and soybeans) because of the relatively high weight of nodules per plant. Plants dependent on fixation allocated a greater proportion of growth to roots and nodules than those receiving nitrate. Studies in Texas (Bolger, 1989) indicated that %Ndfa was similar to that in lucerne when both were adequately supplied with water but fixation in sainfoin was more sensitive to moisture stress. Percentage Ndfa across a range of irrigation rates was 0-72% for sainfoin and 35-85% for lucerne. Acetylene reduction measurements by Krall & Delaney (1982) indicated that sainfoin was 35-75% more effective at fixing N than lucerne. Poor growth of sainfoin was due more to disease than an inability to fix sufficient N. Nitrogen-fixation was proportional to forage yield (Krall 1980). In contrast, Falk (1982), using a ^{15}N method, concluded that sainfoin fixed less N than either lucerne or red clover.

3.1.8. Common vetch (Vicia sativa)

Vicia sativa is also known as spring vetch or tares. Vetches are annual legumes used as a 3-6 month fertility builder that can be sown from spring to autumn. They grow on most soils from light to medium clays. Later sowings of winter-hardy varieties will overwinter and provide early spring growth. The crop is normally ploughed in just before flowering.

Fixation by common vetch sown in autumn as a green manure after barley was about 40 and 90 kg N/ha in the two years of a trial reported by Mueller & Thorup-Kristensen (2001).

Table 3.9. Estimates of the quantity of N fixed by winter vetch.

Fixation (kg N/ha/year)	Comments	Reference
145-208	Various studies	Nutman (1976); Sprent & Bradford (1977)
40 & 90	Green manure; Denmark	Mueller & Thorup-Kristensen (2001)

Although conditions would have been very different from those in the UK, a study of vetch grown as a winter legume in Greece provides information about the distribution of N between above- and below-ground parts of the plant. Immediately before harvest, the total N in roots was 1.3-1.6 times higher than in the above-ground parts of the crop; 54-109 kg N/ha compared with 73-173 kg/ha, depending on the method of cultivation for establishment (Sidiras *et al.* 1999). In Cyprus, vetch grown alone fixed 93-106 kg/ha; when grown with oats, fixation was reduced to 32-61 kg/ha. Percentage Ndfa was 74% for vetch alone and 63-82 % for the vetch/oat mixture (Papastylianou, 1988).

3.1.9. Winter or hairy vetch (Vicia villosa)

Some references to fodder vetch appear to relate to this species, though possibly also to *V.sativa*. *V. villosa* is commonly known as hairy vetch, particularly in America. When grown as a green manure and with winter rye, hairy vetch was the most effective of a range of green manures examined by Willumsen & Thorup-Kristensen (2001). Hairy vetch fixed up to 149 kg N/ha in the above ground plant material but only 80 kg/ha in the previous year when the weather in autumn was less favourable for sowing (Mueller & Thorup-Kristensen, 2001). Information about N-fixation by hairy vetch under North American conditions includes a study by Sullivan *et al.* (1991) in the Appalachians. The legume accumulated 113-128 kg N/ha or 164-169 kg/ha when allowed a longer growth period. Hairy vetch grown as a cover crop in Georgia contained 75 to 80 kg N/ha when the crop was killed in the spring (Nesmith & McCracken, 1994). Ebelhar *et al.* (1984) estimated that the supply of fixed-N from vetch to maize in Kentucky was equivalent to 90-100 kg fertiliser-N/ha annually. Similarly, the N supply to rye in Oklahoma was estimated to be equivalent to 34 and 64 kg fertiliser-N/ha from noninoculated and inoculated crops, respectively (Lynd & McNew, 1983).

Other vetches with potential agricultural use, but for which there are few N-fixation data, include summer vetch or goar (*Vicia lathyroides*), Narbonne vetch (*Vicia narbonensis* L.) and kidney vetch (*Anthyllis vulneraria*). Narbonne vetch is similar to narrow-leaved vetch (*V. angustifolia*). Some crops described as hairy vetch appear to refer to V*icia hirsuta* rather than *V. villosa.* Chickling vetch or grass pea (*Lathyrus sativus* L.) and vetchling (*L. cicera*) are grown as green manures. The related fodder pea (*Lathyrus annuus*) may also be grown. In Canada, chickling vetch, grown for 6-7 weeks as a green manure, fixed 49 kg N/ha (Biederbeck *et al*., 1996).

3.1.10. Field (threshing) peas (Pisum sativum)

Combining peas are grown less frequently than beans because of concerns about lodging and weeds. The crop is generally sown in spring and harvested in August in favourable areas but pea is not well developed as a winter crop in the UK (Taylor & Cormack, 2002). Peas are also grown as a mixed silage crop with a cereal, which provides additional support to the legume and helps reduce lodging. Although it has a relatively short growing season, pea nodulates rapidly and soon begins to fix N (Sprent & Mannetje, 1996).

Table 3.10. Estimates of the quantity of N fixed by field pea.

Fixation (kg N/ha/year)	Comments	Reference
70 (52-77)	Various studies	Royal Society (1983)
105-245	Various studies	Lampkin (1990)
215-246	Germany (whole-plant?)	Maidl *et al.* (1996)
144	Denmark (whole-plant?)	Jensen (1987a)
129-136	Denmark (above ground) - different cultivation practices ± straw	Jensen (1998)
144 (54-165)	Australia (in above-ground plant)	Unkovich *et al.* (1995)
121-175 181-262	Australia (above-ground) (whole plant)	McCallum *et al.* (1999)
161 (123-205)	Australia: winter crop following cotton (including roots)	Rochester *et al.* (1998)
286	Australia (above-ground?)	Kumar & Goh (2000)
40	Canada (as green manure) (acetylene reduction)	Townley-Smith *et al.* (1993)
40 (29-52)	Canada (6-7 weeks growth as green manure)	Biederbeck *et al.* (1996)
Up to 121	Alaska	Sparrow *et al.* (1995)

When grown as forage in Northern Ireland without N fertiliser, either alone or with oats, peas yielded 7.49 and 6.65 t/ha, depending on variety. Crude protein contents at cutting were 151 and 164 g/kg dry matter, respectively. Assuming a protein factor of 6.25, these values are equivalent to total N yields of about 190 and 170 kg N/ha. Unlike beans, mixtures of peas with cereals yielded as much (or more) than peas alone. This was because of reduced lodging where the cereal was present. Where lodging was severe, lower leaves were decomposing by the time of harvest. Dry matter yields from trials in Scotland and England were mainly in the range 5.5-8.5 t/ha (Faulkner, 1985).

In trials in Germany, N-fixation by peas ranged from 215 to 246 kg N/ha. In all seasons the calculated N-balance where only grain was removed was positive, with a net gain being on average 106 kg N/ha. Averaged over a number of seasons, 202 kg N/ha remained on the field after harvest; comprised of 158 kg N/ha in the above-ground biomass and 44 kg N/ha as nitrate-N in the 0-90 cm soil depth (Maidl *et al.,* 1996). A winter pea crop in Germany had fixed 242 kg N/ha by maturity; 88% of this was fixed by the end of anthesis in mid-June (Karpenstein-Machan & Stuelpnagel, 2000).

In another German trial, peas were grown in two long-term differentiated tillage systems, comparing a continuous conventional tillage system (ploughing) and a continuous minimum tillage system (rotary harrow). Although total N accumulation was equal in both tillage systems, there was a significantly higher %Ndfa in the minimum tillage system at maturity of the crop. Values in Year 1 were 62 and 42% for the minimum and conventional tillage systems, respectively and 75 and 54% in Year 2 (Reiter *et al.,* 2001 & 2002). The difference was attributed to the greater mineralisation and supply of mineral-N in the ploughed soil.

In a Danish study, %Ndfa for peas grown alone increased from 40% to 80% during the growth period, whereas it was almost constant at 85% for pea intercropped with barley. The total amounts of N fixed were 95 and 15 kg N/ha in sole cropped and intercropped pea, respectively (Hauggaard-Nielsen *et al*., 2001b). Where the crop contained a high proportion of weeds, the weeds competed for soil-N and %Ndfa was between 90 and 95% for both peas alone and pea/barley intercrops (Hauggaard-Nielsen *et al*., 2001a). In a study in Cyprus, pea grown as a pure stand fixed 23-91 kg N/ha, compared with 10-46 kg N/ha when grown as a mixture with oats. Percentage Ndfa was 36-64% for pea alone and 58-70% for the mixture (Papastylianou, 1988).

Table 3.11. Estimates of the proportion of N derived from the atmosphere (%Ndfa) by field peas.

%Ndfa	Comments	Reference
42-75	Germany	Reiter *et al.* (2002)
90-95	Denmark (above-ground)	Hauggaard-Nielsen *et al.* (2001a)
40-80	Denmark - peas alone	Hauggaard-Nielsen *et al.* (2001b)
85	- pea/barley intercropping	
66 -71	Denmark - estimate for 0 N fertiliser treatment	Jensen (1986a)
77-87	Denmark; different cultivation practices ± straw	Jensen (1998)
<40	New Zealand Spring-sown crop	Haynes *et al.* (1993)
75 (74-85)	Australia: winter crop following cotton (including roots)	Rochester *et al.* (1998)
74 (60-91)	Australia (above-ground)	Unkovich *et al.* (1995)
69	Australia (above-ground)	Kumar & Goh (2000)
52 (39-77)	Canada (6-7 weeks growth as green manure)	Biederbeck *et al.* (1996)
35	At maturity, Alberta, Canada	Kucey (1989)
36-64	Cyprus - peas alone	Papastylianou (1988)
58-70	- pea/oat mixture	
24	Canada (as green manure) (acetylene reduction)	Townley-Smith *et al.* (1993)

Australian data on fixation by grain legume has been reviewed by Evans *et al.* (2001). In field experiments in Southeast Australia, pea accumulated more total N (427 kg N/ ha) than white clover (387 kg/ha). However, %Ndfa at final harvest was lower for pea (69%) than for clover

(90%), so that pea fixed only 286 kg N/ha compared with 327 kg/ha by clover (Kumar & Goh, 2000).

Biederbeck *et al.* (1993 & 1996) examined the use of peas as a short-term green manure in dryland cereal production systems in Canada. During the 6-7 week growth period from emergence to full bloom, apparent N-fixation was 40 kg N/ha (range 29-52 kg/ha) and %Ndfa 52% (range 39-77%). At the time of incorporation, shoots contained 62 kg N/ha or 70 kg/ha when roots and nodules were included. Nodulation was greatly influenced by soil mineral-N and moisture status. An Australian study also provided information about the proportion of N in pea roots; N in nodulated roots comprised 12% of total plant N at peak crop biomass and 25% of the recoverable plant N after harvest of the seed (Armstrong *et al.,* 1994).

Pea genotypes differ in the proportion of N obtained by fixation. Armstrong *et al.* (1994) studied six contrasting pea genotypes at three sites in Southwestern Australia. There were considerable variations between genotypes and sites due to differences in the proportional dependence on fixation; ranging from 60 to 91% across all sites and genotypes. The residual value of the pea crop after harvest was further influenced by variation in the harvest index for N, which ranged from 53 to 90%. In another study, Jensen (1986a) estimated that by maturity, unfertilised crops of two pea cultivars had fixed 171 and 195 kg/ha; the %Ndfa was 66 and 71%, respectively.

Fodder peas or grey peas (*Pisum arvense*) are also grown but there is much less information about how much N is fixed by this species. However, Korsaeth & Eltun (2000) describe a model for estimating N-fixation by various legumes in Norway, which includes parameters for calculating fixation by this crop (Section 5.2).

Peas (and beans) tend to be grown as a fertility boost, part way through the arable phase of a rotation. N fixation varies, partly depending on the amount of soil mineral N present. Generally, the proportion of the crop's N derived from fixation is smaller than from red or white clover. A large proportion of the fixed N is removed from the field in harvested seed, though the haulm, roots and rhizodeposits usually provide a positive N balance in the soil.

3.1.11. Field beans (Vicia faba)

Field bean (faba bean or broad bean) is the major grain legume in northern Europe. It may be autumn or spring sown but slow emergence and low seedling density increase the risk of weed problems. Winter beans are harvested from early to mid-August but this may be delayed to mid- or late October further north: the late harvest date makes beans an unsuitable crop for Scotland. Yields of winter beans may exceed those of spring beans in the south but are less likely to do so in the north. Winter beans have little advantage over spring beans in organic situations as they provide little winter ground cover against erosion, weeds or nutrient loss (Taylor & Cormack, 2002). Broad beans are mainly grown for stock feed as a protein supplement but may also be grown for culinary use.

Robson *et al.* (2002) reviewed the use of field beans as a break crop for organic agriculture and concluded that fixation was between 170 and >330 kg N/ha. Percentage Ndfa ranged from 87% in unfertilised soils to about 42% where N fertiliser had been applied.

Table 3.12. Estimates of the quantity of N fixed by field beans.

Fixation (kg N/ha/year)	**Comments**	**Reference**
250-303	44 plants/m^2	Nutman (1976)
93-106	6 plants/m^2	Sprent & Bradford (1977)
150	Broad bean	Royal Society (1983)
200	- beans for stockfeed	
150-390	Adapted from Kahnt (1983)	Lampkin (1990)
200	Various	van Kessel & Hartley (2000)
	Denmark:	Jensen (1986a)
150-211 (188)	- with 50 kg fertiliser N/ha	
220	- estimate for zero-N	
200-360	Germany; above-ground	Kilian *et al.* (2001)
165-240	Germany	Maidl *et al.* (1996)
170-320	Germany	Hartmann & Aldag (1989)
50	Alaska; intercropped with oats	Cochran & Schlentner (1995)
Up to 204	Alaska	Sparrow *et al.*(1995)
41	Canada; green manure	Townley-Smith *et al.* (1993)
91	Alberta, Canada	Kucey (1989)
8-352 (177)	Australia; winter crop following cotton (including roots)	Rochester *et al.* (1998)
209-275	Australia; whole-plant, includes N fertiliser treatments	Turpin *et al.* (2002)

Table 3.13. Estimates of the proportion of N derived from the atmosphere (%Ndfa) by field beans.

%Ndfa	**Comments**	**Reference**
70	Denmark; zero fertiliser N	Jensen (1986a)
78-88 (83)	Germany	Hartmann & Aldag (1989)
69-80	Germany	Kilian *et al.* (2001)
69-88	Australia; whole-plant, includes N fertiliser treatments	Turpin *et al.* (2002)
69	Alberta	Kucey (1989)
34	Canada; as green manure	Townley-Smith *et al.* (1993)
13-96 (74)	Australia; winter crop following cotton	Rochester *et al.* (1998)
< 40	New Zealand; spring-sown crop	Haynes *et al.* (1993)

Reported values for the net contribution to soil N after removal of the grain varied considerably, in some cases being negative and in others, adding 45-50 kg N/ha. Less of the N is removed if the crop is harvested while still green (Sprent & Mannetje, 1996). The crop has a long growing season and therefore has the potential to fix large amounts of N. Estimates of the quantities of N that can be fixed by field beans and the proportion of N obtained through fixation are summarised in Tables 3.12 and 3.13.

Differences in N-fixation by different faba bean cultivars were examined in a study in Germany. Based on the above-ground crop, fixation by the different cultivars varied from 200 to 360 kg N/ha and %Ndfa from 69 to 80%. Nitrogen-fixation was affected more by differences in %Ndfa than by differences in total N accumulation. The best cultivars left about 100 kg N/ha in residual material on the field after harvest (Kilian *et al*., 2001). In another study, N-fixation by faba beans ranged from 165 to 240 kg N/ha. In all seasons, the calculated N-balance where only grain was removed was positive, with an average net gain of 84 kg N/ha. After harvest, faba beans left less N than peas because of smaller amounts of N in the straw: total residual N was 161 kg/ha compared with 202 kg/ha for peas (Maidl *et al.,* 1996). Residues of faba bean and white lupin crops contained up to 80 kg N/ha in a trial in Germany (Kaul *et al.,* 1996).

Faba bean grown on a low-nitrate soil in Australia with fertiliser rates of 0, 50, and 100 kg N/ha fixed 209-275 kg/ha in the whole plant including roots. Corresponding %Ndfa values were 69-88%. Soil N balances between N fixed and the output in grain, were positive with a range 79-157 kg N/ha (Turpin *et al*., 2002).

3.1.12. Common or French bean (Phaseolus vulgaris L.)

This is an important food crop in Europe, America, Africa and Asia. Varieties are also commonly known as pinto, kidney, dwarf, green, black, white or brown beans. The crop is frequently reported as only fixing small amounts of atmospheric N. In part, this may be due to the short growing season of modern cultivars (Sprent & Mannetje, 1996). Some studies have concluded that with choice of suitable cultivars, effective rhizobia and favourable growing conditions, satisfactory fixation and production can be achieved (Bliss, 1993; Popescu 1998; Santalla *et al.,* 2001). However, other studies have concluded that there is little immediate potential for crop improvement (Kipenolt & Giller, 1993; Redden & Herridge, 1999).

In Britain the crop usually responds to N fertiliser indicating that strains of *Rhizobium phaseoli* are either absent or ineffective (Taylor *et al.,* 1983). In spite of the apparent lack of effective rhizobia, crops are not normally inoculated in the UK. When inoculated with *R. phaseoli*, there were significant increases in nodulation, nitrogenase activity and plant growth. Benefits of inoculation were equivalent to fertiliser applications of 70-105 kg N/ha. In contrast, Griffin & Andrews (2001) found that yields in northern England were not significantly increased by addition of N fertiliser at 50 or 100 kg N/ha or by inoculation.

In a study by Kipenolt & Giller (1993) in Latin America, the amount of N fixed by different cultivars ranged from 18 to 36 kg N/ha (32 to 47% of plant N) in 56 days. Total shoot N ranged from 53 to 77 kg/ha and partitioning of N to pods differed from 28 to 52%. Nodulation patterns were also distinct. The smallest amounts of fixation were observed in those lines which nodulated slowly and did not form substantial nodule mass until after 40 days.

Other bean crops may include black bean (*Castanospernum australe*) but there is little information about N-fixation by this species.

Table 3.14. Estimates of the quantity of N fixed by common bean.

Fixation (kg N/ha/year)	Comments	Reference
40-125	Alberta, Canada; at maturity (excluding roots); crop received 10 kg fertiliser N/ha	Rennie & Kemp (1983)
40	Various studies	Royal Society (1983)
18-36	S. America: 56 days growth	Kipenolt & Giller (1993)

Table 3.15. Estimates of the proportion of N derived from fixation (%Ndfa) in common beans.

%Ndfa	Comments	Reference
36-68 (52)	Alberta, Canada; 10 kg fertiliser N/ha	Rennie & Kemp (1983)
32-47	S. America: 56 days growth	Kipenolt & Giller (1993)

3.1.13. Soybean (Glycine max)

Soybean is usually grown for its seed but may also be grown as a green manure (Robson *et al*., 2002). It originated as a subtropical legume and infection and/or early nodule development are sensitive to low root temperatures (Zhang *et al.,* 1995). Lampkin (1990) reported that the N fixing ability of soybean is less than for field beans (which, themselves, appear to be relatively ineffective). Tables 3.16 and 3.17 include some values for European countries but most data are derived from other parts of the world. In their review of break crops for organic agriculture, Robson *et al*. (2002) concluded that though soybean can derive up to 40% of its N from fixation, it is sensitive to soil N status and %Ndfa can fall to 25% or less on heavily fertilised soil. Crops grown for seed were reported to leave 30-60 kg N/ha for following crops.

Table 3.16. Estimates of the quantity of N fixed by soybean.

Fixation (kg N/ha/year)	Comments	Reference
50-110 (80)	Germany	Hartmann & Aldag (1989)
102	Austria; (tops) at physiological maturity	Zapata *et al.* (1987)
	Canada:	Johnson & Hume (1972)
8	- untreated soil	
57	- soil + ground maize cobs	
66-131	India: various FYM treatments	Kundu *et al.* (1996)

Table 3.17. Estimates of the proportion of N derived from fixation (%Ndfa) in soybean.

%Ndfa	Comments	Reference
53-75 (64)	Germany	Hartmann & Aldag (1989)
 up to 40 up to 25	Various studies - unfertilised soil - heavily fertilised soil	Robson *et al*. (2002)
47	Austria; (tops) at physiological maturity	Zapata *et al*. (1987)
84	Sand culture with low nitrate	Wanek & Arndt (2002)
53	Japan: various FYM treatments	Ishii (1980)
54-69	India: various FYM treatments	Kundu *et al*. (1996)

Net benefits of soybeans to following crops are generally small because of the removal of N in harvested grain.

In Austria, 102 kg N/ha was fixed and 114 kg N/ha removed in pods. Assuming that the contribution from roots was small and that 60 kg N/ha was returned in straw, there would have been a net depletion of 54 kg/ha (Zapata *et al*., 1987). Though less relevant to UK conditions, the potential contribution of fixation to the soil N balance in an Indian study was also negative (-56 to -90 kg N/ha) in spite of fixation of between 66 and 131 kg N/ha (Kundu *et al.,* 1996). The negative balance would have been reduced by 12-36 kg N/ha if the crop residues had been returned to the soil.

3.1.14. Lupins

Lupins are a minor crop in the UK. There are three main species in agricultural use: white-flowering lupin (*Lupinus alba*), yellow-flowering or sweet lupin (*L. luteus*) and narrow-leafed or blue lupin (*L. angustifolius*). White and narrow-leafed lupins are mainly harvested as grain crops. Yellow lupin, about which there is less information, is usually grown as a green manure.

White lupin (Lupinus alba) previously produced very late harvests in the UK but earlier maturing varieties are now available. These include autumn and spring varieties. Lupins prefer more acid soils than peas or beans (<pH 6). Seed should be inoculated with *Bradyrhizobium* spp. Trials in southern Britain indicated that harvest dates for autumn varieties were later than for spring types but autumn varieties were higher yielding (Taylor & Cormack, 2002). Robson *et al*. (2002) reported that the crop has a high requirement for P and K, which could be a limiting factor in some soils under organic management. Fixation was reported to be between 150 and 350 kg N/ha and %Ndfa up to 79%. The net contribution to the soil was between 7 and 113 kg N/ha, depending on genotype, planting date and sowing rate.

Although white lupin has a higher grain and protein yield than either field beans or soybeans, the crop can also make a useful contribution of fixed N to following crops. In a trial at different sites in Germany, removal in seed was always less than N fixed except for one site where fixation and yield were both very low. Up to 80 kg N/ha was made available to the following crop (Hartmann & Aldag, 1989).

White lupin grown with irrigation but without N fertiliser under a Mediterranean climate in California, contained from 147 to 247 kg fixed N/ha (mean 201 kg/ha) in the above-ground plant parts (Larson *et al.,* 1989). In this case, total grain N exceeded N-fixation by 23-68 kg/ha. However, if allowance is made for roots, total fixation in inoculated plants approximately balanced the export in grain. Under similar growing conditions, %Ndfa was reported to be between 67 and 78% (Farrington *et al.,* 1977). Nitrogen in nodulated roots and leaf litter represented <10% of total crop N at maturity. Residues of faba bean and white lupin crops contained up to 80 kg N/ha in a trial in Germany (Kaul *et al.,* 1996).

Narrow-leafed lupin (L. angustifolius), also known as blue lupin, bitter lupin or narrow-leafed lupin can be grown under UK conditions though most of the information about the quantities of N fixed comes from Australia.

Table 3.18. Estimates of the quantity of N fixed by white lupin.

Fixation (kg N/ha/year)	**Comments**	**Reference**
145-208	Various Lupin spp.	Nutman (1976) Sprent & Bradford (1977)
100-150	Various Lupin spp.; adapted from Kahnt (1983)	Lampkin (1990)
240-360	Germany	Hartmann & Aldag (1989)
147-247 (201)	California; (above ground) Mediterranean climate + irrigation, no fertiliser N	Farrington *et al.* (1977)
Up to 162	Alaska	Sparrow *et al*. (1995)

Table 3.19. Estimates of the quantity of N fixed by narrow-leafed lupin.

Fixation (kg N/ha/year)	**Comments**	**Reference**
90-151	Western Australia: wheat/lupin rotation	Anderson *et al*. (1998)
95-283 (177)	SW Australia; (above-ground)	Unkovich *et al*. (1995)
102-225	New South Wales, Australia; cereal rotation	Herridge & Doyle (1989)
177 (uninoculated) 213 (inoculated)	Iceland; + 30 kg fertiliser N/ha	Palmason *et al.* (1992)
174-177 (including roots)	Australia: winter crop following cotton	Rochester *et al*. (1998)

Table 3.20. Estimates of the proportion of N derived from fixation (%Ndfa) in narrow-leafed lupin.

%Ndfa	**Comments**	**Reference**
74-93 (82)	SW Australia; (above-ground)	Unkovich *et al*. (1995)
<40	Australia	Haynes *et al*. (1993)
65-100	New South Wales, Australia; cereal rotation	Herridge & Doyle (1989)
91-93	Iceland; + 30 kg fertiliser N/ha	Palmason *et al*. (1992)
71-77	Australia	Chalk *et al*. (1996)
69-72 (including roots)	Australia: winter crop following cotton	Rochester *et al*. (1998)

Evans *et al*. (2001) reviewed Australian data on the contribution of N-fixation from lupin and concluded that the net effect on the soil N balance, i.e. the difference between fixed-N and N harvested in grain ranged from -29 to +247 kg N/ha (mean 80 kg/ha). The net supply was related to the amount and proportion of crop N derived from fixation but not to grain yield. The average net N input from lupin crops increased from 61 to 79 kg N/ha with increasing annual rainfall from 445 to 627 mm across south-east Australia. Herridge & Doyle (1989) estimated that lupin in a cereal rotation in New South Wales provided 30-140 kg fixed N/ha after grain removal. In a study where lupin was grown after cultivation of a 5+ year-old grass pasture, and therefore with a high available soil-N content, %Ndfa increased from 0 at 50 days after sowing to 41-60% at 68 days and to 76-79% for 155-190 days after sowing, depending on the choice of reference crop. The final N content of the crop was 300-320 kg/ha, equivalent to fixation of about 240 kg N/ha (Smith *et al.,* 1992). Evans *et al*. (1987) measured N-fixation equivalent to 78-255 kg N/ha and %Ndfa between 49 and 85%. After allowing for removal of fixed-N in harvested seed, the potential net contribution to the soil varied between 34 and 138 kg N/ha.

Percentage Ndfa values for lupin monocultures grown in Iceland with fertiliser supplying 30 kg N/ha were 91 and 93% for uninoculated and inoculated crops, respectively. When grown as a mixture with oats or ryegrass the range was 96-97%. Results indicated that lupin had a high potential for N-fixation at low temperatures (average temperature < 10°C) (Palmason *et al.* 1992).

3.1.15. Birdsfoot trefoil (Lotus corniculatus L.) and Large birdsfoot trefoil (Lotus pedunculatus Schk./L. uliginosus)

Greater or large birdsfoot trefoil (*L. pedunculatus*) is a native to northern Europe and Britain and is considered to be a parent of the agriculturally more important birdsfoot trefoil (*L. corniculatus*). *Lotus pedunculatus*, unlike *L. corniculatus*, is very tolerant of flooding and thrives in poorly drained soils. Both species are grown as forage or as green manures. There is little information about these crops grown under UK conditions.

In a study in America, N-fixation and transfer were measured in birdsfoot trefoil/orchardgrass mixtures, including (Farnham & George, 1994a). Three trefoil cultivars and one experimental line were examined. During the 2-year study, %Ndfa ranged from 93 to 95% among the cultivars and total-season yields of fixed-N ranged from 90 to 138 kg/ha. The percentage of grass N derived from fixation and N transfer ranged from 8 to 46% (4 to 42 kg/ha). Under the conditions of this study, the birdsfoot trefoil cultivars differed little in their abilities to fix atmospheric N or to transfer fixed N to the associated grass. Also in America, birdsfoot trefoil grown for hay fixed similar amounts of N to a pure red clover stand: 49-112 kg N/ha (average 92 kg/ha) (Heichel *et al.*, 1985). Percentage Ndfa was between 30 and 85% (average 55%). This was lower than for red clover in three out of the four years. As the root and crown represented 10% or less of the total plant dry matter and also had only 0.5-0.6 of the N concentration of the tops, trefoil was considered to contribute little to the following crop unless the tops were ploughed in.

In an experiment under low-P conditions in New Zealand, *L. pedunculatus* was found to fix more N than white clover grown under similar conditions (Easton, 1976).

3.1.16. Lentil (Lens culinaris Medik.)

Potential yields, N inputs and management of lentil in the UK have been described by Joyce *et al.* (2001a & b). It is an important crop in the semi-arid wheat areas of Canada and the western United States and it is from here that most information about its N-fixation properties originates. For example, inoculated lentil grown in a sandy-loam soil at an irrigated site in Canada had fixed 129 kg N/ha by the time of final harvest. Percentage Ndfa ranged from zero at the first harvest to 92% at the final harvest. The crop provided a net N contribution to the soil of 59 kg N/ha following the removal of the grain (van Kessel, 1994). Lentil is also grown in this region as a short-term green manure and the suitability of a number of legumes, including inoculated lentil, was tested in a trial by Biederbeck *et al.* (1993 & 1996). With a short, 6-7 week, growth period, lentil only fixed 18 kg N/ha (range 13-26 kg/ha). Under these conditions, %Ndfa averaged 36% (range 16-63%). On average, shoots contained a total of 40 kg N/ha at incorporation. This was increased to 45 kg/ha when roots and nodules were included. In this semi-arid climate, nodulation was greatly influenced by soil mineral-N and soil water. At a site in Saskatchewan, Cowell *et al.* (1989) measured %Ndfa values of 77% for a lentil monocrop grown with 10 kg fertiliser-N/ha and 75% when intercropped with flax. In another study in Canada, lentil grown as a green manure achieved a total N yield of 108 kg/ha but fixation (as measured by acetylene reduction) accounted for only 15 kg/ha of this total (Townley-Smith *et al.*, 1993). Lentil fixed up to 72 kg N/ha in a trial in subarctic Alaska, compared with up to 121 kg/ha by red clover (Sparrow *et al.*, 1995).

In Australia, lentil grown as a winter crop following cotton, fixed 169 kg N/ha; %Ndfa was 61% (Rochester *et al.*, 1998).

3.1.17. Galega (Galega orientalis)

The perennial legume *Galega orientalis* originates from the Mediterranean region and has been grown as a cover crop in a number of European countries. Galega grown in a mixture with *Phleum pratense* in Finland persisted well and its yields equalled or exceeded those of red clover (Varis, 1986). The crop required inoculation as its compatible Rhizobium strain did not occur in Finnish soils. At trial sites in the UK, testing various legume/grass mixtures, the N yield for galega was only slightly less than for red clover (Table 3.8) (Halling *et al.*, 2002). In Estonia, galega was been found to be very persistent. When harvested twice during the year, it yielded 8.5-10.5 t dry matter/ha with a crude protein yield of 1.7-1.8 t/ha (Nommsalu & Meripold, 1996). This is equivalent to about 280 kg N/ha in the harvested crop.

3.1.18. Fenugreek (Trigonella foenum graecum)

Fenugreek is an annual legume. It is mainly grown for its seed, for use in curry powders and pharmaceuticals, but it is also grown as a green manure and as a forage crop. Hardman (1981) stated that fenugreek could fix 283 kg N/ha. In trials in Australia, four fenugreek accessions were compared with pea, faba bean, lentil, vetch and medic (McCormick *et al.*, 2001)). Fenugreek yields were 1.4 to 1.7 t/ha, with crops fixing up to 19.4 kg N per tonne dry matter. This is equivalent to only about 30 kg N/ha. Benefits to a following wheat were similar to those for the other legumes. In France, field-grown fenugreek fixed 48% of its total N content during the growing season (Desperrier *et al.*, 1986).

3.2. Factors affecting N accumulation

Factors determining the level of N-fixation in legumes have been reviewed by Buttery *et al.* (1992), Schubert (1995) and Hartwig & Soussana (2001) and specifically in grass/legume pastures by Ledgard & Steele (1992).

Factors that limit plant growth normally also limit fixation, either through direct effects on nodule formation or function or indirectly through the host plant's ability to supply nutrients. However, some forms of stress (e.g. excess soil water, drought, cold or heat) have a greater effect on nodule function than on nitrate uptake so that plants relying on fixation may be more severely affected than plants supplied with fertiliser-N. In these situations, improvements in general growing conditions would be expected to benefit N-fixing plants more than those relying on fertiliser. Fixation can also be affected by soil structure and by disease. Where inoculation is used to introduce more effective rhizobia, the response will be influenced by the effectiveness of the native rhizobia and their competitive ability. Effectiveness can also be reduced, e.g. in soybean, where there is a temporal separation between maximum nitrate assimilation and N-fixation activity.

Buttery *et al.* (1992) considered the negative relationship between plant-available soil N and the proportion of plant N obtained by fixation to be the single most important limitation to N-fixation.

3.2.1. Climate and season

Differences in climate will be greatest when comparing data from overseas studies with expectations for UK conditions but climatic variations between different regions of the UK are also sufficient to affect the quantities of N fixed. For example, Sanders *et al.* (2000) attributed the relatively low quantities of N fixed in grass/clover leys near Aberdeen to the short growing season in Scotland. Differences between years can also have marked effects on the quantities fixed. In grass/clover plots in Denmark, low summer temperatures reduced growth rates and the proportion of clover; N-fixation was reduced to 59 kg/ha compared with 125 kg/ha in a more typical year (Hansen & Vinther, 2001). Cowling (1982) considered that the variation in N-fixation in a grass/white clover sward, from 74 to 280 kg N/ha/year over a 6-year period, was mainly due to the sensitivity of clover growth to the availability of soil water.

Regional differences and year-to-year fluctuations in weather patterns will influence legume growth and fixation activity through effects of temperature, moisture supply and radiation.

Nitrogen deficiencies in grass-legume pastures during spring (Stout & Weaver, 2001) and seasonal patterns of N-fixation such as those observed in the understorey of apple orchards in New Zealand (Goh & Ridgen 1997; Goh *et al.* 2001) can be largely explained in terms of temperature and moisture supply. In other cases, changes in nitrogenase activity are more likely to be due to changes in the physiological growth stage of the crop, for example the onset of flowering or seed formation (Warembourg *et al.,* 1997).

Drought

Fixation is very sensitive to moisture stress with drought severely inhibiting both nitrogenase activity and nodulation (Ledgard & Steele, 1992). However, it is unclear whether the reduction in fixation activity is due to plants favouring soil mineral-N over fixation in drought conditions or whether this reflects a lower N demand in stressed plants (Hartwig & Soussana, 2001). Schubert (1995) proposed that drought (and other environmental constraints) regulate fixation by a feedback mechanism, which is triggered by disturbed plant growth and accumulation of reduced N within the plant. Engin & Sprent (1973) examined the effect of drought on N-fixation in white clover. The initial effect of water stress was to reduce nodule efficiency though longer periods of stress also reduced nodule growth. Fixation (acetylene reduction) was halved within two days in plants without water and fell to very low levels after 12 days. On rewetting, plants that had been stressed for two days were able to recover almost full activity but recovery took longer in plants that had been subjected to longer periods of stress. Clover was considered to recover from drought more rapidly than soybean.

Low & Armitage (1959) also found the growth of white clover to be sensitive to the supply of available soil water. Ledgard *et al.* (1987) measured a decrease in %Ndfa from 85 to 70% during dry summer conditions in grass/clover pasture in New Zealand. Also in New Zealand, Crouchley (1979) measured fixation of 90 kg N/ha in grass/clover pasture during a year with a dry summer, compared with 240 kg/ha when the summer was wet. Under conditions simulating mild drought, fixation by subterranean clover ceased after 5-6 weeks due to desiccation of the nodules (Davey & Simpson, 1989). However, plants compensated by developing more nodules on roots in the moister subsoil. Results of a study of N-fixation by grain legumes in Portugal demonstrated the effect of drought on beans and peas (Carranca *et al.,* 1999). Faba bean fixed 76-125 kg N/ha in the first year of the study when there was regular rainfall, compared with 55-72 kg/ha in the second year under drought conditions. With peas, fixation was reduced from 31-107 to 4-37 kg/ha in the drier year.

Deeper-rooting perennials such as lucerne and red clover are less affected by drought than white clover and other shallow-rooting legumes. In SW Australia, perennial pastures containing lucerne provided consistently greater annual herbage production, had more stable legume contents and fixed 90-150% more N than neighbouring subterranean clover-based pastures (Bowman *et al*., 2002). Even during a drought year when annual pastures failed, lucerne still managed to fix more than 70 kg N/ha.

There are also interactions between K supply and the susceptibility of legumes to drought. In a pot experiment described by Kurdali *et al.* (2002), drought reduced %Ndfa in faba bean from 81 to 68%; however, addition of K fertiliser increased both dry matter production and total N fixed. Percentage Ndfa appeared to be unaffected by K and it appeared the beneficial effect of K on water-stressed faba bean resulted from stimulating growth of the plant rather than improving the fixation efficiency.

Although drought is generally detrimental to fixation processes, Hartwig & Soussana (2001) considered that under field conditions, N-fixing plants may still be at an advantage over those reliant on soil-N because N mineralisation and mass-flow will also be restricted in dry soils. As an example of this, they cite a study by Høgh-Jensen & Schjoerring (1997a) where the reduction in N-fixation caused by N fertiliser was less under drought conditions than where adequate water was available. In contrast, Ledgard & Steele (1992) opined that mineral-N is likely to accumulate in the soil during dry conditions. As a result, the elevated soil-N content would continue to inhibit fixation even after the soil has begun to re-wet. There may also be other, indirect, factors affecting the relative drought tolerance of N-fixing and N-fertilised plants under field conditions. For example, Lodeiro *et al.* (2000) grew common beans (*Phaseolus vulgaris*) under drought conditions, either reliant on fixation or receiving N as inorganic fertiliser. Dry weight of pods in the N-fixing plants was far less affected by drought than in the fertilised beans. This was attributed to restricted N-supply during the early development of the N-fixing plants, which led to a smaller leaf area and reduced transpiration.

Thus, fixation is affected by drought. There is still debate over the precise mechanism, whether it is physiological or that plants have greater and easier access to soil mineral N after a drought. Some species are more affected by drought than others. Deep rooting species (red clover, lucerne) are less affected.

There appears to be varietal differences between clover cultivars and their susceptibility to drought but the overall effect of these differences may be small when assessed on an annual basis (Ledgard & Steele, 1992).

Waterlogging

Most legumes are adversely affected by excess soil water. Studies by Goodlass & Smith (1979) using pea plants with their roots exposed to concentrations of ethylene similar to those likely to occur in waterlogged soils demonstrated that the nodulation and fixation processes are very sensitive to ethylene. Nodulation in pea appeared to be more sensitive than in white clover.

Data from irrigated white clover pastures in Australia demonstrate the effect of soil moisture content on fixation over the full range of conditions from saturation to drought (Mundy *et al.,* 1988). Following flood irrigation and saturation of the soil, fixation activity gradually increased as the soil moisture content declined, reaching a maximum just before the pastures became water-stressed. Activity was inversely related to volumetric water content down to the limiting moisture content, with an approximately 5-fold difference between activity immediately after flooding and at the maximum. These changes were in response to short-term fluctuations in soil moisture: however, there is evidence that white clover plants can adapt to long-term waterlogging (Pugh *et al.,* 1995). Clover plants that were flooded from germination had significantly greater shoot weights than those subjected to normal watering. Flooded plants that were drained 24 hours before measurements had substantially greater nitrogenase activity than normally watered or continually flooded plants. In contrast, there was a marked decrease in nitrogenase activity when plants that had been watered normally were flooded, suggesting a sensitivity to sudden changes in moisture conditions. This longer-term tolerance may be due to morphological adaptations in the roots and nodules of waterlogged plants. Nathanson *et al.* (1984) also demonstrated positive effects of flooding on growth, nodulation and N accumulation by soybean - a species not normally tolerant of flooding. Unlike most legumes, *Lotus uliginosus* exhibits a metabolic preference for flooding. James & Crawford (1998) demonstrated increased growth and nodulation in *L. uliginosus*, but not in *L. corniculatus*, when grown in deoxygenated water rather than aerated water.

As would be expected, root function (including fixation) is decreased by waterlogging.

Temperature

Temperature affects both the N-fixation process and growth of the host plant. Early studies demonstrated that low temperatures generally inhibit root hair infection more than nodule initiation, nodule development or N assimilation (Gibson, 1971). The effects of temperature differ between species. Zachariassen & Power (1991) grew eight legume species at soil temperatures of 10, 20 and 30^{o}C in a greenhouse experiment to determine their response to temperature. Initially large-seeded annual species such as soybean and faba bean grew fastest at all temperatures. For the first 42 days at 10 ^{o}C, white clover, crimson clover and hairy vetch also grew rapidly. At 20 and 30 ^{o}C, soybean growth was often more than double that of the other species. Growth was maximal at 10^{o}C for field pea, hairy vetch and crimson clover; at 20 ^{o}C for faba bean and white clover; and at 30 ^{o}C for soybean and sweetclover (*Melilotus alba*). Variations in N uptake and N-fixation were similar to those for yield. At 10^{o}C, total N uptake and fixation were greatest for hairy vetch and faba bean. At later sampling dates, N uptake and fixation by white clover were also relatively high. At 20^{o}C, soybean and faba bean exhibited high growth and N uptake. Field pea and crimson clover performed poorly at 20^{o}C (Power & Zachariassen, 1993).

A number of studies have demonstrated that fixation in clover is reduced at lower root temperatures. For example, N-fixation in white clover growing in solution culture increased 11-fold between root temperatures of 3 and 13^{o}C but changed little above this (up to 25^{o}C) (Macduff & Dhanoa, 1990). The measured rates were estimated to be equivalent to fixation of 8 kg N/ha at 3^{o}C rising to 97 kg/ha at 25^{o}C. Low temperatures reduce both nodule mass and nitrate reductase activity (Gordon *et al.,* 1989). The rate of shoot growth of white clover grown under controlled conditions was greatly reduced when root temperatures were lowered from 12 to 6 ^{o}C; however, the rate of stolen growth was less affected. Low root temperatures inhibited N-fixation more than NH_4 uptake. Hatch & Macduff (1991) grew white clover in flowing culture solution containing 10 mM NH_4NO_3. Total N accumulation (mineral-N + fixed-N) increased 3-fold as root temperature increased from 3 to 17^{o}C but the proportion obtained by fixation decreased with increasing temperature. At 5^{o}C, 51% was obtained by fixation, compared with 18% at 25^{o}C. The results suggested that N-fixation in the presence of a sustained low concentration of mineral-N is less sensitive to low root temperatures than either NH_4^+ or NO_3^- uptake. Lowering root temperature also increased the accumulation of vegetative storage protein in clover stolons

(Bouchart *et al.,* 1998). Low temperatures have less effect on root dry weight (Macduff & Dhanoa, 1990).

Kessler *et al.* (1990) examined the effect of above-ground as well as root temperature on fixation by white clover. Nitrogen-fixation was higher at 23°C shoot temperature (Ndfa 90% at low nitrate supply) than at 13°C (Ndfa 83%), irrespective of whether root temperature was also increased. Lower root temperature (5°C) caused a marked reduction in total N accumulation and %Ndfa. This was mainly attributed to a change in demand for fixed N by the plant with a smaller direct effect on the fixation process. Similarly in lucerne, changes of air temperature had less effect on rates of N-fixation than did changes in root temperature (Harding & Sheehy, 1980). The fixation rate was 51% greater at 15°C air temperature than at 5°C; however, raising the temperature to 25°C only increased the rate by a further 0.3%. Increasing the root temperature from 5 to 15°C resulted in a 72% increase in activity with a similar further increase when the temperature was increased to 25°C.

The effect of low temperatures on nodulation in narrow-leafed lupin has been investigated by Peltzer *et al.* (2002) who compared nodulation of *Bradyrhizobium*-inoculated plants at 25, 12 and 7°C. The lower temperatures severely inhibited nodulation and there appeared to be a critical temperature between 7 and 12°C, below which nodulation did not occur.

In a study by Rennie & Kemp (1981), different cultivars of pea bean (*Phaseolus vulgaris*) were shown to respond differently when grown at temperature ranges of 10-23 °C or 15-23 °C. One cultivar was unaffected by the low temperature regime except that initiation of fixation was delayed by 21 days. These plants compensated by producing greater nodule dry weight and 40% greater maximum acetylene-reducing activity. Growth and fixation of the other three cultivars was adversely affected by the lower temperature. This was because of lower nodule activity rather than because of lower nodule mass or numbers.

Measurements in Finland indicated that lucerne and red clover nodules remained active down to 1.5°C soil temperature/0.5°C air temperature, though activity was only 2-4% of the season maximum (Lindström, 1984). Dart & Day (1971) observed that nitrogenase activity of several temperate legumes continued down to 2°C. Common vetch (*V. sativa*) and subterranean clover were the least affected by low temperatures. There is evidence that nodules may survive even lower temperatures. Bergersen *et al.* (1963) examined the overwintering of nodules on white clover and *Trifolium ambiguum* planted at 2100 m in the Snowy Mountains in Australia. Nodules were present on plants when they were lifted in spring after the snow had melted, having persisted throughout the winter. Although the nodules were at first shrivelled, the survival of the vascular system allowed N-fixing tissues to develop more rapidly than new nodules.

Low temperatures may also modify how the presence of a competing grass influences N-fixation in grass/legume mixtures. This was investigated by growing white clover in monoculture or in different planting ratios with timothy or perennial ryegrass in growth chambers at day/night temperature regimes of either 7.5/5°C or 15/10°C (Nesheim & Boller, 1991). Competition with grass led to a marked increase in %Ndfa but the increase was much smaller at the low temperature (e.g. a 16% increase at low temperature compared with a 76% increase at the higher temperature). This was closely related to N uptake by the grass and the reduction in the amount of available nitrate. The amount of N fixed per clover plant decreased markedly with reduced temperature. Low temperature consequently accentuated competition for nitrate. The capacity of clover to compete successfully was limited by its slower growth and N accumulation.

Soybean, though grown in temperate climates, was originally a subtropical legume and as such would be expected to be particularly sensitive to low temperatures. Matthews & Hayes (1982) considered that soil temperatures during the early growth period may limit the growth of soybean in Northern Ireland. Under experimental conditions, plants failed to nodulate at 10°C root temperature but nodulation and fixation increased with increasing temperature between 15 and 25°C. Legros & Smith (1994) compared the effects of temperature (10-25°C) on fixation in soybeanwith that in lupin, a species better adapted to temperate climates. Dry matter accumulation of N-fixing soybean was more sensitive to low temperature in the root zone than plants receiving mineral-N. This was attributed to poor nodule development and low nitrogenase activity at the lower temperature. In spite of lupin's temperate origins, fixation in this species seemed as sensitive to low root zone temperature as in soybean.

The origins of the rhizobial component of the symbiosis will also influence the relationship between fixation and temperature. Prévost & Bromfield (1991) compared the effectiveness of arctic and temperate rhizobia with sainfoin at different temperatures. At 9°C, the arctic strains were generally more competitive than the temperate strains but were less competitive at the highest temperature (20°C). Shoot dry weight, nitrogenase activity and number of nodules were similarly affected, except that at 15°C the arctic strains were generally as effective as the temperate strains.

Excessively high temperatures will also inhibit fixation. For example, fixation in subterranean clover was found to be little affected by increasing the temperature from 10 to 15°C but declined above this and was approximately halved at 25°C (Gates & Silsbury, 1987). Similarly, in an earlier study, nitrogenase activity in red clover, faba bean, common vetch and barrel medic (*Medicago trunculata*) declined rapidly above 30°C, though considerable activity continued in lucerne at 37.5°C (Dart & Day, 1971). Maximum activity with the temperate species occurred between 20 and 30°C.

3.2.2. Soil type and soil properties

Whitehead (1982) investigated the growth of white clover on 21 UK soils in a pot experiment. Analysis of the clover herbage indicated that yield appeared to be reduced by a deficiency of K and/or Ca in some soils. There were significant positive correlations between yield and soil contents of clay and organic matter, water content at 100 cm tension and cation exchange capacity (CEC). Soil pH (in 0.01M $CaCl_2$) ranged from 5.1 to 7.4 but was not significantly correlated with yield. There was a two-fold variation in the amount of N fixed but fixation was only significantly correlated with CEC.

A survey of 71 sites in the dairying districts of Victoria, Australia attempted to identify the soil factors influencing N-fixation in white clover-based pastures (Riffkin *et al.,* 1999b). On light-textured soils (sandy loams), soil K, numbers of rhizobia, total soil N and density of the nematode *Pratylenchus* sp. accounted for 72% of variation in %Ndfa. On medium-textured soils (clay loams), the crude protein content of perennial ryegrass and plant-available P in the soil accounted for 30% of variation in %Ndfa. The amount of N fixed was influenced by different factors, again depending on soil texture. Soil chemical properties accounted for 31% of the variation on the medium-textured soils whereas on light-textured soils, nematode density, pasture quality, and soil chemical properties accounted for 77% of the variation. Amounts of N fixed per tonne of herbage dry matter averaged 8.2 kg/t on the light-textured soils and 7.3 kg/t on the medium-textured soils, with average %Ndfa values of 67 and 60%, respectively. Effects of soil texture on N-fixation were attributed to the different cation exchange and water-holding capacities.

As would be expected, soil factors play an important part in crop growth and subsequent N fixation. Adequate levels of nutrients and lime are required, as is good soil structure. Pests and disease can reduce fixation. A high total soil N content (and organic matter content), if it results in elevated mineralisation of N, could potentially decrease fixation.

Nutrient supply

Nutrient availability affects both the host plant and the rhizobia. Because of its less-extensive rooting system, clover is a poor competitor for nutrients in mixed pastures and inputs of the main nutrients, other than N, must be sufficient to supply the requirements of the clover under these conditions; otherwise the proportion of legume will decline. Nodule initiation, development and function have relatively high requirements for Mo, Fe, Co, Ca, B and Cu.

After N, P is usually the next-limiting nutrient in temperate soils. Phosphorus has an essential role in the legume symbiosis, either by directly affecting nodule development and function or indirectly by affecting growth and metabolism of the host plant. Potassium is reported to have a role in improving the plant's resistance to environmental stress.

In a recent review of nutritional constraints on N-fixation, O'Hara *et al.* (2001) concluded that there are situations where limited availability of P can adversely affect rhizobia growth, survival and competition. Although there was no unequivocal evidence that P concentrations commonly found in soil solutions limit growth of free-living root nodule bacteria, concentrations are much lower in the rhizosphere and may be limiting. There is also evidence of a greater requirement for P in acid media containing low concentrations of Ca. Other properties of rhizobia would indicate a relative insensitivity to P-deficiency. They have an effective transport sytem for P uptake and can also store relatively large amounts of P. As a result, P supply to bacteroids may be non-limiting, even when the host plant is deficient. *Phaseolus vulgaris*, however, appears to be an exception.

Mefti *et al.* (1998) observed that P applications increased nodulation and N-fixation in common bean. The mechanisms by which P deficiency affects N-fixation were investigated by Almeida *et al.* (2000), who grew white clover at different levels of P supply. Severe P deficiency prevented nodulation or stopped nodule growth if the deficiency occurred after the plants had formed nodules. At low P, %Ndfa decreased but specific N-fixation increased and partially compensated for poor nodulation. Poor growth or poor performance of the nodules was not due to C limitation. The highest N concentrations occurred in severely P-deficient plants, indicating that the assimilation of N exceeded the amount of N required by the plant for growth. The results indicated that nodulation and the proportion of N derived from symbiotic fixation are down-regulated by a N-feedback mechanism.

The effects of simultaneously varying P, K, lime and Mo supplies on the growth and shoot morphology of white clover at establishment were investigated by Bailey & Laidlaw (1999) in a glasshouse experiment. Phosphorus and lime applications had similar, additive effects on dry matter production. The benefit of both treatments was due to improvements in plant-available P. It was concluded that the survival of white clover in swards at establishment is critically dependent on P supply, and that one of the main benefits of liming is the resulting improvement in P availability. Phosphorus deficiency decreased stolen branch numbers in young plants but only reduced the dimensions of leaves and petioles when the deficiency became acute. It was suggested that this preferential maintenance of leaf and petiole expansion under moderate P deficiency could be an ecological adaptation to enable clover to retain favourable positions in the upper canopy and maximise its chances of survival in mixed swards.

The impact of three rates of K fertiliser (0, 75, 150 kg K_2O/ha) on nodulation, dry matter production, and N-fixation by faba bean and chickpea was evaluated under three moisture regimes in a pot experiment by Kurdali *et al.* (2002). Water stress reduced N-fixation in both species, with %Ndfa in chickpea being particularly affected. The higher level of K fertiliser increased both dry matter production and total N fixed in faba bean but had no effect on chickpea. Percent Ndfa, however, appeared to be unaffected by K fertiliser as a means of alleviating drought stress in either species. Therefore, it appears that under the experimental conditions the beneficial effect of K on water-stressed faba bean resulted from stimulating plant growth rather than improving the N-fixation efficiency. However, in well-watered plants, there is a high requirement of the symbiotic system for K to ensure optimal growth and N-fixation. The impact of fertiliser K on N-fixation was also examined with faba bean and common bean grown in silica sand under high and low water regimes; field capacity to 25% depletion and < 50% of field capacity, respectively (Sangakkara *et al.,* 1996a). In both species, 0.1 mM K was insufficient for nodulation at either moisture regime, although plants continued to grow. Supply of 0.8 or 3.0 mM K solution allowed nodules to develop and fix N. Fixation appeared to be adequate for plant growth. High K supply increased N-fixation and shoot and root growth under both water regimes. Where nodulation occurred, variations caused by either K or water supply had no effect on %Ndfa. The symbiotic system in both faba bean and common bean was less tolerant to limiting K supply than the plants themselves. However, as long as nodulation occurred, assimilation of fixed N was not selectively affected by K, unlike N assimilation from fertiliser.

These investigations also examined interactions between N-fixation, temperature and K status (Sangakkara *et al.*, 1996b), comparing an optimal 23/18°C day/night temperature regime with a 30/23°C regime. No nodulation was observed in faba beans at the higher temperature. Potassium increased nodulation and N-fixation of faba bean under optimal temperatures and at both temperatures in common bean. In contrast, specific activity of nodules and %Ndfa were not affected by K at either temperature. Potassium reduced the impact of high temperatures, especially in faba beans, by enhancing vegetative growth, nodulation and total N-fixation.

In the glasshouse study referred to above (Bailey & Laidlaw 1999), K, unlike P, had little effect on clover growth or shoot morphology. However, there was some evidence that plants suffering from acute K deficiency preferentially partitioned resources to stolons, i.e. those organs associated with exploratory growth. Molybdenum application had no effect on dry matter production or shoot morphology but did improve the N status of shoots, presumably by enhancing N-fixation.

Høgh-Jensen (2000) observed that %Ndfa remained high in white clover growing with grass under conditions of limited P and K availability. Berg & Lynd (1985) investigated effects of K-supply on growth and nodulation of Austrian winter pea (*Pisum sativum*) in Oklahoma. Available-P was also limiting in the test soil but where P and Ca fertiliser were applied, top growth, nodule weight, nodule number and nitrogenase activity all showed significant responses to K applications.

Soil pH

In their review of N-fixation in grass/clover pastures, Ledgard & Steele (1992) considered soil acidity to be a major factor influencing legume persistence. Generally, rhizobial growth and activity appear to be more sensitive to low soil pH than is the host plant (Wood *et al.,* 1984; Evans *et al*., 1987). Soil acidity may be a particular problem in upland areas (Newbould & Rangeley, 1984).

A survey of grassland soils in Northern Ireland indicated that only soils with a pH of 5.5 or above contained sufficiently large populations of effective rhizobia to maintain significant levels of N-fixation (Wood *et al.,* 1985). In addition to the harmful effects of the H^+ ion itself, effects of acidity are due to aluminium and manganese toxicity as well as to potential Ca, Mg, Mo or P deficiencies (Jarvis & Hatch, 1985; Coventry *et al.,* 1987; Schubert, 1995).

Legume species and legume/rhizobia genotypes differ in their susceptibility to low pH.

Tang & Thomson (1996) examined the effects of pH and bicarbonate on the growth and nodulation of a wide range of grain legume species grown in nutrient solution, either supplied with mineral-N or reliant on N-fixation. Shoot growth of lentil was very sensitive to low pH (<7), whereas lupins (*L. angustifolius* and *L. albus*) were sensitive to high pH (≥6). Effects of pH were similar for both N-fertilised and N-fixing plants. Other species had a broader optimal pH range when supplied with N but were generally more sensitive to low pH when reliant on N-fixation (<pH7 for *Vicia sativa*, <pH6 for *Pisum sativum* and *Vicia faba*). Nitrogen-fixation in these species appeared to be more sensitive to low pH than the host plant. Nodule numbers, nodule mass and N concentrations in shoots were lower at low pH. In the case of lentil, the results indicated that the host plant was more sensitive to low pH than the rhizobium symbiosis. For lupins, *L. albus* and *L. angustifolius*, the host plant and N-fixation appeared to be equally sensitive to pH ≥ 6. Addition of bicarbonate decreased growth, nodulation and N concentrations in shoots of most species. Schubert (1995) also reported that field bean is extremely sensitive to low pH. Although fixation activity was reduced at low pH, N concentrations in the plant were optimal, indicating that fixation was not limiting growth and that it was the host plant that was most directly affected. At early stages of development there was evidence that restricted fixation was restricting growth at low pH (due to delayed nodulation and reduced nitrogenase activity)

(Schubert *et al.,* 1990). In contrast, lupins are sensitive to alkaline conditions. The sensitivity is greatest on fine-textured soils (Tang *et al.,* 1995).

3.2.3. Soil N status

It has long been known that increased availability of mineral-N in the soil has a negative effect on N-fixation. In general, legumes will obtain less of their N requirement from the atmosphere if there is an adequate supply available from the soil. Thus, soil conditions and cropping patterns that reduce the soil-N status will tend to increase the quantity of N fixed while conditions that increase soil-N will reduce fixation.

In many cases, however, small amounts of mineral-N may be beneficial to legume growth, nodulation and subsequent N-fixation (Hartwig & Soussana, 2001). Combined-N, as nitrate, ammonium or urea, will inhibit all components of symbiotic N-fixation if present in sufficient concentrations. Waterer & Vessey (1993) stated that it is generally accepted that nitrate is particularly inhibitory to nodule growth and nitrogenase activity, though somewhat less inhibitory to the initial infection process. A number of authors have stated that N fertiliser appears to inhibit the N-fixation process itself rather than by reducing nodule mass or number (Jensen, 1987b; Biederbeck *et al.,* 1996; Høgh-Jensen & Schjoerring, 1997a). Davidson & Robson (1986a & 1986b) observed that fixation and nodule weight in clover responded within 2-3 days to changes in nitrate availability, falling on exposure to high nitrate and rising equally rapidly when nitrate was withdrawn or reduced. Nitrate supply also affects root morphology. Root biomass and rooting density in pea were found to increase with increased mineral-N availability, leading to more numerous but finer roots for N-fertilised treatments (Voisin *et al.,* 2002).

Nitrogen fertilisers also reduce N-fixation *via* their impact on the clover content of grass/clover swards. Nesheim & Oyen (1994) concluded that reduced fixation in N-fertilised red clover/timothy swards in Norway was mainly due to a decrease in the proportion of clover: The proportion of N derived from fixation was less affected by fertiliser. Similarly, Boller & Nösberger (1987) observed that application of N fertiliser lowered the proportion of red and white clover in grass/clover mixtures but had little effect on %Ndfa. However, other workers have observed a direct effect of N fertiliser on %Ndfa; e.g. Crush *et al.* (1982), Cookson *et al.* (1990), Danso *et al.* (1988). Application of 390 kg fertiliser-N/ha to sheep-grazed pasture in New Zealand reduced annual N-fixation from 111 to 47 kg N/ha compared with unfertilised pasture. The decline occurred predominantly in spring and summer. Although the decrease in spring was due largely to a decrease in clover dry matter production, the reduced fixation in summer was mainly due to a decrease in %Ndfa from 49 to 24% (Ledgard *et al.,* 1996). Percentage Ndfa values in grass/clover plots in Denmark were significantly and negatively correlated with the log-transformed values of mineral-N content in the soil and total N in grass (Hansen & Vinther, 2001).

The net effects of high levels of N fertiliser can be appreciable. For example, in a mixture of white clover, red clover and ryegrass receiving either 20 or 400 kg fertiliser-N/ha, %Ndfa was reduced to 50-64% in the high-N treatment, compared with 73-96% in the low-N treatment. The amounts of fixed-N varied between 31 and 72 kg/ha in the high-N and 118 to 161 kg/ha in the low-N treatment (Høgh-Jensen & Schjoerring, 1994). Although the use of synthetic N fertilisers is not permitted in organic agriculture, appreciable quantities of N can be added to the soil as animal manures or composts. The effect of such amendments on N-fixation are considered in Section 4.4.

Changes in soil-N status, sufficient to affect the grass/clover balance and N-fixation, can also occur in the absence of N fertiliser or manure inputs. Ledgard & Steele (1992) described the successional pattern in mixed pastures where the gradual of build-up of soil-N from the legume leads to grass dominance, which is then followed by a decline in N status allowing the clover content to increase again. The pasture growth model of Schwinning & Parsons (1996) describes these oscillations in grass and clover growth in response to changing N supply.

Many factors will affect the soil mineral N supply and, hence, influence the N fixation by the legume. Although fertiliser N applications are not relevant in organic systems, manure applications may affect fixation. The level of soil-N in pastures also fluctuates during the year and may be high during dry summer conditions leading to a reduction in %Ndfa. At other times of the year, the high potential uptake of N by ryegrass in early spring will deplete soil-N and encourage fixation later in the season when conditions are more favourable for legumes (Ledgard & Steele, 1992). Changes in soil-N availability affecting N-fixation can also arise as a result of agricultural operations such as cultivation that encourage N-mineralisation in the soil. As mineral N accumulates in the soil/crop system, N fixation will decline, so that legumes in second and subsequent years are likely to fix less N. However, there are indications of different species showing different responses to the presence of mineral N.

The increasing dominance of the grass component of mixed swards with increasing N is generally attributed to clover's inability to compete for soil-N. For example, pure stands of subterranean clover receiving N fertiliser took up similar quantities of mineral-N as ryegrass (*L. multiflorum*) but in mixed stands the growth of clover suffered due to lack of N, both from reduced N-fixation and the inability to compete with the grass for soil-N. The grass had an inherent capability to absorb almost twice the amount of mineral-N as the legume under the same conditions (Munoz & Weaver, 1999).

Larger-leaved white clover cultivars are generally better able to withstand the negative effect of N applications on clover production in mixtures (Elgersma *et al.,* 2000). Similarly, studies in New Zealand demonstrated differences between the tolerance of nine clover cultivars in sheep-grazed pastures (Ledgard *et al*., 1996). During summer and autumn, %Ndfa for the white clover cultivar, Kopu was similar in grass/clover pastures receiving either 0 or 390 kg fertiliser-N/ha but for the other cultivars examined, %Ndfa was reduced by up to two-thirds in the fertiliser treatment. The amount of N fixed by Kopu was reduced by only 20% whereas it decreased by 40-80% for the other cultivars, including other large-leaved cultivars.

Legume species differ in their sensitivity to the effects of increased nitrate. Harper & Gibson (1984) examined the effect of zero and two concentrations of nitrate on fixation and nodulation in various legumes grown in solution culture. Time to the appearance of nodules in pea (*P. sativum*) and subterranean clover was little affected by increased nitrate whereas for lupin (*L. angustifolius*), nodules appeared slightly sooner with added nitrate. Nitrogenase activity of pea, lupin and subterranean clover was slightly increased by the intermediate nitrate concentration but activity in soybean was reduced. Activity was reduced in all species at the higher nitrate level, in the order soybean and lupin (both >90% reduction), pea (69% reduction), subterranean clover (27% reduction). Wanek & Arndt (2002) also observed a marked reduction in %Ndfa for soybean with increasing nitrate. Percentage Ndfa in sand culture was reduced from 84% at 0.25mM nitrate to 66% at 2.5 mM and to 3% at 25 mM nitrate.

Palmason *et al*. (1992) reported that lupin (*L. angustifolius)* appeared to be able to maintain higher rates of N-fixation in high N soils than many other forage and pasture legumes. These measurement were carried out at low temperatures (average <10°C), which might explain the apparent conflict with the previous study. The rates of fertiliser application were also relatively low. Lupin (*L. angustifolius*) and field pea (*P. sativum*) were also included in a controlled environment study by Cowie *et al.* (1990) examining the relative effect of increasing external nitrate supply on the nodulation of three winter crop legumes. Plants were grown at concentrations of 2 and 8 mM nitrate. At the higher concentration, it was again lupin that exhibited the smallest reduction in nodule number and nodule weight. The greatest reduction was in pea, with chickpea intermediate. In a further study with peas, beans and lucerne grown in pots, N-fixation decreased proportionally with increasing N. At the highest N rate, %Ndfa was 12, 2 and 33% for lucerne, pea and bean, respectively (Vernichenko & Szegi, 1984).

Turpin *et al*. (2002) reported results of a field experiment comparing N-fixation by chickpea and faba bean. In the early stages of crop growth, when the N supply was high in the N-fertilised soil, faba bean was more dependent on N-fixation than chickpea. Percentage Ndfa was 45% for faba bean compared with 12% for chickpea with fixation of 57 and 16 kg N/ha, respectively. Chalifour & Nelson (1988a) found that increased nitrate availability inhibited fixation more in pea than in faba bean though this was dependent on the rhizobium isolate that was used (Chalifour & Nelson, 1988b). Jensen (1986b; 1987b) also found differences between responses of pea cultivars and strains of rhizobia.

Nitrate concentrations of approximately 1 and 5 mM decreased N-fixation in faba beans to 16 and 1%, respectively, of the values for control plants that received no nitrate. The reduction was mainly due to a decrease of specific N-fixation per unit nodule weight and to a lesser extent due to a reduction of nodule growth (Kage 1995). In contrast, Guo *et al.* (1992) found that the depressive effect of mineral-N on nitrogenase activity in faba bean, white lupin (*Lupinus alba*) and medic (*Medicago rugosa*) was mainly due to inhibition of nodule formation and nodule growth, rather than to a direct influence on the specific activity of the nodules.

3.2.4. Rhizobia and inoculation

Ledgard & Steele (1992) described the nodule development process and the various ways in which this may be affected by soil conditions. Initially the colonisation and survival of effective rhizobial strains depends on satisfactory soil and environmental conditions. Subsequent infection of the host plant is also sensitive to the soil environment and will be reduced by factors such as low soil pH and the presence of excess nitrate. Inoculation may be necessary where legumes have not been grown before and there are no naturalised rhizobia. Most UK soils contain large *Rhizobium* populations which readily nodulate common legumes such as clovers, peas and beans. Other crops (e.g. lucerne) need different species of rhizobia that may not be present in all soils. In these circumstances, inoculation is necessary if crops are to be reliant on N-fixation. In some soils the native strains of rhizobia are relatively ineffective and even the commonly-grown legumes will benefit from inoculation. New strains of clover inoculants have been shown to improve N-fixation by up to 40% in some locations (Mytton, 1997). The survival of the added rhizobia is influenced by environmental and soil conditions and by their competitiveness with resident strains. The behaviour of rhizobia in the field has been reviewed by Amarger (2001).

Nutritional constraints on root nodule bacteria affecting N-fixation have recently been reviewed by O'Hara (2001). Processes in the development of some legume symbioses have a specific requirement for Ca, Co, Cu, Fe, K, Mo, Ni, P, Se and Zn. Boron is not required by rhizobia but is essential for the establishment of effective legume symbioses. Inadequate supplies of P, Ca, Fe and Mo in particular, can also reduce legume productivity by affecting subsequent nodule development and function. Few studies have shown evidence of direct effects of nutritional constraints on root nodule bacteria in soils but data clearly show that there are situations where low availability, for example of P or Fe, adversely affects rhizobial growth, survival and competition.

The effect of previous cropping history on the effectiveness of inoculation was demonstrated by trials with common bean in four regions of Sweden. Where beans had never been grown, inoculation increased seed yield and number of root nodules but was ineffective in a region where beans are commonly grown (Bengtsson, 1991). In trials in Canada, inoculation increased the yield of peas (*P. sativum*) in 9 out of 22 trials (by an average of 14%). Positive responses were only slightly more frequent on land with no history of legumes than on land that had previously grown legumes, with frequencies of 45% and 38%, respectively. However, the magnitude of the inoculation benefit was appreciably greater (19% vs. 5%) on land with no history of legumes. The limited effectiveness of inoculation was attributed to adequate nodulation of pea by indigenous rhizobia (McKenzie *et al.,* 2001).

3.2.5. Companion species

Growth of legumes with a companion species either as a mixed crop or intercrop will influence fixation in sometimes opposing ways. The presence of the non-legume will reduce the number of N-fixing plants per unit area and may further reduce growth of the legume through competition for light, moisture and soil nutrients. However, at the same time, a companion species can provide physical support to reduce lodging; for example, in pea crops (Karpenstein-Machan & Stuelpnagel, 2000). More generally, N uptake by the companion species may reduce the availability of mineral-N in the soil and thus encourage the legume to obtain a greater proportion of its N through fixation. The presence of weeds in the crop may have similar effects. Increasing planting density of the legume can to some extent have a similar effect to intercropping, presumably because of a greater demand for soil-N under the denser crop.

During the establishment phase, an aggressive grass may be more effective at utilising soil-N and encouraging fixation than one that is slow to establish. In established pastures, aggressive grasses are more likely to reduce the proportion of legume and quantity of N fixed (Ledgard & Steele, 1992). Although this competition for N can encourage fixation, the presence of a more-competitive, companion species may at the same time reduce the availability of other nutrients to the legume; for example, P and K availability may be reduced in grass/clover swards (Høgh-Jensen, 2000). The presence of a non-legume, usually with a lower N content than the legume, will alter the C:N ratio of the bulk residues and their subsequent decomposition in the soil. The rate of net N-mineralisation has been shown to be lower in soil under grass monocultures than under grass/clover mixtures. This was attributed to a higher C:N ratio in the active soil organic matter fractions under grass than under mixtures (Elgersma & Hassink, 1997).

Many studies have demonstrated that %Ndfa is greater for clover grown with grass than for pure stands (Vallis *et al.,* 1977; Vallis, 1978; Haynes, 1980; Frame & Harkess, 1987; Frankow-Lindberg, 1989; Goodman, 1991). For example, Høgh-Jensen & Schjoerring (1997b) reported that %Ndfa in grass/clover mixtures receiving between 3 and 72 kg fertiliser-N/ha remained above 80%, compared with 60-80% for equivalent pure clover stands. In spite of the higher proportion of N obtained from fixation, the average quantity of N fixed for all fertiliser treatments over three years was less for the mixture than for the pure stand (e.g. 83 vs. 109 kg N/ha for the 3 kg/ha N-fertiliser treatment). In an earlier study, Craig *et al.* (1981) measured specific nodule activity in red clover (as estimated by acetylene reduction) and concluded that activity was similar in pure stands and in mixtures with grass. Activity in lucerne conformed more to the expected pattern and was either similar or higher when lucerne was grown with grass than when grown alone.

Potential interactions are more complex where legumes are grown as a mixture with other legumes. Where subterranean clover was grown with lucerne, the mixture fixed more N (420-510 kg N/ha) than clover grown alone (314 kg/ha) (Dear *et al*., 1999). In comparison, 143-177 kg N/ha was fixed by clover grown with grass (*Phalaris aquatica*). Subterranean clover usually fixed a higher proportion of its N when grown with the grass than with lucerne. Lucerne was effective at scavenging soil mineral-N and derived a lower proportion of its N from fixation than clover; however, the authors concluded that including lucerne with the clover would increase the net input of N to the soil.

Biological N-fixation in mixed legume-cereal cropping systems has been reviewed by Fujita *et al.* (1992). Factors influencing the amount of N fixed include choice of species, plant morphology, density of component crops, management and competitive abilities of the components. Climbing legumes (indeterminate types) are less affected by intercropping. Shading by cereals tends to reduce fixation.

Many studies have demonstrated the effects of intercropping on %Ndfa in legumes other than clover. In a study by Hauggaard-Nielsen *et al.* (2001b), %Ndfa in sole cropped pea increased from 40% to 80% during the growth period but was almost constant at 85% when peas were intercropped with barley. The total amounts of N-fixed were 95 and 15 kg N/ha in sole cropped and intercropped pea, respectively. In contrast, where the crops contained a high proportion of weeds, 90-95% of above-ground N was derived from fixation, independent of the cropping system. This was because the weeds in the pea monocrop provided a sink for soil-N in the same way as the barley in the intercrop (Hauggaard-Nielsen, *et al.* 2001a).

In another study of pea-barley intercropping, the average %Ndfa was 82% for pea in the intercrop, compared with 62% for the monocrop (Jensen, 1996b). At maturity, the average amounts of N-fixed were 177 and 51 kg N/ha in the monocrop and intercrop, respectively. The barley component was up to 30 times more competitive than pea for inorganic-N and consequently obtained a more than proportionate share of the inorganic soil-N. Fixation for the intercrop was less than expected, indicating that the competition from barley had a negative effect, perhaps because of shading. Similarly, Izaurralde *et al.* (1992) reported that %Ndfa for barley-pea intercrops was on average 39% higher than for sole-cropped pea. In a trial at four sites in Saskatchewan, Canada, %Ndfa for monocropped pea receiving 10 kg fertiliser-N/ha ranged from 28 to 79%, compared with 33 to 88% when intercropped with either rape, mustard or oats (Cowell *et al.,* 1989). At only one of the sites (and for lentil at a fifth site) did increasing the fertiliser rate to 50 kg N/ha reduce %Ndfa in the monocrop. Fertiliser rate did not significantly affect %Ndfa in any of the intercrops.

In a study designed to separate the effects of root and shoot interactions in intercrops, shoot competition between cereals and peas was found to have no significant effect on the proportion of N derived from the soil and atmosphere. However, root competition from cereals significantly increased the proportion of N derived from fixation from 76 to 94% (Tofinga *et al.,* 1993).

Intercropping with either ryegrass or oats had a much smaller effect on N-fixation in lupin (*L. angustifolius*) (Palmason *et al.* 1992). At 117 days after planting (mean temperature <10 ^{o}C), monocropped lupin derived an average of 92% or 195 kg N/ha of its N from fixation. Intercropping increased %Ndfa to a mean of 96%. Total N fixed per hectare in intercropped lupin was approximately half that of the monocrop, in line with the decrease in legume seeding rate and legume yield.

Increasing planting density of the legume can to some extent have a similar effect to intercropping, presumably because of a greater demand for soil-N under the denser crop. For faba bean grown alone, increasing crop density from 100 to 500 plants/m^2 increased %Ndfa from 65 to about 80% (Danso *et al.,* 1987). Nitrogen-fixation increased from about 65 to 85 kg/ha though there was little difference between the more densely planted treatments. Percentage Ndfa was further increased to a maximum of 95% when beans were grown with barley. Fujita *et al.* (1992) stated that plant density appears to have little effect on the quantity of N derived from fixation.

3.2.6. Transfer of fixed N to the companion crop

The N economy of a companion crop can benefit from the presence of the legume either through transfer of fixed-N from the legume or through a 'N-sparing' effect, whereby the legume, obtaining much of its N from the atmosphere, leaves more mineral-N in the soil available to the non-legume (Danso *et al.,* 1993; Chalk, 1998).

Where transfer of fixed N occurs, this should normally be included in any assessment of the net input from fixation, though care is required to avoid ‘double-counting’, particularly in systems that are not at equilibrium and where fixation in one year contributes to transfer in later years (e.g. Ledgard, 2001). Nitrogen transfer can occur through root excretion and decomposition, leaching from leaves and in leaf-fall and animal excreta.

There is conflicting evidence of how much of the current season's fixation is transferred in legume/cereal mixtures, suggesting that this may only occur under certain conditions (Fujita *et al.,* 1992). There is thought to be negligible release of N from nodules but there is evidence that the release from cells shed from growing roots may be substantial. Though the factors are not well understood, N release may be influenced by shoot harvest, high temperature, moisture stress and Fe and P stress. Higher crop densities may also promote transfer through increased proximity of the roots of the legume and non-legume.

Though the direct contribution from nodules is unclear, Wardle & Greenfield (1991) observed considerable differences between the amounts of N mineralised from detached nodules from a range of legume species. After 56 days incubation in soil, relatively little N was mineralised from ground nodules of red clover and pea compared with *Lotus pedunculatus*, *Vicia faba* or, especially, white clover nodules.

Transfer of fixed N can be substantial in grass/clover mixtures. There is a high turnover of roots and nodules of living clover plants (Butler *et al.,* 1959) and greater opportunity for transfer to occur through decomposition and mineralisation pathways than in annual crops.

Cowling (1982) summarised information about N transfer from a number of early studies on grass/white clover swards in the UK. The average amount of N fixed annually was between 90 and 200 kg N/ha; of this, 52-78% (mean 65%) was measured in the clover with the remainder, equivalent to 29-73 kg N/ha, as 'indirect fixation' transferred to the companion grass. More-recent studies using ^{15}N labelling may provide more accurate estimates of annual transfers. For example, Jørgensen *et al.* (1999) reported that under a cutting regime, apparent transfer of clover-N to grass was negligible in the seeding year but in the following two years, clover-N deposited in the rhizosphere or released by turnover of stolons, roots and nodules contributed 19 and 28 kg N/ha to the grass. Høgh-Jensen & Schjoerring (1997b) also found only small amounts of fixed-N transferred to the associated ryegrass during the first production year, while up to 21 kg/ha was transferred in each of the following years. The transfer amounted to 3, 17 and 22% of the total N fixed in the first, second and third production year, respectively. Similarly, Boller & Nösberger (1987) found that transfer of N from red and white clover to grass tended to increase with time, suggesting that this was mainly due to indirect transfer from decomposition of dead clover tissue accumulating in the soil. Vinther (2000) measured a transfer of about 10 kg N/ha/year in the first and second production year of a grass/clover sward in Denmark, compared with fixation of 150 and 277 kg N/ha in the two years. Goodman (1991) concluded that no transfer occurred between red clover and ryegrass in the first year and that transfer was not triggered by defoliation. Considerable quantities of N were transferred from white clover to grass after the first winter, apparently because of root death during the winter.

Other estimates of the annual transfer in ungrazed grass/clover swards are between 17 and 113 kg N/ha (McNeill & Wood, 1990; Heichel & Henjum, 1991; Farnham & George, 1993; Elgersma & Hassink 1997; Elgersma *et al.* 2000). In a recent study, Høgh-Jensen & Schjoerring (2000) used a direct ^{15}N labelling technique to determine N-transfer. They concluded that the ^{15}N dilution technique, as used for most previous measurements, underestimated transfer by more than 50% and that transfer is more important than previously recognised. With the direct labelling method, N-transfer was estimated to be 45 and 75 kg N/ha for white clover in the first and second production year, respectively. Corresponding values for red clover were 17 and 36 kg N/ha.

Ledgard & Steele (1992) quoted a range of 3 to 102 kg N/ha/year for the amount of N transferred 'below-ground', predominantly through decomposition of legume roots and nodules, corresponding to 2 to 26% of the N fixed by the clover. This will have also included transfer of some N from senescence and decomposition of clover leaves. However, this 'above-ground' transfer is considerably more important in grazed pasture where clover herbage is eaten and returned to the soil in the excreta of the grazing animal. This can be of a similar magnitude to the 'below-ground' transfer (see Section 4.3).

Much of the below-ground transfer can be a short-term flux of N fixed during the current season. Although measured under a Mediterranean climate where turnover rates are likely to be higher than in the UK, as much as 50% of the N fixed by red clover crops in a year was found to be potentially available to the soil micro-organisms as litter. The maximum transfer was in spring and winter. Of the remainder, 20 to 35% was recovered in living plant parts during regrowth in March of the second year (Warembourg *et al*., 1997).

Damage to the roots of the legume can increase the quantity of N transferred. Where ryegrass and white clover were grown together in solution culture, significant transfer of N from clover to grass only took place where clover roots had been physically damaged (Hatch & Murray, 1994). Similarly, infesting plants with the larvae of Sitona weevil to deliberately damage clover roots significantly increased dry matter yield and N content of associated ryegrass plants (Murray & Hatch, 1994). The weevil infestation significantly reduced foliar biomass of the clover and impaired N-fixation (Murray *et al.,* 1996). Hanel & Simek (1993) observed significant positive correlations between seasonal changes of phytophagous nematodes and the number of nodules on red clover and between seasonal changes of nitrogenase activity and bacteriophagous nematodes. There was no evidence that nematodes had a negative effect on N-fixation.

Nitrogen transfer was compared in subterranean clover-, white clover- and lucerne-mixtures with cocksfoot in a 3-year trial in Australia (Simpson 1976). Herbage was cut and removed at intervals. Although subterranean clover appeared to fix less than half the quantity of N fixed by white clover and lucerne, a much higher proportion of the N was transferred to the grass. Malarino *et al.* (1990) compared N transfer to grass from white and red clover and from *Lotus corniculatus*. Significant transfer did not occur until the second year after sowing and was often greater from white clover than from red clover or *L. corniculatus*. In a study by Brophy *et al.* (1987), 13% of the N fixed by *L. corniculatus* was transferred to grass, compared with 17% of the N fixed by lucerne. Maximum transfer occurred in areas with a high proportion of legume to grass.

The transfer of N from clover to associated grass also differs between white clover cultivars, in particular as result of differences in leaf size. Transfers of above-ground N were 15, 24 and 34% for a large, a medium and a small-leafed variety, respectively (Laidlaw *et al.,* 1996). Large-leafed varieties have a higher leaf:stolon ratio (Rhodes & Harris, 1979) and under a cutting regime they contribute more N directly to the harvested herbage and transfer less to the grass; as a result, they also contribute less N to the total sward per unit weight of harvested clover (Elgersma & Schlepers, 1997).

In contrast to grass/clover swards, evidence of N transfer between other legume species and companion crops is often conflicting.

Russelle *et al.* (1994) showed there was little net loss of symbiotically-fixed N from living lucerne roots into the surrounding soil. Net N accumulation in soil during crop growth was thought more likely to be due to other processes, such as decomposition of dead roots, nodules and above-ground litter. Studies with lucerne and birdsfoot trefoil indicated that lucerne released more N through decomposing roots than nodules, whereas birdsfoot trefoil contributed more N to the soil through decomposing nodules than roots (Dubach & Russelle, 1994). Neither process could fully account for published estimates of N transfer.

Jensen (1996b) concluded from a field experiment that the intercropping advantage in pea-barley intercrops was mainly due to the reduced competition for mineral-N, rather than to any facilitative effect by which symbiotically fixed-N was made available to the barley. However, the more controlled conditions of a pot experiment demonstrated a more significant transfer (representing up to 19% of the N in barley after 70 days growth). From this it was concluded that rhizodeposition may be a significant source of N to intercropped barley, especially at low rates of N-fertilisation (Jensen, 1996a). The role of arbuscular mycorrhizas in this transfer was also studied in a controlled environment (Johansen & Jensen, 1996). No significant transfer of N was detected from intact pea plants to barley in the non-mycorrhizal controls. Although mycorrhizal colonisation slightly increased the quantity transferred, the net effect was almost insignificant since N was also transferred from barley to pea. However, removal of the pea shoots, and resulting death of the pea roots, increased N transfer to barley, particularly with the mycorrhizal plants. The results indicate that arbuscular mycorrhizas may play a significant role in the flow of N when the root system of one of the plants is decomposing.

Other studies have been unable to detect transfer between various legume species and the companion crop; for example in barley-pea intercrops (Izaurralde *et al*., 1992), intercropped pea and mustard (Waterer *et al.* 1994), from vetch (*Vicia sativa*) to oats (Papastylianou, 1988; Papastylianou & Danso, 1991) and from faba bean to oat (Cochran & Schlentner, 1995). In a study in Iceland, significant N transfer occurred from lupin (*L. angustifolius*) to intercropped Italian ryegrass but not to intercropped Westerwolds ryegrass or to oats (Palmason *et al*., 1992; Danso *et al.,* 1993).

Transfer of N from *Phaseolus* bean to intercropped maize was studied in glasshouse experiments by Giller *et al.* (1991). When plants grew vigorously, no transfer of N from bean to maize was detected. However, in a further experiment where growth of maize and bean plants was reduced by insect damage, up to 15% of the N in the beans was transferred. There was no significant difference in N-transfer to mycorrhizal and non-mycorrhizal plants. Reeves (1992) stated that though N transfer from N-fixing legumes via vesicular-arbuscular mycorrhizas (VAM) to associated non-fixing plants had been demonstrated in greenhouse experiments, this had not been shown to occur where soil-N was limiting, a condition representative of most legume/non-legume intercrops. In this study, maize was grown with beans in the presence or absence of VAM fungi but infection did not result in transfer of fixed-N or soil-N from bean to maize.

Studies at IGER (Clements *et al.,* 2000) have investigated sowing cereals into a permanent clover understorey. Though the cereal appears to benefit from N fixed by the clover, there have been no measurements to determine whether this involves direct transfer of N or a longer-term release of N from mineralisation of clover roots and residues.

Uncertainties about the extent of transfer of fixed N to companion crops adds to uncertainties about the total quantities of N fixed and of the subsequent fate and availability of this N.

3.2.7. Age of crop, length of growth period and season

Most published estimates refer to annual rates of N-fixation.

Knowledge of relative rates of fixation at different seasons and stages of growth is important for assessing how much of this annual total is fixed by legumes that are grown for less than a full year, for example, with short-term cover crops or where a ley is cultivated during summer or early autumn. Relative rates of fixation in grass/clover swards are largely determined by temperature and moisture supply. However, Vessey & Patriquim (1984) also observed a decline in fixation at the start of flowering in white clover. The stage of vegetative or reproductive growth may be more important for annual grain legumes. For perennial legumes, longer-term fluctuations in factors such as soil mineral-N contents will also influence fixation.

Fixation in white clover exhibits a seasonal pattern. The average daily N-fixation rate for a white clover/perennial ryegrass mixture in Denmark varied from less than 0.5 kg N/ha/day in autumn to more than 2.6 kg/ha/day in June. The average fixation rate for a pure clover stand was greater and varied between 0.5 and 3.3 kg N/ha/day but with the same seasonal pattern as for the mixture (Jørgensen *et al*., 1999). Percentage Ndfa in grazed grass/clover pasture ranged from 70 to 99% with the lowest values at the beginning and end of the growing season (Vinther & Jensen, 2000). Low soil temperatures may be responsible for the relatively low %Ndfa values observed in spring and autumn (Vinther, 2000). Marriott (1988) investigated seasonal variation in the N-fixation activity (as assessed by acetylene reduction) of white clover in an upland sward in Scotland. The sward was cut to simulate grazing. There was little activity until April, when 10-cm soil temperatures first exceeded 3°C. Activity increased to maximum rates in June and July and returned to low levels in late October. For most of the season, excluding a period of drought in August, activity was positively correlated with leaf dry weights.

Percentage Ndfa in grass/clover mixtures in Switzerland also tended to decline during late summer (Boller & Nösberger 1987). This decline was more consistent and more marked for white than for red clover; typically values were 80-90% in spring/early summer and fell to 55-70% in late summer. The proportion of N derived from fixation in red clover/Italian ryegrass mixtures also varied with stage of growth during a 48-day harvesting cycle (Boller & Nosberger, 1988). There was greater reliance on fixation after the middle of the cycle: Ndfa was >95% compared with 86-90% in the first half of the cycle. The pattern for white clover/perennial ryegrass mixtures on a 36-day cycle was more variable. Percentage Ndfa was initially 63-66%, increasing to 89% and then falling to 71% for the final quarter of the cycle.

The milder climate in New Zealand allows pasture growth throughout the year, though fixation and biomass production are reduced during winter. Highest fixation occurs during late spring and early summer and is related to a combination of temperature and moisture effects (Goh & Ridgen, 1997). In annual pastures of subterranean clover in western Australia, %Ndfa for an ungrazed sward started from a low value of 58% and increased to 73-88% for the rest of the season. Clover in a more productive grazed sward behaved similarly except for a significant mid-winter depression to 55%Ndfa, probably caused by excessive defoliation through overgrazing (Sanford *et al.* 1995). For other subterranean clover pastures in this relatively low rainfall area (300-600 mm rain/year), seasonal profiles for accumulation of fixed-N were skewed towards the late winter and spring period (Bolger *et al.*, 1995). High levels of N-fixation activity in red clover appear to be little affected by flowering and seed development (Machova, 1992).

As would be expected from the previously described relationship between the build-up of soil-N and N-fixation (Section 3.2.3), fixation in grass/clover swards is also likely to decline with increasing pasture age (independently of changes in the proportion of clover).

Measurements on grass/clover leys near Aberdeen provided some evidence for this (Sanders *et al.*, 2000; Sanders *et al.,* 2001). The percentage N derived from fixation was highest in 1 year-old leys and N-fixation was significantly lower in 3 year-old leys. Although soil nitrate was generally highest in 3 year-old leys, indicating a build-up of N, it was lower in 2 year-old than in 1 year-old leys.

A decline in fixation with increasing sward age is not necessarily a characteristic of mixtures under all conditions. Edmeades & Goh (1978) compared N-fixation in white clover-based pastures in New Zealand aged 2, 6, 15 and >20 years. The oldest pasture contained 20% clover compared with 38-46% in the other pastures. This was reflected in less N-fixation in the older pasture (45 kg/ha compared with 88-142 kg N/ha/year). However, %Ndfa was highest in the two older pastures (87-88%), compared with 82% in the 6- and 2-year old pastures. Studies of fixation by red clover, white clover or lucerne mixtures with reed canarygrass in northcentral USA showed that fixation was greatest during the second year of the stands. The proportion of legume N derived from fixation increased progressively from Year 1 to 4 and averaged > 93% for all legumes in Year 4 (Heichel & Henjum, 1991). If the grass component of mixed swards provides an effective sink for soil mineral-N, it is possible that reductions in N-fixation as a result of increasing pasture age and N build-up will be less marked in mixed swards than where clover is grown alone.

Nykänen *et al.* (2000) studied the effect of pasture age on yield and clover content of perennial red clover/timothy leys in Finland. Red clover is shorter-lived than white clover and is more suited to short-term leys. In spite of this, yields from experimental plots were highest in 2 and 3 year-old leys and lowest in 1 year-old leys. However, the clover content (20-80%) and total N content of the herbage varied too much to allow clear conclusion to be drawn about the effects of sward age. Yields were also measured in fields on a number of organic farms. There was no significant difference between yields from 1 and 2 year-old leys but yields decreased from 2 to 3 year-old leys. Clover contents diminished in the same order as the yields.

In some other legume species, most notably grain legumes, fixation is particularly sensitive to environmental conditions at the reproductive stage of growth due to the high N demand for pod-growth and the declining photosynthetic activity arising from leaf senescence (Salon *et al.,* 2001).

In Alaska, (Sparrow *et al.,* 1995) observed that the rate of fixation peaked at or soon after flowering in some legumes; in others, it either plateaued or continued to increase after flowering until the end of the growing season. Unlike faba bean and lupins (*L. luteus* and *L. angustifolius*), seed yield of pea plants can often be increased by late N applications, indicating that N supply may be limited by low fixation during reproductive growth. In a study by Adgo & Schulze (2002), pea plants showed a marked decline in N-fixation during reproductive growth (with remobilisation of N from leaves to pods). This was more marked for a modern German pea variety than for two, less selectively-bred, Ethiopian varieties. Of the total N fixed at harvest, 77% was fixed by mid-flowering in the German variety, compared with 55 and 71% for the Ethiopian varieties. In related studies, a semi-leafless German pea variety stopped fixing N at the start of pod formation (Schulze *et al.* 1998). Two varieties of faba bean were also examined. As with the Ethiopian pea varieties, about 75% of the total N-fixation occurred during pod-filling. Danish studies indicated that about 25% of the total fixation in pea plants took place pre-flowering, about 25% during the 2 weeks of flowering and the remainder post-flowering (up to 104 days after emergence). Fixation increased to a maximum of 10.3 kg N/ha/day during early pod-formation. At initiation of pod-filling, when the crop lodged, there was a steep decrease in fixation but some activity resumed at later stages of pod-filling (Jensen, 1987a). Kucey (1989) also reported that levels of fixation in pea were low during the early part of the growing season and increased later.

There is evidence of a reduction in fixation at the reproductive stage for common bean (Becher *et al.,* 1997), lupin *(L. albus)* (Schulze *et al.,* 1999) and soybean (Imsande, 1988). However, in field trials with soybeans in Canada, fixation increased rapidly at the beginning of flowering and maximum rates were maintained during pod formation and early pod development (Johnson & Hume, 1972). Similarly, Pongsakul & Jensen (1991) reported that at the flowering stage, only 18 to 34% of the total N in inoculated soybean was derived from N-fixation, whereas as much as 74% was derived from fixation at late pod-filling. Field-grown soybean in Austria had fixed 102 kg N/ha by physiological maturity. Only 5% of this N was fixed in the first half of the growth period compared with about 45% during the reproductive stage and 43% between pod-filling and physiological maturity (Zapata et al. 1987).

Studies in Canada indicated that fixation in common bean increased to anthesis or to various stages of pod-filling depending on cultivar and year. Slight fixation activity continued to physiological maturity but had ceased by harvest (Rennie & Kemp, 1984). Similarly, the rate of N-fixation in common bean in field and glasshouse trials in Mexico increased as the plant developed and was at a maximum during the reproductive stage (Peña-Cabriales *et al.,* 1993). In a greenhouse study, nodule weight in common bean increased to a maximum at 35 days after planting and then declined sharply; however, plants continued to fix and accumulate N up to 56 days after planting (Mefti *et al*., 1998).

The quantity of N fixed by relatively short-duration cover crops will be influenced by how rapidly the crop establishes and develops an effective rhizobial symbiosis.

A field experiment in Nebraska compared the effect of planting date and length of growth period on the development of a wide range of cover crops (Power & Koerner, 1994). All species were planted in spring, with a second seeding in early summer. At most samplings, growth of soybean was equal to or greater than that of the next best species. In most situations, hairy vetch also performed well. Peas and faba bean grew very rapidly for the first 60 to 90 days after planting. Small-seeded legumes generally exhibited relatively slow growth for the first 60 days. However, rapid crop development is not necessarily a guide to patterns of N-fixation. With soybean grown in Canada, no N-fixation was detected until 36 days after sowing (Johnson & Hume, 1972) or at 49 days after inoculation for plants where the root zone temperature was maintained at 15°C (Zhang *et al*. 1995). Fixation in lupin (*L. albus*), which would be expected to be better adapted to cool temperate areas, seemed to be about as sensitive to low root zone temperatures as in soybean (Legros & Smith, 1994).

Date of planting can have a marked effect on the amount of N fixed. For example, early sowing of peas in south-eastern Australia (late April-early May) increased N-fixation by as much as 96 kg N/ha compared with sowing in late June-early July. The potential increase in soil N from the stubble left after harvest ranged from up to 98 kg N/ha with early sowing to as little as -38 kg N/ha with late sowing (O'Connor *et al.,* 1993).

3.3. Conclusions

- To understand the contribution of legumes to soil fertility, it is necessary to quantify the amount of N they fix from the atmosphere, because this represents a true import onto the farm.
- Uptake of soil N by the legume is not an import onto the farm though, if the crop retains N that would have otherwise leached, it can be considered to contribute to fertility.
- Quantifying fixation is difficult, for several reasons:
    - Several different methodological approaches with advanatages and disadvantages (and often making comparison of data difficult)
    - Whereas, the N content of the above-ground component is easily measured, that below ground is very difficult to quantify. Estimates of the below-ground contribution differ between authors, ranging 20-60% of above-ground N.
    - Due to the complex nature of N cycling, there is a risk of double counting, especially in a cut/mulch system, where N might be mineralised after cutting and be taken up by the crop again.
- A wide range of legumes is available to the organic grower. Information on N fixation capacity and yield under UK conditions is limited for the more minor crops.
- The most commonly grown for fertility-building under UK conditions are:
    - White clover/grass
    - Red clover

  - Lucerne
  - Peas and beans
- Most data are available for white clover/grass, red clover, peas, beans and lucerne.
- Published estimates of N fixed, both as kg N/ha and % derived from atmospheric N vary widely between experiments.
- Prediction of N fixation is made more difficult by differences between varieties as well as between species.
- Many environmental factors also affect N fixation and growth of the legume:
  - Climate: particularly prone to drought and waterlogging
  - Soil factors: nutrition (especially P) and soil structure
- It is likely that the most robust advice that can be developed will be for red and white clover.
- The feeding potential of the less common forage crops is not known and some, e.g. sweet white clover, have been reported to be toxic in some circumstances.

4. THE INFLUENCE OF MANAGEMENT

Various aspects of management will influence the quantity of N provided by legume crops. Effects can be divided between those, such as crop removal, which influence the net accumulation of N and those that influence the N-fixation process directly. Harvesting of forage or grain will remove much of the fixed N and reduce the benefit to following crops. The benefit will be further reduced if straw and other legume residues are also removed from the field. In contrast, where crops are mulched or grazed, much of the fixed N will be returned to the soil in plant debris or excreta. Nitrogen-fixation processes will be affected directly by defoliation of the legume and indirectly through effects on the mineral-N content of the soil. Other aspects of management affecting N-fixation include position of the legume in the cropping rotation, duration of cropping, methods of cultivation and applications of manures and composts.

4.1. Effects of cutting and mulching on N capture and loss

The most immediate effect of cutting green manure crops or leys containing legumes is the impact of defoliation on root nodules and on the N-fixation process. However, with green manures where the cut material is returned to the soil as a mulch, fixation is also likely to be affected by the additional mineral-N released from decomposition of the returned foliage. Green manures may be cut and mulched as many as 3 to 6 times during the season depending on growing conditions (Phillips *et al.,* 2002) and can recycle large quantities of N to the soil. This N may be used by the legume in preference to fixing N from the atmosphere.

The proportion of clover in grass/clover mixtures is generally considered to decline with increasing interval between defoliations (Søegaard, 1994). Frequent cutting improves light conditions within the sward and favours the performance of white clover (Kessler & Nösberger, 1994). However, Reid (1986) found that total herbage yield and clover yield of white clover/grass swards in Scotland were greater with less-frequent cutting, 3 or 5 times/year, than with 10 cuts/year. Cutting and mulching of mixed swards may also be less effective at maintaining a higher proportion of clover than where the herbage is removed (Loges *et al.,* 1997 & 2000b).

Cutting and mulching can result in mineral N accumulation, which will reduce fixation. It may be better to remove the foliage from the field, though this then requires the foliage to be managed (presumably as forage and, ultimately, as manure). In a mixed sward, decreasing the cutting frequency could potentially decrease fixation (increased competition from the grass), but defoliation of forage legumes also causes a dramatic decrease in nitrogenase (N-fixation) activity.

Although this latter point has been recognised for a long time, the underlying mechanisms are not fully understood (Hartwig & Nösberger, 1994; Hartwig & Trommler, 2001). It has been hypothesised that after defoliation, nitrogenase activity is adjusted in response to the reduced demand for symbiotically fixed nitrogen. As the plant has a limited capacity to store organic-N, nitrogenase activity may have to be reduced to avoid build-up of toxic concentrations of ammonia within the plant tissues. Such an interpretation is supported by the fact that complete defoliation of N-starved plants reduces nitrogenase activity less than in plants that are well-supplied with N (Hartwig *et al.,* 1994).

Following defoliation, N reserves in roots and stolons are mobilised to support the initial regrowth of leaves. In white clover plants this mobilisation typically represents about 55 and 70% of the N in roots and stolons, respectively. Most of this remobilisation occurs during the first 6 days after defoliation, after which, the plant returns to obtaining most of its N from exogenous sources (Corre *et al.,* 1996). In nodulated lucerne plants, shoot removal caused a severe decline in N-fixation within 6 days after cutting (Kim *et al.,* 1993). Fixation remained low during the first 10 days after shoot removal, then increased rapidly and by day 24 was greater than the initial value. Similarly in red clover, nitrogenase activity was reduced by 80% within 24 hours after defoliation and by a further 7% in the following week (Machova, 1992). Net mobilisation of N from nodulated roots and stems accounted for most of the N in new leaf growth for up to 5 days after defoliation of subterranean clover (or for at least 2 days in N-fertilised swards). In unfertilised swards, nodules degenerating as a result of leaf removal were a major source of mobilised N (Culvenor & Simpson, 1991).

Defoliation of white clover plants reduced fixation by more than 70% (Ryle *et al.,* 1985). Nodule weight declined after defoliation but there appeared to be no shedding of nodules. The original rates of fixation were re-attained after 5-9 days. Nitrogen-fixation by red clover and *Lotus corniculatus* plants was also reduced to low levels 8 days after defoliation in a glasshouse study by Collins & Lang (1985). Fixation then increased over the following 16 days.

Effects of cutting management on the performance of grass/clover swards have been investigated in a number of studies. These generally refer to circumstances where the harvested material is removed from the field, rather than mulched. In a 3-year trial with white clover/perennial ryegrass plots cut when dry matter reached either 1200 or 2000 kg DM/ha (equivalent to 7-9 or 5-7 cuts/year), N yield and N-fixation were greatest with the less frequent cutting in two years but were greatest with the more frequent cutting in the final year (Elgersma & Schlepers 1997). In an experiment on a mixed sward of white and red clover with ryegrass, cutting either 3 or 6 times per season had no effect on fixation (Høgh-Jensen & Schjoerring 1994). In a similar study with red clover/orchardgrass mixtures, %Ndfa and N-fixation were generally not significantly different in treatments harvested 3 or 6 times per season (Farnham & George 1994b). It was concluded that the more frequent cutting increased N-fixation slightly but not N-transfer from clover to the associated grass. The effect of the severity of defoliation, rather than its frequency, was investigated in an experiment comparing the effect of two cutting heights (4 or 10 cm above ground level) on fixation in white clover/ryegrass mixtures in Switzerland. The cutting height did not influence clover N yield or %Ndfa (Seresinhe *et al.* 1994).

Nitrogen dynamics are likely to be very different where the cut herbage is returned to the soil. However, there is little information about the direct effects of mulching on the N-fixation process.

In experiments in Germany, red clover/ryegrass plots were managed by mulching two or three times/year or by cutting three times/year and removing the herbage for fodder (Schmitt & Dewes 1997). The proportion of clover was higher in plots cut for fodder than in the mulched plots. At the first sampling date, total N accumulation was highest in the plots cut for fodder, although these plots had a lower proportion of fixed-N. At the final sampling date, there was more fixed-N in grass from the mulched plots. Soil-derived N was similar in both treatments. It was suggested that the mulch acted as a N fertiliser in promoting the yield of grass. Other recent studies in northern Germany compared the growth and fixation of three legume species when managed for forage or as a green manure (Loges *et al*. 1999 & 2000b). Red clover and lucerne mixtures were both more productive than white clover mixtures (Table 4.1). However, white clover left the greatest amount of N in crop residues. For all three legumes, mulching as green manure reduced N-fixation compared with the forage management, particularly for red clover and lucerne. The N released from the mulch would be expected to inhibit fixation less in grass/legume mixtures where the grass component could utilise the mineralised N. However, the amounts fixed were little different from those in pure stands (Loges *et al*. 1999).

Table 4.1. Effect of forage or green manure management on yield, residual N and N-fixation for three legume/grass mixtures (Loges et al. 2000b).

Crop & management	Harvestable biomass (t DM/ha)	Legume content of sward (%)	N in plant residues (kg/ha)	N-fixation (kg/ha)
White clover/grass				
- forage use	6.04	67	117	248
- green manure	3.63	48	296	209
Red clover/grass				
- forage use	9.46	79	112	343
- green manure	9.25	66	220	154
Lucerne/grass				
- forage use	7.53	74	115	320
- green manure	8.57	71	199	136

Though unrepresentative of UK conditions, some information about the effects of mulching is provided by a growth chamber experiment which examined the effect of litter applications on N-fixation by *Pueraria phaseoloides,* a perennial legume widely used as a cover crop in rubber and oil palm plantations (Vesterager *et al.* 1995). Plants supplied with the highest amount of litter produced 26% more dry matter and fixed 23% more N than plants grown in soil with no litter application; %Ndfa decreased slightly from 87 to 84%. In these circumstances, there was a positive correlation between uptake of N from litter and the amount of N fixed. Fixation appeared to be increased as a result of other nutrients supplied by the litter.

Measurements by Sears *et al*. (1965) in New Zealand provide an extreme example of how higher levels of fixation can be maintained by removing harvested herbage rather than returning it to the soil. A white clover/grass mixture was grown on an impoverished subsoil fertilised with all major nutrients other than N. Under these particularly favourable conditions, clover was estimated to have fixed 683 kg N/ha/year when cuttings were removed, compared with 409 kg/ha when cuttings were returned. Though not reported in the literature, it is possible that the return of large amounts of herbage to the soil in mulched treatments may also reduce fixation by temporarily smothering the legume stubble and delaying its regrowth.

The net contribution of fixed-N to the soil will also be influenced by any N losses that occur during the growth of the legume. In the absence of grazing, losses from perennial forage crops are likely to be relatively small as much of the N is removed from the field in the harvested crop, particularly if a non-legume is also present to act a sink for soil-N. Only small quantities of N are leached from ungrazed grass/clover swards (Elgersma & Schlepers 1997) and losses from lucerne are also low (Grignani & Laidlaw 2002).The greatest loss would be expected to occur from green manure crops that are mulched and the fixed-N returned to the soil. In these circumstances, N would be expected to accumulate during the growing season and increase the risk of loss in autumn. Loges et al. (1999) observed that the high N input from green manures of at least 210 kg N/ha increased the risk of leaching after incorporation of the manure. It is possible that where soils contain high concentrations of nitrate, the legume may utilise soil-N in preference to fixing further N and thereby reduce the quantity of N susceptible to loss. As discussed in Chapter 6, the greatest risk of loss occurs when grass/clover leys and other legume crops are cultivated.

4.2. Effects of forage or grain harvest on N capture and loss

Harvesting of forage crops or of grain legumes both remove fixed-N from the field. Although, N accumulated in stubble and roots will remain, the net effect on the soil N balance may be small or even negative, particularly with grain legumes which generally obtain a smaller proportion of their N from the atmosphere. The benefits will be even less if straw or other crop residues are removed as well as the grain.

As with cereal straw, bean straw can also be baled and used for bedding or feed (Taylor & Cormack 2002). If the harvested forage or grain is fed to animals on the farm, the fixed-N that it contains will be retained within the farm system. The N will ultimately be returned to the soil in animal manure, but not necessarily to the same field. The efficiency of this recycling will depend on the scale of N losses during housing of the stock, storage of the manure and subsequent spreading.

The net contribution of a legume to the soil-N balance will be influenced by the partitioning of fixed-N within the plant, particularly between the grain and other plant parts. For example, lupin was shown to fix more N than field pea and also contained a significantly lower proportion of its total plant N in the mature seed (Unkovich *et al*. 1995). Accordingly, the net input of fixed-N as lupin shoot residues (average 68 kg N/ha) was considerably greater than that for pea shoot residues (3 kg/ha). When N in root and nodule biomass was included, total potential N benefits from above- and below-ground residues after grain harvest were estimated to be about 75 kg N/ha for lupin and 26 kg/ha for pea.

The data in Table 4.2 are from a study in Germany in which a wide range of legumes were grown and the N content of the above- and below-ground parts of the crop determined. It is clear from these results that there is a higher proportion of the plant N in the roots of fodder legumes than for grain legumes. As a result, fodder legumes will generally contribute more N to the soil, even where the crop is exported from the field. Typical quantities of N removed in the seed of the most common temperate grain legumes are shown in Table 4.3 (Sprent & Mannetje 1996). Yields in the table are typical farm values; those for organic farms are likely to be towards the lower end of these ranges.

Table 4.2. Offtake of N in shoot and root of various legumes (von Fragstein 1995).

Crop	Shoot (kg N/ha)	Root (kg N/ha)	Total (kg N/ha)	Root (%)
White lupin (*Lupinus alba*)	448	93	541	17
Blue lupin (*L. angustifolius*)	429	73	502	15
Yellow lupin (*L. luteus*)	213	86	299	29
Faba bean (*Vicia faba*)	320	57	377	15
Field pea (*Pisum sativum*)	291	40	331	12
Dwarf chickling vetch (*Lathyrus sativa*)	273	24	297	8
Spring vetch (*Vicia lathyroides*)	238	36	274	13
Soy bean (*Glycine max*)	178	31	209	15
Average	*299*	*55*	*354*	*16*
Red clover (*Trifolium pratense*)	381	118	499	24
Egyptian clover (*T. alexandrinum*)	412	125	537	23
Persian clover (*T. resupinatum*)	402	123	525	23
Swedish clover (*T. hybridum*)	303	173	476	36
White clover (*T. repens*)	322	131	453	29
Lucerne (*Medicago sativa*)	469	157	626	25
Yellow clover (*Melilotus officinalis*)	332	132	464	28
Kidney vetch (*Anthyllis vulneraria*)	209	143	352	41
Sainfoin (*Onobrychis viciifolia*)	184	140	324	43
Italian clover (*T. incarnatum*)	210	88	298	30
Average	*319*	*128*	*447*	*29*

Table 4.3. Amounts of N removed in the dry seed of temperate legumes (Sprent & Mannetje 1996).

Crop	Yield (kg/ha)	Growth period (days)	N removed (kg/ha)
Pea (*P. sativum*)	1000-2000	60-80	35-90
Field bean (*V. faba*)	3000-6000	90-220	105-210
Lupin (*L. albus*)	1000-2000	150-200	35-90
French bean (*P. vulgaris*)	1000-2500	50-80	35-107

Seed N assumed to be between 3.5 and 4.5% in dry matter

Peas grown in Alberta fixed 117 kg N/ha (excluding roots) and 219 kg N/ha was removed in pods. Corresponding values for field bean were 92 kg N fixed/ha and 121 kg/ha removed in bean pods (Kucey 1989). Fisher (1996) stated that most of the fixed-N in dry beans and peas is removed in the grain. However, where peas are harvested green (e.g. for freezing) much of the fixed-N is left in the unharvested parts of the plant (Sprent & Mannetje 1996). Pea roots are seldom found to contain more than 15-30 kg N/ha; however, most simple root measurements are inefficient at recovering finer roots and are likely to have underestimated the quantity present (Jensen 1995).

Mayer et al. (2003) investigated why the benefit of grain legumes was often greater than could be explained by the small contribution from their residues to the N balance. They concluded that this was because of N rhizodeposition, defined as root-derived N in the soil after removal of visible roots. The distribution of N in the plant at harvest is shown in Table 4.4, together with a breakdown of the forms of N in the rhizodeposition fraction. A large part of the ^{15}N label in this fraction could not be recovered and was thought to be immobilised in microbial residues. Measurements were made after harvesting the crop and do not provide information about how much of the rhizodeposition occurred during crop growth rather than from senescence of the mature crop.

Table 4.4. Distribution of N in faba bean, pea and lupin at maturity, expressed as % of total plant N (including rhizodeposition) and recovery of rhizodeposition-N in different soil pools (Mayer et al. 2003).

	Faba bean (*V. faba*)		Pea (*P. sativum*)		White lupin (*L. albus*)	
	Distribution of N in plant at maturity (as % of total plant N)					
Grain	62.0		72.2		61.1	
Stems & leaves	20.8		12.2		20.3	
Roots	3.8		2.8		2.8	
Rhizodeposition	13.4		12.8		15.8	
	% of ^{15}N label derived from rhizodeposition in different soil pools					
Micro-root N	16		31		7	
Microbial N	14		18		14	
Mineral-N	5		3		7	
N not recovered	65		48		72	

Goins & Russelle (1996) examined the effects of repeated herbage removal on root turnover and N transfer to the soil in the first year of a lucerne crop. During the year, this released an estimated 60 kg N/ha (and 830 kg carbon/ha).

Most estimates of N-fixation by forage legumes only include N in the above-ground parts of the plant. As the same plant parts are removed in normal agricultural harvesting operations, this will account for most of the estimated above-ground fixation. The benefit to following crops will therefore be largely dependent on the fixed-N left in the unharvested roots and stubble. With some crops this can be an important source of N.

Estimates suggest that an amount equivalent to between 20 and 70% of above-ground clover N may be partitioned to non-harvested plant parts (Heichel *et al.* 1985; Høgh-Jensen & Kristensen 1995; Jørgensen & Ledgard 1997; McNeill *et al.* 1997). The proportion of the annual fixation partitioned to roots will depend on the stage of growth and root turnover. Kristensen *et al.* (1995) concluded that the equivalent of 24-29% of the harvested fixed-N would be transferred to roots in the first two years after establishment but none in later years.

4.3. Effects of grazing on N capture and loss

Much of the N that is ingested by grazing animals is returned to the soil in excreta; therefore, more N would be expected to accumulate under grazing than where forage is cut and removed. In Australia, grazing of subterranean clover swards, increased total soil-N and grain protein of the following crop compared with mowing and mulching. Soil mineral-N was usually also higher but grain yield was unaffected (Heenan *et al.* 1998).

Grazing influences N-fixation in pastures by altering the proportion of legume in mixed swards, through defoliation and through the inhibitory effects of N in dung and urine on the fixation process. The recycling of N in excreta also represents an important route for transfer of fixed-N from the legume to grass in mixed swards. This can be of a similar magnitude to 'below-ground' transfer (e.g. 3-102 kg N/ha/year or 2-26% of the N fixed) (Ledgard 1991; Ledgard & Steele 1992). The effects of grazing on pasture composition will differ for different types of livestock, as well as the intensity of grazing.

Herbivores exhibit different preferences for the individual components of mixed pastures (Ledgard & Steele 1992). As a result, clover contents are likely to be less with sheep than with cattle and greatest with goats which preferentially select grass and weed species. Intensive grazing, especially frequent defoliation during spring, has been shown to favour a high proportion of legume and to increase N-fixation. For example, increases in fixation of 33% and 10% were observed with more intensive grazing in studies in Argentina and New Zealand (Refi *et al.* 1989; Brock *et al.* 1983). However, grazing also influences the competition between grass and clover through the high inputs of N to the soil in excreta and this will favour grass dominance. This reduction in the proportion of clover may persist for up to 3 months and was considered to be relatively more important in reducing overall fixation than the shorter-term (30-60 day) effect of high soil-N reducing %Ndfa in clover (Ledgard *et al.* 1982; Saunders 1984; Vinther & Aaes 1996). The overall effect of grazing has been estimated to be a reduction of 24% in annual fixation for a typical intensive dairy farm in New Zealand (Ledgard & Steele 1992) and 14-21% for organic pastures in Denmark (Vinther & Aaes 1996).

The high input of readily mineralised-N to the soil in excreta would be expected to reduce the proportion of N that clover obtains from the atmosphere. Thus, Ledgard *et al.* (1982) in New

Zealand observed a 40-60% reduction or almost complete inhibition of fixation in urine patches, depending on the time of application. This effect persisted for at least 10 weeks after application. In a Danish study, Hansen & Vinther (2001) found that estimates of %Ndfa averaged over the pasture were generally lower (70-87%) for grazed grass/clover pastures than for ungrazed plots (89 – 95%). Similarly, in a study reported by Eriksen & Høgh-Jensen (1998), the mean %Ndfa in a ryegrass/white clover field was lower for grazed pasture (64%) than in mown plots (79%). Variations in %Ndfa within the plots were higher under grazing, 12-96% compared with 64-92% under cutting, reflecting the uneven distribution of excreta. However, application of urine to plots indicated that within the time span of the experiment, N-fixation per unit of clover dry matter was unaffected by urine. This suggested that newly deposited urine was not the main factor contributing to the greater variation in %Ndfa under grazing.

Results from a similar study by Vinther (1998) demonstrate the short-term effects of urine on %Ndfa and longer-term effects on the proportion of clover. Application of cattle urine and dung to perennial ryegrass/white clover plots affected N-fixation by promoting the growth of grass and thereby reducing the proportion of clover. The proportion of clover-N derived from the atmosphere was also reduced. In untreated control plots, clover constituted between 40 and 50% of the total dry matter production and %Ndfa was between 80 and 90%. Addition of urine caused a significant increase in grass growth rates, which was the primary reason for the decrease in the proportion of clover, and reduced %Ndfa to 20-40%. Together, these resulted in a 45% reduction in N-fixation in urine affected areas over a 4-month period. During the same period, application of dung resulted in a total reduction of 20% in N-fixation in the 10-cm area around the dung pats. Assuming a stocking density of 4-6 cows/ha, it was estimated that overall fixation would be reduced by 10-15% compared to a sward not receiving excreta.

Jørgensen & Jensen (1997) also investigated the short-term effects of simulated cattle dung pats on N-fixation by white clover. Percentage Ndfa varied between 88 and 99% in the 16 weeks following application of the dung. Dung had no effect on %Ndfa in grass/clover mixtures but decreased %Ndfa in pure clover stands by 2-3%. Dung applications did not influence the amount of N fixed. The uptake of dung-N in grass/clover mixtures in the field was similarly followed using ^{15}N-labelled simulated dung pats. It was concluded that fixation around dung patches in grass/clover swards was not influenced in the short term by the release of N from the dung. However, fixation may be reduced because of reductions in the proportion of clover in the zone around the dung patch. Elsewhere it has been stated that death of plants under dung pats may be followed by recolonisation of the patch area by clover and clover dominance for up to 1.5 years (Weeda, 1967). This would presumably counteract any reduction in clover growth within the surrounding area.

Effects of grazing are sometimes difficult to predict because of the interactions that occur in grazed pastures. For example in New Zealand, clover yields in autumn were higher in white clover/ryegrass pasture receiving 200 kg fertiliser-N/ha than for a zero-N treatment but N-fixation was the same. This was attributed to more severe grazing during summer in the zero-N treatment, resulting in higher surface soil temperatures and a deleterious effect on clover stolons. In treatments receiving 400 kg fertiliser-N/ha, a 33% increase in cow stocking rate decreased %Ndfa from 48 to 43% due to more N cycling in excreta but doubled clover dry matter production and N-fixation compared with the less intensive grazing. These benefits were attributed to the lower pasture mass under the more severe grazing pressure, which reduced grass competition, particularly during spring (Ledgard *et al*. 2001).

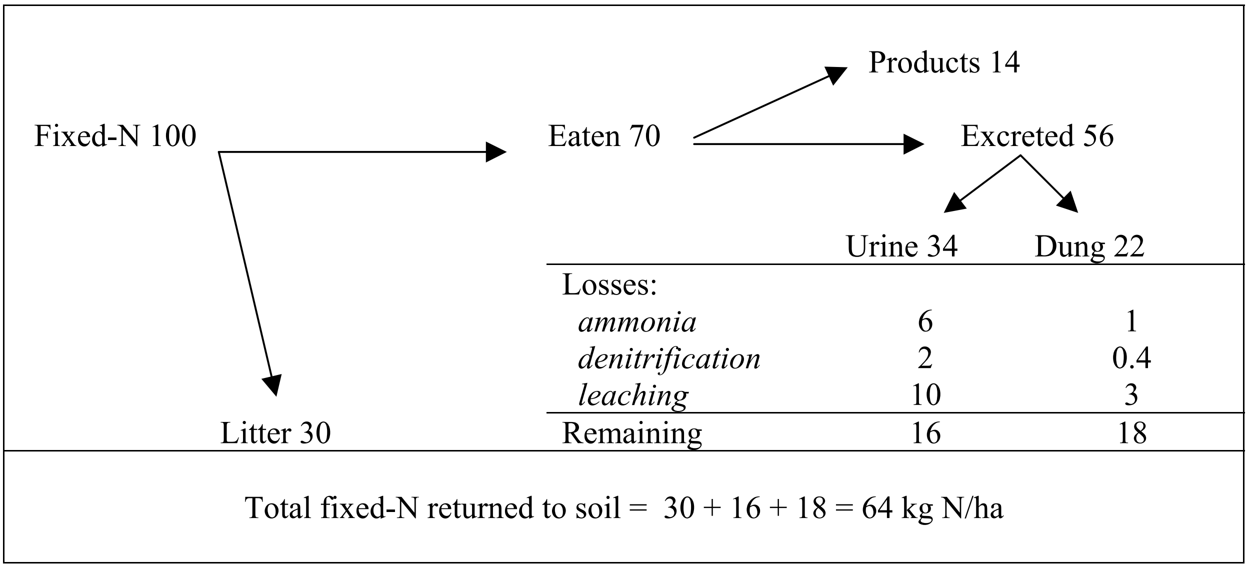
The effects of grazing intensity were investigated in a study with subterranean clover-based pastures in Australia (Unkovich *et al*. 1998). Seasonal pasture yield under light grazing by sheep was 11.5 t dry matter/ha compared with 7.9 t/ha under intensive grazing, the difference being mostly attributable to reduced grass growth under intensive grazing. However, total N accumulation was the same in the two pastures, at about 300 kg N/ha. The lower dry matter production under intensive grazing was compensated for by higher N concentration and increased clover content of the sward, and faster clover growth late in the growing season. Nitrogen-fixation by clover was slightly greater under intensive grazing (153 kg N/ha) than under light grazing (131 kg/ha). There was little difference between %Ndfa values under intensive (78%) and light grazing (84%), despite higher availability of soil mineral-N with the higher stocking rate.

Grazed pastures will accumulate more N than those under a cutting management because much of the N that is consumed by grazing animals will be recycled to the soil in their excreta. The availability of this N to subsequent arable crops may also be increased by intensive grazing (Unkovich *et al.* 1998). However, estimating how much of the total N that has been fixed will accumulate in the soil is difficult because of the losses that occur during N cycling in grazed pastures. These losses may be considerable. Indeed, Ball & Keeney (1981) questioned the value of excreted N to grazed pastures because of the inefficiencies and large losses involved. Typically, cattle on well-managed pastures will utilise 65-75% of the herbage produced and will excrete 80% of the N they consume. Assuming 100 kg fixed N/ha in herbage and losses as described by Ledgard (2001), the fate of this N might typically be as shown in Table 4.5. The proportion of urine-N lost by leaching is estimated from Cuttle *et al.* (2001) but depends on when in the grazing season the urine is deposited. Losses will be greatest for urine deposited later in the season when there is less time for the sward to utilise the high concentrations of N added to the soil. Together, these figures suggest that of the 100 kg N fixed, 64 kg could contribute to the soil N pool. This is comprised of 30 kg added directly in unutilised herbage and, after accounting for losses, a further 34 kg returned *via* excreta. This simple example ignores the possible uptake and recycling of N from litter and excreta. For dairy cattle, there are additional losses from the field in the form of N excreted in the dairy during milking and on tracks while travelling to and from milking.

Nitrate leaching from grass/clover leys on three organic farms in the UK averaged 36 kg N/ha in the seeding year (range 1-114 kg/ha) and 11 kg/ha in subsequent years (range 0-52 kg/ha) (Stopes *et al.* 2002). Estimates from a range of studies indicate that the overall quantities leached from unfertilised grass/clover pastures are in the range 5 to 75 kg N/ha, with the majority of values below 30 kg/ha (Ledgard 2001). Total denitrification, ammonia volatilisation and leaching losses averaged 6, 7 and 23 kg N/ha, respectively. As the primary source of N-loss from grazed pastures is volatilisation and leaching from urine patches, the overall loss will increase with increasing stocking rate (and hence greater number of urine patches). Large leaching losses of about 200 kg N/ha have been measured where pure stands of clover were grazed (Macduff *et al.* 1990).

When taken with average values of above- and below-ground fixation, these typical losses are in general agreement with suggestions that grass/clover leys could accumulate about 120 kg N/ha annually (Scholefield & Smith 1996).

Table 4.5. Example of the fate of fixed-N in grass/clover swards grazed by cattle, assuming 100 kg/ha fixed-N in the above-ground herbage (values in kg N/ha/year).



Note: The feeding potential of the less common forage crops is not known and some, e.g. sweet white clover, have been reported to be toxic in some circumstances.

4.4. Interactions with manures and composts

It is necessary to supply adequate P and K to ensure satisfactory growth of legumes, particularly where there are large offtakes of soil nutrients, as in silage crops. On organic farms, these nutrients are most likely to be supplied as animal manures and composts. As these materials also contain N, their use may inhibit N–fixation in the short-term and reduce clover contents in the longer term.

The conflicts inherent in applying manures to grass/clover swards have been discussed by Baars (2000). Animal slurries may be expected to have a greater immediate effect on fixation than farmyard manure or well-prepared composts which normally have a lower proportion of N in a readily-available form (Dewes & Hünsche, 1999).

However, recent Defra-funded studies (Cuttle, 2003) indicate that slurry applications need not necessarily reduce the quantities of N fixed. Individual applications of cattle slurry to grass/clover swards affected N-fixation to differing degrees. Most applications caused only a small reduction in %Ndfa but in the most marked case, %Ndfa was reduced from 84 to 58% by the application of slurry. Even in this case, the actual quantity of N fixed appeared to be little affected. The reduction in the *proportion* of fixed N could be explained by an increase in total plant-N due to uptake of mineral-N from the slurry, rather than because of a reduction in the *quantity* of N obtained from the atmosphere. Additional work is required to confirm these findings. It was suggested that the K supplied in the slurry may have offset the deleterious effects of slurry-N in this K-deficient soil (as also proposed by Chapman & Heath (1987)). Nesheim *et al.* (1990) observed more marked effects of cattle slurry applied to grass/clover swards at two sites in Switzerland. Slurry (at 50 m^3/ha) reduced %Ndfa from 87 to 63% at the first harvest at one site and from 94 to 83% at the second site. N-fixation over two harvests was reduced from 67 to 28 kg N/ha and from 36 to 22 kg/ha at the two sites. Nitrogen-fixation and proportion of clover were reduced less by the slurry than by inorganic fertiliser supplying an equivalent amount of N.

Yields of grass-clover leys responded positively to applications of cattle slurry during a study by Steinshamn (2001). The positive response in spring was unaffected by the proportion of clover, whereas in the subsequent regrowth it tended to diminish with increasing clover content. On average, slurry application reduced the proportion of clover in dry matter by 7%-units in spring growth and 13%-units in the regrowth.

In a greenhouse experiment with soybeans, Moharram *et al.* (1999) observed that nodule numbers per plant increased with increasing compost application in both inoculated and uninoculated plants. The highest nodule numbers were obtained with an intermediate level of compost and coincided with the highest %Ndfa in the plants. Contrasting results were obtained in a pot trial with soybean in Japan. The number of nodules, nodule weight and N fixed/plant were reduced by increasing rates of farmyard manure (FYM); however, nodule formation was inhibited less by FYM than by urea. The N fixing capacity/unit weight of nodules increased with increasing rate of FYM. The inhibition by FYM decreased with time and at harvest FYM increased seed yields and N fixed but did not decrease %Ndfa. It was considered that FYM increased seed yield by improving N-fixation rather than by increasing available-N (Yoshida 1979). There was a beneficial effect of manure in a study with vetch (*V. sativa*) in Greece. Growth and nodulation were much better on plots that had received FYM than where N and P had been applied as mineral fertiliser (Sidiras *et al.* 1999). An investigation in Canada demonstrated that nodulation of soybean was stimulated by addition of organic matter or manure (Johnson & Hume 1972).

4.5. Effects of soil management and crop rotations

Various aspects of soil management can influence N-fixation. In many cases this will be through their effect on the soil mineral-N levels experienced by the legume, with the legume obtaining a greater proportion of its N from the atmosphere in low-N soils. Thus, more N is likely to be fixed where legumes follow crops that have previously depleted soil-N levels. This is likely to be the situation in most organic rotations, where leguminous crops normally follow a N-depleting phase.

Nevertheless, there will be differences in N-availability in different soils; for example, between soils on stockless farms and on predominantly livestock farms which are able to include a greater proportion of leys in the rotation or between soils of contrasting textures. However, it is possible that soil-N status has less effect on fixation in mixed swards than where the legume is grown alone. In high-N soils, N uptake by the non-legume component of mixtures may reduce mineral-N concentrations sufficiently to avoid the inhibitory effects on fixation (see Section 3.2.5).

Cultivation practices that increase mineralisation of soil organic matter will lead to increased levels of soil-N with the result that following legume crops obtain less of their N from the atmosphere. A number of studies have demonstrated greater fixation in minimum tillage systems, presumably because this minimises the flush of mineralisation that occurs with more disruptive, conventional cultivation practices such as ploughing.

As described in Sections 3.1.2 and 3.1.10, a study in Germany demonstrated that %Ndfa was higher in both pea and red clover when grown in a minimum tillage system compared with conventional ploughing (Reiter *et al*. 2001 & 2002). The effect of the cultivation treatments was twice as great with pea as with clover. This was explained by the shorter growth period of pea and its greater sensitivity to the lower N mineralisation in the minimum tillage system in springtime. Similarly, a study in Canada showed that N-fixation was 10% higher for lentil and 31% higher for pea when grown using zero tillage as compared to conventional tillage practices (Matus *et al.* 1997). There was also a 12% increase in fixation where lentil was grown in more diversified rotations with cereal and oilseed crops. In a study reported by Simon & Skrdleta (1983), comparing ploughing and no tillage, zero-tillage significantly reduced dry matter production in broad beans but not in peas. Nodulation in both crops was reduced by zero-tillage.

Table 4.6. Effect of tillage and straw incorporation on N-fixation by pea (Jensen 1998).

Treatment	Total N (kg/ha)	%Ndfa	N fixed (kg/ha)
No-till	169	79.5	136
Tilled	170	77.4	131
Tilled+straw	148	86.6	129

A study in Denmark also compared fixation by pea in no-till and conventionally tilled plots (Jensen 1998). In this experiment, there was no significant difference between %Ndfa or the quantity of N fixed in the two treatments. However, incorporation of barley straw to immobilise soil mineral-N did significantly increase %Ndfa (Table 4.6). Similarly, Evans *et al.* (1995) found that addition of straw at a maximum application of 10 t/ha increased %Ndfa in peas to 96% compared with 67% without straw.

4.6. Conclusions

- The literature provides considerable evidence that management factors can influence N fixation by a legume.
- Effects on fixation can be divided into
  - Those that influence the net accumulation of N
  - Those that influence the N-fixation process directly
- High concentrations of soil mineral N are generally thought to reduce fixation capacity. Factors that will increase the soil mineral N pool include:
  - Manure application

  - Cutting and mulching
  - Grazing
- Fixation tends to decrease with legume age, mainly because the soil mineral N pool tends to increase.
- A consequence of generally increasing fertility on an organic farm (by slowly building soil organic matter levels) is that this could decrease fixation.
- Cutting and mulching is a standard practice in organic rotations, yet it may be that such a practice is decreasing fixation and the amount of N imported into the rotation from the atmosphere.
- Harvesting of forage or grain will remove much of the fixed N and reduce the benefit to following crops. The benefit will be further reduced if straw and other crop residues are also removed from the field.
- Other aspects of management affecting N-fixation include:
  - Position of the crop in the cropping rotation
  - Duration of cropping
  - Methods of cultivation
- Because of the conflicting interactions between N fixation and soil N status, management decisions often have to be a compromise.
- If growers can understand the main factors affecting fixation, then they can try to manage their crops to achieve the objectives they want.
- Unfortunately, management to maximise fixation may be conflict with the overall farm plan – e.g. cutting/mulching may be the only option in a stockless system; grazing of grass/clover swards is necessary on livestock farms.

5. USE OF MODELS TO ESTIMATE N-FIXATION

In view of the practical difficulties of measuring N-fixation in the field and the unsuitability of available methods for routine on-farm use, a number of workers have attempted to develop more convenient, indirect ways of estimating N inputs from this source. Such approaches have advantages and disadvantages. The previous chapters have shown that there are many factors that influence fixation, some of which can be more easily incorporated into models than others.

The challenge with any advisory model is to restrict the amount of input information and parameters that are required (so that it is easily used), but to ensure that the information is sufficiently detailed to include the most important variables. An advisory model should also be sensitive to the major management effects, so that it can be used to advise on best practices.

As discussed in Section 1, there are two aspects to providing a model for encouraging better use of fixed N: estimating fixation and estimating utilisation of N during the arable phase following destruction of the legume. The models in this Section deal with the first stage.

Watson *et al*. (2002) summarised the factors that models tend to include for predicting N-fixation - not all models take account of all factors:

- Yield of legume and grass
- Yield of grass-only reference crop (or some other indicator of soil N supply)
- % legume in mixture
- Years after establishment
- N content of legumes
- N content of legumes plus grass
- N content of grass-only reference crop
- % legume N derived from fixation
- Correction for fixed-N in stubble and roots
- Sward management

5.1. Simple yield-based models

Several studies have shown **N-fixation and legume yield to be strongly correlated**; for example, in white clover, red clover, subterranean clover and lucerne (Bolger *et al*. 1995; Goh & Ridgen 1997; Heuwinkel & Locher 2000; Kumar & Goh 2000; Loges *et al*. 2000a; Goh *et al*. 2001). This relationship has been used to provide estimates of N-fixation, assuming that a particular amount of N is fixed for every tonne of clover dry matter. Hence, N-fixation can be simply calculated from an estimate of the clover yield. This requires that %Ndfa and N concentration remain constant, which is not always the case but average Ndfa values may be suitable for determining annual fixation. However, from the interactions between N-fixation and the various soil and environmental variables discussed in the previous sections, it is apparent that %Ndfa for a particular crop will differ between soils, climates and managements. Examples of approaches are shown below:

Van der Werff *et al.* (1995) estimated N-fixation in **grass/clover pastures** on mixed, organic farms on sandy soils in the Netherlands by assuming values of:

- 40 kg N fixed per tonne of dry matter for red clover
- 54 kg N fixed per tonne of dry matter for white clover.

Vinther & Jensen (2000), for **grazed grass/clover pasture** in a grass/arable rotation on a sandy loam in Denmark, assumed that the quantity of N fixed per tonne of white clover shoot dry weight was:

- 38.6 kg N fixed per tonne of dry matter for first and second year mixtures
- 45.0 kg N fixed per tonne of dry matter for undersown grass-clover.

These were similar to other values from the literature, cited in the paper: i.e.

- 30-46 kg N fixed per tonne of dry matter for white clover
- 24-36 N fixed per tonne of dry matter for red clover.

Wheeler *et al.* (1997), in New Zealand, estimated the amount of N fixed as:

- 40 kg N fixed per tonne of dry matter for white clover on a high rainfall site
- 46 kg N fixed per tonne of dry matter for subterranean clover on a low rainfall site

In Australia, Bowman *et al.* (2002) concluded that the amounts of N fixed were predominantly regulated by the legume content and herbage yield of pastures rather than by any marked differences in the ability of the legume to fix N. Their data indicated that **lucerne and subterranean clover fixed 22-25 kg N for every tonne of legume dry matter produced.**

Sanford *et al.* (1995) adopted a similar approach in a study with subterranean clover in western Australia and concluded that a reliable estimate of fixation could be obtained from assessments of cumulative biomass yield of clover N and a single determination of %Ndfa at peak productivity in mid to late spring.

5.2. More complex models

There have also been more complex, modelling approaches to estimating fixation. Wu & McGechan (1999) adapted the soil N dynamics model SOILN to provide a representation of C and N processes in grass/legume mixtures. Nitrogen-fixation was determined as the potential fixation reduced by appropriate environmental factors, particularly temperature. Schwinning & Parsons (1996) extended the pasture model of Thornley *et al.* (1995) to provide an explanation of the population oscillations that occur in grass/clover pastures as a result of grazing, N-fixation and mineral-N availability. Spatz & Benz (2001) used an approach based on this model to simulate N-fixation by white clover in permanent pasture. The fixation rate (g N/m^2/day) was described in terms of clover dry matter and soil mineral-N by an expression of the form:-

$$\text{N-fix} = e*c*XC*\{1 - f[MN/(2 + MN)]\}$$

where XC is the structural carbon (dry matter) of clover (g/m^2), MN is the content of mineral-N in the soil (g/m^2) and e, c and f are constants.

The regression model described by Väisänen *et al.* (2000) also includes a factor for soil-N; in this case as soil nitrate-N measured in spring (to a depth of 20 cm). For grass/red clover swards in Finland, biological N-fixation (BNF) was calculated as:

BNF (g/m^2) = 0.020 x clover yield (g/m^2) – 0.268 x soil nitrate ($g\ N/m^2$)

This equates to a maximum fixation of **20 kg N per tonne clover DM**, modified downwards for soil mineral N content. This estimate is lower than yield-based estimates reported above (by approximately a factor of 2), possibly because of the growing conditions in Finland.

Fixation in standing crops of lupins has been estimated from crop height, plant population density and a bioassay of soil mineral-N (based on N uptake by a cereal crop) (Evans & Heenan 1998). Estimates also included adjustments for rainfall, sowing date and cereal-N. The authors also examined procedures for estimating the potential contribution of N-fixation to soil-N, and the effects of lupin and cereal N budgets on soil N balances based on differences in fixed-N and grain-N.

A study of N balances for contrasting cropping systems in Norway by Korsaeth & Eltun (2000) included a procedure for estimating N-fixation by a number of legume species. Fixation ($g\ N/m^2$) was calculated as the product of:

$Y \times L \times N_{leg} \times F \times R$

where Y = crop yield (g dry matter/m^2)
L = proportion of legumes (g/g)
N_{leg} = N content of the legumes (g N/g dry matter)
F = fraction of N_{leg} originating from fixation (g N/g N)
R = a factor accounting for the net accumulation of fixed N below stubble height.

F was calculated from the expression: $F = F_{max} - aN_{net\ inorg}$ ($F \geq 0$) where F_{max} is the maximum fraction from fixation, a is a constant and $N_{net\ inorg}$ is the net amount of inorganic N applied as fertiliser and/or available from slurry.

Values of these parameters were included for white and red clover at first and second cut, and for grey peas (*P. arvense*) and common vetch (*V. sativa*).

The relationship between N-fixation and clover yield also appears to hold at smaller scales. Hansen *et al.* (2002) measured fixation and sward characteristics at 81 randomly selected points within a grass/clover ley grazed by dairy cows. Fixation exhibited a significant but weak positive correlation with clover dry matter yield but was not correlated with the proportion of clover in the sampled herbage. This was in spite of a wide range of clover contents, from 18 to 78%. At the field scale, however, Gruber *et al.* (2001) used the proportion of clover to estimate fixation in a comparison of organic and conventional grassland farming in Austria, assuming a relationship of 3 kg N/ha fixed per percentage legume.

The simple model described by Kristensen *et al.* (1995) was designed specifically for use on commercial farms. Fixation is again estimated from the proportion of clover in the sward but in this case, also takes account of the age of the pasture, summarised in Table 5.1. These values include fixed-N in roots and stubble. It was concluded that there was a net accumulation of fixed-N below stubble height in the first two years after establishment equivalent to 24 – 29% of the harvested fixed-N but no further accumulation in later years.

Table 5.1. Annual N fixation in grass/clover swards (kg/ha/year) as influenced by clover content and sward age, adapted from Kristensen et al. (1995).

Sward age	Clover content (%)		
	10-29	30-49	>49
Years 1-2	80	157	248
Years 3-5	47	84	128

This approach is particularly suitable for use on commercial farms as estimates are based on a visual assessment of clover content rather than a measurement of clover yield, which is unlikely to be available on most farms. The relationship between visually assessed clover content and the content as more usually determined from dry matter yield was described as:

$$\% \text{ clover (visual)} = (3.35 + \% \text{ clover in dry matter})/0.669$$

These methods assume a linear relationship between the proportion of clover and the quantity of N fixed. This may be an over-simplification, which will also affect estimates based on clover yields. The interactions between soil-N status and fixation discussed in Section 3.2.5 suggest that %Ndfa in grass/clover swards is likely to decrease with increasing clover content as the proportion of grass roots declines and the grass becomes a progressively less effective N-sink. This has been discussed by Baars (2002) who demonstrated that a curvilinear equation more closely described the relationship between measured clover yield and N yield. In practice, however, errors arising from adopting a simpler linear relationship may be relatively unimportant compared with the other uncertainties inherent in the various estimates of N-fixation. In these studies by Baars (2002), the amount of N fixed per tonne of clover differed between swards receiving different manure treatments: values were 44.2 kg N/t for swards with mineral (PK) fertiliser, 39.9 kg/t with FYM and 31.1 kg/t with slurry.

Watson & Goss (1997) established simple linear regressions from the literature relating N-fixation by grass-white clover mixtures to the extra dry matter production of mixed swards (M_d kg/ha) compared with unfertilised pure grass swards. Nitrogen-fixation was obtained from the expression:

$$\text{N-fixation (kg N/ha)} = A + 0.067M_d$$

where A is a constant with a value of 6.8 for cut swards and -168.1 for grazed swards. The approach overestimated N-fixation for grazed grass by an average of 15%. A similar approach had previously been used by Barry *et al.* (1993) to estimate fixation in lucerne/grass mixtures.

The requirement for an unfertilised grass reference plot would preclude the ready application of this approach to estimating N-fixation on commercial farms.

Papastylianou (1999) described a series of equations based on quantities of N that are readily measured in the crop and soil to estimate the net amount of N fixed by legumes in short- and long-term cropping systems. The method requires a non-fixing reference crop. The calculations take full account of the above- and below-ground system components, including the non-fixing crop that follows the legume in the rotation. An example was provided for a long-term vetch/barley rotation in Cyprus. The calculated fixation using this method (184 kg N/ha) was twice that estimated by methods that include only the above-ground vetch production.

5.3. Conclusions

- Many factors affect N fixation. Representing all of these within models is almost impossible.
- This conflicts with the need for advisory models to be as simple as possible, in terms of required input data.
- But the information needs to be sufficiently detailed that models can estimate N fixation and the influence of key management factors on it.
- There have been many attempts to produce models. The main factors that the models tend to include are one or more of the following:
  - Grass/clover swards - % clover
  - Legume dry matter yield
  - Sward age
  - Soil mineral N content
- A sensitivity analysis and comparison of model predictions would be a useful starting point in comparing the relative value of the respective approaches for UK conditions.
- Grass/clover is the most modelled system. Many other legume systems have not been modelled at all.
- Model output tends to be kg/ha fixed N. It is sometimes necessary to clarify whether this refers to the whole plant or is above-ground fixation only.
- It is difficult to link these estimates of fixation to utilisation models because they do not generally provide information on the residue quality: C:N ratio, lignin content.
- The literature provides little data on fractionation of the C and N in the fertility-building crop.

6. UTILISING N FROM FERTILITY-BUILDING CROPS

6.1. Introduction

So far, this review has focused on the quantity of N fixed by fertility-building crops, i.e. the amount of N imported to the field by atmospheric N fixation. This has been the focus because this represents the net increase in the N status of the rotation. However, N fixation by the fertility-building crop is only one part of the process in which atmospheric N is trapped and utilised within the rotation. It then has to be released and made available to the following crops.

First, however, it is necessary to consider the pools of N in the soil-crop system at the end of the fertility-building stage:

- Soil mineral N in the soil profile, the amount depending on history and management of the fertility-building crop. Much of this may well have derived from mineralisation of organic residues during the fertility-building stage (or from recent manure applications).
- N in the microbial biomass.
- N in roots and nodules and from rhizodeposition.
- N in leaf litter (e.g., at various stages of decay), either from natutral leaf drop or from cutting and mulching the fertility-building crop. This may also be from, for example, straw residues if the crop has been harvestsed and removed from the field (e.g. peas/beans).
- N in above-ground components, such as stubble and foliage.
- N in manure residues, if manure has been applied recently or the crop has been grazed.
- N in native soil organic matter.

Therefore, the N that can potentially be used by the subsequent crops may be in mineral or organic forms. Most will be in a range of organic fractions of varying recalcitrance. Generally, the organic forms of N associated with the fertility-building crop can be termed ‘residue N’.

It should also be noted that not all of the residue N will necessarily be fixed N – some will have derived from uptake of (a) N released from the native soil organic matter and (b) soil mineral N in the soil at the time of establishment of the fertility-building crop.

The proportion of non-fixed N will depend on many factors, as described in the previous Sections. How effectively the residue N is used by the subsequent crops in the rotation will depend on many factors, including:

- the rate of net mineralisation
- efficiency of uptake by crops
- N removal in harvested products
- N (and C) return in plant residues and
- losses of N

The rate of depletion will be reduced if manures are applied or if the rotation includes further legumes during this phase.

This Section therefore considers the factors affecting mineralisation, interaction with loss processes and methods of predicting N release.

6.2. Factors affecting N mineralisation

The mineralisation of both C and N in soils is intimately linked. Nitrogen mineralisation is performed by non-specific heterotrophic soil microorganisms under aerobic and anaerobic conditions when they use organic N compounds as energy sources (Jarvis *et al.*, 1996).

During the mineralisation process, some of the C and N mineralised is incorporated into the cells of the soil microorganisms, the excess C and N is liberated as carbon dioxide and ammonium respectively. Where the N content of the organic substrate being mineralised is insufficient to supply the nutritional requirements of the growing microbial population additional N may be obtained from the soil mineral N (ammonium and nitrate) pool. This consumption of N by the microbial population is called immobilisation. However, when the soil microbes die some of the immobilised N is mineralised and again becomes available for plant uptake, loss or re-immobilisation. This cycling of N is called mineralisation/immobilisation turnover (MIT). Both mineralisation and immobilisation often occur simultaneously. Consequently, it is 'net' N mineralisation, the balance between gross mineralisation and gross immobilisation, that determines the availability of mineral-N in the soil.

Field and laboratory studies have shown that temperature and moisture are the most important environmental factors controlling soil N mineralisation, because of their effects on microbial growth and activity.

The mineralisation of soil organic matter (SOM) by Mesophyllic soil organisms is optimal at 25-37 ^{o}C, with a basal rate at about 5 ^{o}C. In contrast, Psychrophiles are active at low temperatures and may contribute to mineralisation in winter and early spring. Gill *et al.* (1995) estimated that only 21-38% of the annual net N mineralisation in long-term grassland occurred in Nov-Feb. The soil water content is also important because of it effects on the microbial population and soil/plant interactions. In general, mineralisation is optimal between - 0.33 and - 0.1 bar (80-90% water filled pore space). The microbial biomass may account for 0.5 - 15% of the total soil N pool, but its turnover rate (i.e. flux of N through the biomass) is 5-10 times greater than the soil organic N as a whole. It is considered to comprise of Autochthonous (slow decomposers) and Zymogenous (fast turnover) species (Smith *et al.*, 2002). The active microbial biomass generally declines with increasing soil depth. Some studies suggest that the proportion of fungal and bacterial biomass is important in regulating the activity of the soil microbial population (Landi *et al.*, 1993).

Relatively little work has been done on the effects of soil fauna on the mineralisation of SOM. Consequently, it is not often explicitly addressed in models of C and N turnover, and is often deliberately excluded in incubation studies. However, it is known that earthworm activity enhances C and N mineralisation by increasing soil mixing which in turn enhancing contact between organic residues and the soil microbial population. Microbivorous fauna such as protozoa and nematodes may also enhance N mineralisation and recycling of N in root exudates.

Organic matter within small pores is less accessible to some soil organisms. The distribution of water and oxygen also varies with pore size, with more water and less oxygen retained in small soil pores. Thus the balance between mineralisation and immobilisation will vary with pore size. In general, mineralisation will decline with decreasing pore size. Therefore, clay soils often contain more organic matter than coarser textured soils.

It is widely accepted that the proportion of physically protected organic matter increases with increasing clay content of the soil, because more is located in small pores (<1.2 um) and is adsorbed on clay surfaces (Jarvis *et al.*, 1996).

Ultimately, an increase in SOM may lead to enhanced net N mineralisation. Estimates of N mineralisation derived from data in the MINIM database (Glendining, 1997) indicated possible regional differences in net N mineralisation in the UK. Clay soils mineralised most in the South-west and South-east regions while in Eastern regions most N was mineralised from loam soils. Less N was mineralised from clay soils in this region than in the South-east and South-west.

Cultivation practices affect SOM turnover because of the dramatic changes to the physical, chemical and biological interactions within the soil following ploughing. Intensive cultivation increases soil porosity and temperature and decreases the stability of soil aggregates, resulting in decreases in SOM content and water holding capacity. The physical disruption of SOM by ploughing often enhances net N mineralisation as a result of increasing aerobicity and exposure of organic matter to microbial decay (Silgram & Shepherd, 1999).

As well as the soil and management factors described above, the chemical and physical quality of the returning residue has a large influence on the rate of decomposition. Rahn (2002) found both %N and %C to be good predictors of the decomposition over the first phase described by Berg (1986). Anderson (1973), working on hardwood litters, and Flanagan & Van Cleve (1983), working on grasses, both found the rate of decomposition to be well correlated to the C:N ratio. Thomas & Asakawa (1993) found the release of N from grasses and legumes depended on the C:N ratio, while De Neve *et al.* (1994) found the same ratio to be a good predictor of N mineralisation from vegetable residues.

A key factor is the C:N ratio of the crop residue, which influences the rate of decomposition and nutrient availability. Young green material with C:N of 15 will break down rapidly and release N. Older more 'woody' material with C:N of 80:1 will break down more slowly and release N over a longer period. Well-mulched young green manure residues decompose slowly in the soil because they are relatively stable, having already undergone a significant amount of decomposition. Mature residues with C:N > 40:1 may temporarily immobilise N and reduce supplies to the crop.

Typical C:N ratios of some organic materials are as follows:

- Soil micro-organisms 7
- Soil 10-12
- Clover 13
- Compost 15

- Grazing rye 36
- maize stems 60
- wheat straw 80
- fresh sawdust 400

Philipps *et al.* (2002) hypothesise that there is potential to use different green manures alone or in combination to release N at different stages during growth of the following crop. This may be ambitious, to say the least.

In some cases, the C:N ratio might be too simplistic a measure of degradability because it does not always reflect the accessibility of the C and N to the microbial population. For example, lignin content has been postulated as an important additional factor to take into account when assessing degradability.

Iritani & Arnold (1960), Whitmore & Groot (1994), De Neve *et al.* (1994) and Bending *et al.* (1998) have used the chemical properties of residues to predict N mineralisation, without exploring the nature of the decomposition in detail. Swift *et al.* (1979) introduced the concept of resource quality affecting decomposition processes and Palm & Rowland (1997) took this one stage further by suggesting a minimum dataset required to describe plant quality. In studies using hardwood litters, Berg (1986) and Melillo *et al.* (1989) suggested that the decomposition of litter should be divided into two phases: the first comprising the soluble substances and non-lignified carbohydrates, while the second contained the lignified carbohydrates and lignin. Berg (1986) found that the N content limited the initial decay and that control of decomposition passed to the lignin content in the later stages. Taylor *et al.* (1989) reported that the C:N ratio was the best predictor of mass loss for materials with a range of lignin contents. Bending *et al.* (1998) also noted that N mineralisation from horticultural and agricultural residues in laboratory studies was controlled by different quality factors at different stages of decomposition.

6.3. Nitrogen losses

Nitrogen losses from soil fertility-building crops occur once the N is in mineral form. Loss pathways include:

- Volatilisation as ammonia, NH_3
- Denitrification: loss of N as N_2 or NO_x
- Leaching, predominantly as nitrate, NO_3

Significant **volatilisation of ammonia** will occur from farmed soils during grazing and particularly following applications of animal slurries and manures. There are options available to the organic farmer for reducing volatilisation from slurries and manures. Although losses during grazing are more difficult to control, they are of less significance as they normally represent a much smaller proportion of the total loss.

Strictly speaking, volatilisation is only a direct loss of N from the fertility-building crop itself where it results from the crop having been fed to livestock on the farm. Whatever the source, it does represent a net loss of N from the farming system.

Plant leaves may also lose ammonia to the atmosphere. In most cases this loss is associated with the decomposition of plant material (for example during mulching of cut foliage), but volatilisation can also occur from living plants if supplied with excess N. Whitehead (1995) estimated that the volatilisation of ammonia from decomposing herbage in lowland grassland in the UK was equivalent to 1.4 kg N/ha/year.

Nitrogen can be lost from anaerobic sites in soils through the action of denitrifying organisms converting nitrate to nitrous oxide and dinitrogen gases (**Denitrification**). The denitrification potential of a soil is closely related to the supply of easily decomposable organic matter, not only as a source of C for soil organisms but also because its decomposition utilises oxygen and increases the anaerobicity of the soil (Paul & Clark, 1996). Manures and decomposition of organic materials can produce large accumulations of nitrate substrate in the soil in autumn. The maintenance of high levels of readily decomposable organic matter in organically farmed soils therefore provides conditions favouring denitrification. Nitrous and nitric oxides are also produced in aerobic soils during the nitrification process. As most of the N in organic systems enters the soil in the ammonium form, either directly in manures or after mineralisation of organic matter, there will be a further risk of loss during the conversion of this ammonium-N to nitrate.

Denitrification is generally greater under grazing than from cut swards (Whitehead, 1995). The increased denitrification is a result of the urine excreted by grazing animals, which not only increases the concentration of nitrate in the soil but also increases the moisture content and the amount of soluble organic matter. The limited amount of information available indicates that 0.1 to 0.7% of the N in dung and 0.1 to 3.8% of the N in urine is lost to the atmosphere as nitrous oxide (Oenema *et al.*, 1997). The overall loss, including effects of compaction caused by treading, corresponds to between 0.2 and 9.9% (mean 2%) of the N excreted by grazing animals. There is less information about the additional loss of N as dinitrogen. In a laboratory study in which a clay-loam soil was treated with cattle urine, losses of nitrous oxide over 30 days were equivalent to 1-5% of the urine-N plus N mineralised from SOM, whereas 30-65% was lost as N_2 (Monaghan & Barraclough, 1993). These losses may be greater than would occur in the field as the soil conditions during the experiment were selected to favour denitrification and the restricted airflow during the incubation limited the volatilisation of ammonia.

Indirect evidence of substantial denitrification losses from crop residues was obtained from a lysimeter study in which labelled residues of subterranean clover were incorporated into soil. There was an overall loss of 26% of the added N during one year (Müller, 1987). As only 2% of the loss could be attributed to leaching, denitrification was considered to have accounted for much of the unrecovered N. In a study of denitrification on an organic farm, Baggs *et al.* (1996) found only small increases in N_2O production following incorporation of winter catch crops and green manures. Emissions were less than those from bare ground. This appeared to be due to immobilisation of mineral-N by the incorporated residues. In the absence of concurrent measurements of N_2 losses, it is difficult to assess the significance of the measured N_2O losses.

High organic matter contents in organically farmed soils favour denitrification. Measures to avoid accumulations of nitrate in the soil in autumn and winter will reduce both denitrification and leaching losses.

The main loss of N in drainage is through **leaching of nitrate**. Ammonium ions are retained by exchange sites in the soil and are, therefore, less readily transported in percolating water. Although N fertilisers contribute to the loss from conventional agriculture, mineralisation of SOM and organic residues is considered to provide much of the nitrate leached during winter under the climatic conditions of NW Europe (Powlson, 1993). Much of the understanding of factors influencing leaching from conventional agriculture will therefore be equally applicable to organic farming.

The risk of loss and the processes influencing leaching vary for different phases of the cropping rotation. The greatest risk follows the cultivation of the ley phase when large quantities of N are mineralised. Although high losses at a particular stage of the rotation will influence the immediate, short-term availability of N, the long-term effect on the N status of the soil can only be assessed over the full rotation.

Nitrate leaching losses from cut grassland, where herbage is removed from the field, are generally small. This can be attributed to the well-established rooting system and permanent crop cover which is able to utilise N as it is made available. Greater losses occur where pastures are grazed because of the large returns of N in excreta. Urine deposition from grazing animals, though limited to only a proportion of the pasture area, can provide the equivalent of up to 1000 kg N/ha in urine patches. This N is rapidly converted to mineral forms that are susceptible to loss through leaching and as gaseous products. As the quantities of N are far in excess of the sward's immediate requirements, high concentrations persist in the soil, increasing the risk of loss. Much of the nitrate leached from grazed grassland originates from these localised 'hot-spots', irrespective of whether N is supplied as fertiliser or by biological fixation.

Most studies of leaching from grassland have examined pastures receiving N fertiliser. There is a direct relationship between the level of N input and the quantity leached (Barraclough *et al.*, 1992) and research has tended to concentrate on heavily fertilised swards where the risk of leaching is greatest. Ryden *et al.* (1984) demonstrated that leaching losses from grazed grass/clover swards were much smaller than those from intensively fertilised grass monocultures. However, differences are less evident where grass/clover swards are compared with grass receiving moderate fertiliser inputs. The productivity of grass/clover pastures is considered to be broadly equivalent to fertilised grass swards receiving 100-200 kg N/ha (Davies & Hopkins, 1996). At these levels of fertiliser input, leaching losses from grazed swards are typically in the range 1-12 kg N/ha (Barraclough *et al.*, 1992) and are similar to those reported for grass/clover swards. Tyson *et al.* (1996) reported annual leaching losses of 13 kg N/ha from grazed grass/clover pastures on a heavy clay soil in Devon and 50 kg/ha from equivalent grass swards receiving 200 kg fertiliser N/ha. Cuttle *et al.* (1998) compared leaching from unfertilised grass/clover swards and grass swards receiving 250 kg fertiliser-N/ha. Herbage production and the numbers of sheep that could be supported by the sward appeared to be the main factor determining the amount of N leached from pastures. The 6-year study indicated that where pastures of similar productivity were compared, losses were similar whether N was supplied by fixation (6-34 kg N/ha leached) or as fertiliser (2-46 kg N/ha leached). Hutchings & Kristensen (1995) modelled the factors influencing nitrate leaching from grassland and similarly concluded that differences in the quantities leached from clover- and fertiliser-based swards were likely to be small at the stocking rates commonly found on grass/clover pastures. In contrast, very large losses of about 200 kg N/ha occurred where pure stands of clover were grazed (Macduff *et al.*, 1990).

Whereas in conventional agriculture, the quantity of N leached increases with increasing N inputs and stocking rate (Barraclough *et al.*, 1992), results of experiments at three locations in Germany suggest that in organic agriculture N leaching is limited by a self-regulation of N supply *via* fixation (Schmidtke, 1997). Fixation is controlled by soil N availability and the proportion of legumes in the total crop. With higher N supply from the soil the legumes took a lesser proportion of their N from the atmosphere. This reduced mineral-N in the soil and decreased the risk of N leaching.

Though infrequent, there is a risk of direct leaching or run-off of mineral fertiliser where rain follows shortly after application. This will be avoided in unfertilised grass/clover swards. There is also evidence that leaching losses increase with increasing age of the sward (Barraclough *et al.*, 1992). This would be expected to influence leaching during the grassland phase of ley/arable rotations. Eriksen *et al.* (1999) reported that leaching losses were greater from second year grass/clover leys (28 kg N/ha) than in first-year leys (20 kg/ha) on an organic farm in Denmark.

Leaching from arable land is increased where fertiliser rates exceed the crop's requirement (MacDonald *et al.*, 1989) but the mineralisation of N from SOM is often the major contributor. In particular, losses are associated with the temporary nature of annual crops. If soils are left bare in autumn or crops are poorly developed, there will not be an effective rooting system to utilise the soil N that is mineralised after harvest and this will be at risk of leaching over the winter. Increasing the fertility of organically farmed soils by building up the content of SOM and incorporating organic residues and manures increases this risk. Similarly, the flush of N mineralisation following cultivation of leys is another feature of organic systems that may increase the risk of nitrate leaching (Stopes & Philipps, 1992; Scheller & Vogtmann, 1995).

The greater risk of leaching during the arable phase was demonstrated in a study on 17 Norwegian farms that were either organic or in the process of converting to organic production (Solberg, 1995). The potential for nitrate leaching (determined as nitrate-N in the 0-60 soil depth in October) increased in the order; leys (6 kg N/ha) < undersown grain = green fodder (14 kg/ha) < turnips/vegetables (17 kg/ha) < grain without undersown ley (30 kg/ha) < potatoes (33 kg/ha) < fallow (100 kg/ha). Similar measurements (0-75 cm depth) on 26 organic farms in Denmark showed the potential for nitrate leaching to increase in the order; grass/clover or lucerne fields (12 kg N/ha) < bare fields following cereals (48 kg/ha) < fields cultivated with cereals (57 kg/ha) (Kristensen *et al.*, 1994). Eriksen *et al.* (1999) demonstrated marked differences in nitrate leaching at different stages of a dairy/crop rotation on an organic farm in Denmark. The lowest losses were from first-year grass/clover leys (20 kg N/ha) and increased to 28 kg/ha for the second-year ley. Greater quantities of nitrate were leached (43-61 kg/ha) during the three years of arable cropping after the ley was ploughed. The overall annual leaching loss from the farm was equivalent to 38 kg N/ha.

Cameron & Wild (1984) estimated a total loss of about 100 kg N/ha leached over two winters following cultivation of temporary grass under conventional management. Other studies have indicated considerably greater losses (Ryden *et al.*, 1984; Lloyd, 1992). Results from the ploughing of ungrazed 1 to 6-year grass/clover leys on a sandy loam soil at Woburn indicated that leaching losses in the first winter increased from about 110 to almost 250 kg N/ha with increasing length of ley (Johnston *et al*., 1994). The main flush of nitrate appeared to occur in the first and second winter after ploughing the ley. Studies on organic farms have shown 38 kg N/ha leached where a grazed grass/clover ley was cultivated for winter wheat in September, compared with 10 kg/ha where cultivated in February for a spring crop (Philipps *et al*., 1995). Elsewhere, ploughing a 4-year ley in October resulted in 70 kg N/ha leached over the following winter (Watson *et al*., 1993). In New Zealand, cultivation of a 3-year ryegrass/white clover ley in either early or late autumn resulted in winter leaching of 78 and 40 kg N/ha, respectively, whereas delaying cultivation until late winter reduced this loss to 5 kg/ha (Francis *et al*., 1992). Considerable losses can also occur where green manures are cultivated. For example, over 100 kg N/ha was leached following ploughing a 1-year red clover crop in September, this was equivalent to about one third of the N in the above ground crop (Stopes *et al*., 1995). Leaching was substantially reduced where cultivation was delayed until spring. Although the cultivation of grassland can result in large leaching losses, the overall impact is reduced because only a proportion of the ley area on a farm will be ploughed at any one time. Similarly, the overall impact on the N budget of individual fields will be reduced because these large losses will only occur in one or two years during the rotation.

It is well established that the degree of soil disturbance also influences mineralisation of SOM and the quantities of N available for leaching. Hence, minimal cultivation techniques can reduce mineralisation and N leaching (Colbourn, 1985). However, where soils have been ploughed, increasing the depth of ploughing has slowed the rate of N mineralisation (Richter, 1989). Lloyd (1992) observed little difference in the quantities of N leached whether grassland was ploughed or was cultivated using less disruptive techniques.

The necessity of autumn cultivations to control weeds on organic farms may conflict with recommendations to minimise soil disturbance at this time of the year.

Catch crops are effective at reducing nitrate leaching from what would otherwise be bare soil (Stockdale *et al*., 1995; Rayns & Lennartsson, 1995). A lysimeter study in Denmark demonstrated that ryegrass undersown as a cover crop halved nitrate leaching from spring barley with average annual reductions of 20-35 kg N/ha (Thomsen & Christensen, 1999). On sandy soils in the UK, the average leaching loss of 47 kg N/ha from bare soils following cereals was reduced to 22 kg/ha by sowing an overwinter catch crop (Shepherd, 1999). The catch crops were only effective where they had become well established before the start of drainage in autumn. Thorup-Kristensen *et al*. (2003) reviewed the use of catch crops and green manures. Legume catch crops were considered to be less effective than non-legumes at recovering surplus N from the soil in autumn. This was not found in all experiments and the risk of poor N uptake could be avoided by growing the legume in a mixture with a suitable non-legume.

Taking all these factors into account, overall leaching losses from organic farms are generally lower than from conventional farms (Edwards *et al*., 1990; Younie & Watson, 1992; Eltun, 1995). However, the study by Kristensen *et al*. (1994) found average nitrate content in soils in autumn from organic farms (31 kg N/ha) to be similar to those in soils from conventional farms that also applied manure (29 kg/ha). Both were greater than for

conventional farms that did not use manure (22 kg/ha) and it was concluded that nitrate contents were related to the use of manures rather than mineral fertilisers.

Although nitrate is generally considered to be the main form of N leached from agricultural soils, there is evidence that soluble forms of organic N also contribute to the loss. Murphy *et al.* (1999) have reviewed the occurrence and behaviour of soluble organic N (SON) in agricultural soils. There have been few measurements of SON in agricultural soils and little is known of its role in N cycling. Indications are that the SON pool may be as large as the mineral N pool and in some soils, particularly under grass, may be appreciably larger. Significant concentrations of SON have been measured in drainage from conventionally managed grass plots in Devon, UK. In soils from an organic farm (0-25 cm depth), SON accounted for 80% of the total KCl-extractable N. The size of the SON pool increased with increasing number of previous years under grass/clover ley. Though it represents only a small proportion of the total organic-N in soil, SON has been identified as an important pool in the cycling of N in natural ecosystems.

Annual leaching losses of nitrate from grass/clover leys are typically 5 – 30 kg N/ha and for arable crops, 20 – 60 kg/ha. There is a risk of losses of 100 kg/ha or more if soils are not managed appropriately following cultivation of leys or green manure crops. Nitrate leaching may increase following slurry/manure applications and may be reduced by growing catch crops and minimising autumn cultivations. Overall leaching losses from organic farms are between 10 and 50 kg N/ha (Watson *et al.*, 1994; Philipps & Stopes, 1995; van der Werff *et al.*, 1995; Schluter *et al*, 1997). Few leaching studies include measurements of soluble organic N, which may be a significant contributor to the total loss.

6.4. Interactions with crop uptake

The above inputs to the soil and internal cycling processes contribute to the mineral-N pool that is potentially available to the crop. Nitrogen will be removed from the pool by plant uptake and through loss processes to determine the overall N balance for the soil. These are dynamic processes and a close synchronisation between uptake and N mineralisation is required to provide N when it is required by the plant and to minimise opportunities for immobilisation and loss. Atkinson *et al.* (1995) discussed the different spatial and temporal patterns of N supply in relation to plant uptake in organic and conventionally farmed soils.

In particular, concentrations of mineral N remain relatively constant in organically farmed soils and do not exhibit the high peaks that follow fertiliser applications (though there may be exceptions following cultivations and where N-rich slurries or manures are applied).

Whereas fertiliser-N is applied to the soil surface, the supply of N from incorporated residues, etc. is more evenly distributed within the plough layer. It has been shown on organic farms that the supply of nitrate between 15 and 30 cm depth may exceed that from the 0-15 cm layer (Watson *et al.*, 1993). Plants for organic systems may therefore require a more extensive rooting system with the ability to take up nutrients at low concentration. However, it must be recognised that much of the root activity of conventionally grown cereals and other crops also occurs below the plough layer (Barraclough, 1986).

Typical values for the amount of N removed from the soil in a range of harvested crops are shown in Table 6.1. The values were calculated from data applicable to organic farms. Estimates of removals in crops grown on conventional farms as cited by Powlson *et al.* (1994) are generally about 30% greater. An exception is the removal in maincrop potatoes which is about 20% less than the organic estimate. However, the estimate for the conventionally-grown crop is lower than other estimates for similarly grown potatoes and other data suggest that the N content given for the organic potatoes in Table 6.1 is too high. A more typical content would be 3.6 kg N/t (e.g. Cooke, 1982), corresponding to an offtake of 100 kg N/ha.

Estimated removals for the range of organically grown crops are between 45 and 250 kg N/ha with particularly large removals in potatoes, beans and silage crops.

Table 6.1. Typical quantities of N removed from the soil on organic farms in arable crops and grass/clover silage (calculated from Lampkin (1992) and Lampkin & Measures (1999)).

Crop (fresh weight unless indicated otherwise)	Harvested yield (t/ha)	N content (kg/t)	Offtake in crop (kg N/ha)
Rye (grain)	3.8	15	57
Wheat (grain)	4.0	15	60
Winter barley (grain)	4.0	20	80
Spring barley (grain)	3.5	18	63
Oats (grain)	4.1	17	70
Cereal straw	3-4	5	15-20
Field beans	3.2	65	208
Carrots	30	2	60
Potatoes (main crop)	28	4.5	126
Potatoes (early)	15	3	45
Cabbages	30	3.5	105
Grass/clover silage (* dry weights)	10*	25*	250

Although they are a guide to the overall N balance of the soil, these values are not a measure of the total N uptake or requirement of the crop. The minimum estimate of uptake will be the sum of the N in the harvested crop and unharvested residues but will be greater than this where crops exhibit senescence and loss of N prior to harvest. The offtake of N in leguminous crops will include N supplied by biological N_2 fixation and only part of the offtake will be derived from the soil. However, as described earlier, some legumes are reliant on the soil for a large proportion of their N requirement and the removal of N in the harvested crop may be sufficient to result in a net depletion of soil N.

Temporal patterns of N uptake by the crop may be particularly important in organic systems where N is released gradually by mineralisation of organic matter.

For example, maximum uptake of N by winter wheat occurs in spring when soils are only beginning to warm and mineralisation is still slow (Powlson, 1993). This is likely to limit the supply of N at a critical time for wheat crops on organic farms. Mycorrhizal fungi have been shown to absorb and translocate N to the host plant; however, because of the much higher diffusion coefficient for nitrate than phosphate, this is of less importance for N than for P nutrition (Paul & Clark, 1996).

6.5. Predicting N release

Predicting N release can be done either by modelling (simple or complex) or by using soil tests. Both methods generally require some prediction of weather because, as described above, mineralisation is a process driven by temperature and moisture content.

Soil tests for predicting N release have some limitations. Sampling for soil mineral N (ammonium plus nitrate N) gives a snapshot of what is currently available to the crop. However, this is of limited value where subsequent release of N from the organic pool is likely to contribute significantly to crop uptake. Consequently, Shepherd (1992) found only a poor relationship between measured soil mineral N and N fertiliser requirement of cereals following grass because of the contribution of mineralised N: the relationship was much better where previous crops were not grass.

Soil tests have been developed for assessing potential mineralisation and these generally comprise either aerobic or anaerobic incubations under controlled laboratory conditions, or an extraction with hot KCl. Whereas these methods can provide an indication of the mineralisation potential (and are particularly useful for ranking soils), there is still the problem of relating measured amounts to likely release under field conditions.

Therefore, modelling of mineralisation tends to be a more common method. Moreover, because of the interaction of N mineralisation with potential N loss processes, there may be a need to model more than mineralisation. For example, if a fertility-building crop is ploughed in autumn, N leaching (as described above) can represent a substantial N loss and this needs to be accounted for when predicting **N supply** rather than **N release**.

The modelling of soil MIT processes has inevitably resulted in fairly detailed single (Stanford & Smith, 1972), double (Deans *et al.,* 1986) or triple (Parton *et al.,* 1987) exponential first order reactions being described in the past. Even second order exponential models have been resorted to in the pursuit of exactitude (Whitmore, 1996).

Models have been extensively reviewed by Paustian *et al.* (1997). Highlighted in this account is the need to include often complex functions to describe the growth dynamics of the microbial population. As this microbial population uses the organic material as its energy source, the process is also inevitably one of C mineralisation, with the N dynamics being a by-product of these central processes. Furthermore, the growth and decay of the microbial biomass on the organic matter resource is modified by the usual biological controls of temperature and water availability.

This approach is undoubtedly essentially correct but though it is widely adopted models differ in how they handle the many elements of the C and N interactions that contribute to governing the rates at which these processes proceed. Carbon is either assigned to three sink pools after the decay of organic material, such as those assimilated into microbial biomass, excreted as carbon dioxide and the residual elements from catabolism remaining as humus (Jenkinson & Rayner, 1977; Bradbury *et al,* 1993), or entirely cycled through the microbial biomass with excretion of carbon dioxide (Rahn & Lillywhite, 2002). Further differences are seen in how the composition of the original material is perceived to affect the breakdown rate, though the amount of N in the material is always considered important and lignin is also usually a controlling factor (Rahn & Lillywhite, 2002). As most models have the release or otherwise of N in the system as their determining end-point, the relative amounts of C and N in the material and the dynamics of their interaction are a prime focus of these models. Depending upon the composition of the material, the changes in microbial growth and availability of N can fluctuate over very short periods of days, which leads to models that operate over timesteps of days or weeks (Bradbury *et al*., 1993).

Such models entail a high degree of detail and require many parameters if they are to run correctly. Although they have been found to model C dynamics fairly accurately they still fail to capture N dynamics fully. This is possibly because of the uncertainty of amounts and states of N in the soil ecosystem to begin with, and of the effect of secondary microbial and chemical processes which can alter its sink destination.

Such models can therefore either fail in their primary objective of determining the temporal fluctuations of N in the soil and its fate, or are over-complicated and not parameterised for simpler functions requiring less precision. If all that is required is a guide to how much N is likely to be available to crops from soil mineralisation processes on relatively few occasions during a crop life cycle for setting fertiliser recommendations, then an altogether simpler, but less precise approach could be employed.

Such an approach would be to model the N dynamics from residue decomposition directly, and avoid measuring the short-term fluctuations that occur due to changes in edaphic conditions. This can be done by summarising much of the process change modelled in the above approach, by concentrating on the gross change between relatively long-term (monthly) time-steps. In doing this, water availability fluctuati[illegible] often cancel each other out or are rendered unimportant, and temperature fluctuations can be summarised by measuring thermal time rather than real time. Although there are problems with using the concept of thermal time for mineralisation processes (Bhogal & Harrison, 1999), it has been successfully employed as a tool with sufficient precision for measuring mineralisation processes and N dynamics in the field in both grassland (Clough *et al*., 1998,) and arable soils (Honeycutt *et al.,* 1988).

In short, there is an abundance of N mineralisation models available, which aim to predict N release. These approaches vary in complexity, both in terms of their approaches to mathematically representing what is essentially a biological process and in terms of the information required to initialise the model. This latter point will potentially prevent some approaches from being used in an advisory system. Simple, table-based models may be one way forward, but these are less able to deal with extreme conditions (e.g. wet vs dry winters).

6.6. Conclusions

- Mineralisation of the incorporated residues is a microbially driven process. The rate of breakdown is controlled by soil temperature, soil moisture and aerobicity. Whereas the C:N ratio of the residue is also a good guide to rate of release, the physical quality of the residue also governs its availability to the microbial population, e.g. lignin content.
- Nitrogen can be lost from the organic farming system via denitrification, ammonia volatilisation and leaching of (mainly) nitrate.
  - Losses of N as ammonia can be large following manure application (but can be controlled by rapid incorporation of the manure) or during deposition of excreta during grazing. These losses represent a loss from the farming system and from the soil fertility-building crop either indirectly (if loss is from manure produced by feeding the crop as fodder) or directly (if grazing the fertility-building crop).
  - Denitrification losses can be large, particularly in warm moist soils following incorporation of N-rich residues or manure.
  - Nitrate leaching occurs predominantly during the autumn/winter. Nitrate losses can therefore be large if the fertility-building crop is ploughed in the autumn. Autumn manure applications (particularly those with a high mineral N content) also risk substantial loss after an autumn application.
- These loss processes therefore compete with crop uptake and efficient utilisation of the N fixed by fertility-building crops must therefore include appropriate management practices to minimise losses.
- A complicating factor is the potential lack of synchrony between N mineralisation of the residues and crop uptake: a build up of soil mineral N at times of low rates of crop uptake increases the risk of N loss.
- There are numerous models for predicting mineralisation of crop residues, with variations in complexity and the levels of information required to drive the models. Soil tests as predictors have less value.
- However, because of the competition between loss processes and crop uptake following mineralisation, some account of these losses also has to be made in order to predict the N available for the crops following the soil fertility-building phase. It is not sufficient to model mineralisation alone.

7. ROTATIONAL ASPECTS

7.1. Farm practices

Lack of technical information and advice for organic producers is felt to be a major problem by many farmers.

The diversity and range of rotations and crops that they are attempting to grow is very wide. Some examples of rotations used by farmers attending the project workshops are shown in Table 7.1. These example rotations illustrate both the diversity available to farmers and the commonality of reliance on legumes throughout the rotation. Farmers want to know the relative merits of the wide range of legume species both in terms of the N fixing capability and implications for pests and diseases in other crops within the rotation.

Long sequences of legumes are most common in livestock systems, usually grown in a mix with grass for forage. Conflicts can occur with respect to the management of the sward to optimise grazing potential or forage dry matter production, whilst enhancing the residue of soil N sufficiently to support the rest of the rotation. The return of animal manures contributes to the long-term fertility of these rotations. As well as clover, beans are also commonly grown as a legume that can also contribute to animal feedstock. The stockless systems are characterised by shorter (1-2 year) legume sequences, in which the legume is often grown for seed. The legume may also be grown as a 'set-aside' crop, a practice recommended by Stopes *et al.* (1996). A wider range of legumes seems to be grown and there is greater evidence of over winter cover crops.

It is important in stockless organic systems to maintain fertility throughout the rotation and this can be more difficult without the option of animal manure inputs. It is usually done (as illustrated in the rotations above) by combining fertility-building crops such as annual legumes with cash crops such as cereals. Non-legume crops can also contribute, for example the inclusion of potatoes has been found to be beneficial not only in terms of maintaining soil N levels due to mineralisation of haulm but also with respect to weed control (Phillips *et al.*, 1998).

The optimum ratio of fertility crops to cash crops will depend on the nutrient retention capacity of the soil.

For instance, on the silty clay loam at Terrington, a five year rotation of clover-potatoes-wheat-beans-barley has been successful (Defra projects OF0145 and OF0301). Danish workers Willumsen & Thorup-Kristensen (2001) recommend using green manures as often as possible in vegetable rotations. In contrast, in Canada, Townley-Smith (1989) found little benefit from a single year of an annual legume, whilst other Canadian workers (Bullied *et al.*, 2002) reported greater benefit from chickling vetch and lentil than from a single year of alfalfa hay. Evans *et al.* (2001b) working in Australia found that grain legumes contributed to the overall soil nitrogen balance in a rotation but did not produce enough N to fully support a following wheat crop without use of soil reserves. Harper *et al.* (1995) measured the total N accumulated by crimson clover (*Trifolium incarnatum L.*) from N fixation, soil mineral N uptake, and NH_3 absorption and found that it provided the equivalent of 70% of N removed by the following sorghum crop.

Table 7.1. Typical organic farming rotations, as employed by a group of organic growers.

Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9
With livestock								
Grass/red clover	Grass/red clover	Grass/red clover	Grass/red clover	Brassicas	Lettuce/ spinach/ chard	Cereal	Back to yr 1	
Grass/red clover	Grass/red clover	Grass/red clover	W wheat / maize	Beans	Sp oats	Back to yr 1		
Grass/ clover	W wheat	Potatoes	W wheat	Sp barley (u/s)	Back to yr 1			
Setaside (red clover)	Outdoor pigs	Wheat (w or sp)	W wheat	Sp wheat (under sown)	Back to yr 1			
Grass/ clover with pigs	Potatoes	Carrots	W wheat	Beans	W wheat (under sown)	Back to yr 1		
Stockless								
Red clover	Red clover	Potatoes	wheat	Beans	Triticale	Back to yr 1		
Grass/ clover	Grass/ clover	Mixed veg.	Back to yr 1					
Grass/ clover	Potatoes/ onions (for. rye cover)	Fennel/ brassica	Cereal (under-sown)	Back to yr 1				
Grass/ clover	Cereal	Lettuce (phacelia /st. turnip cover)	Sp wheat	Back to yr 1				
Grass/ clover	Grass/ clover	Cereal	Legume	Cereal (u/s)	Back to yr 1			
Red clover	W wheat (cover mustard)	Sp barley	Red clover	W wheat	Beans	W wheat	Set-aside (lupins)	W wheat
Grass/ clover	Wwheat u/s trefoil	Vetch	Wwheat u/s trefoil	Beans u/s trefoil	Sp wheat (under-sown)	Back to yr 1		
Clover (seed)	W wheat	Triticale	Beans (cover)	Sp cereal (u/s)	Back to yr 1			
Red clover	Red clover	W wheat	Triticale	beans	Sp barley	Back to yr 1		
Grass/ vetch setaside	Cereal	Beans	Cereal	Back to year 1				
Grass/w clover	Potatoes/ veg.	W wheat	Beans	Cereals (u/s)	Back to yr 1			

u/s = undersown

In mixed arable/livestock systems, there are generally longer runs of grass/clover leys in the rotation which may be to the detriment of N fixation in later years (Sanders *et al.*, 2002).

UK farmers have expressed concern about maintaining an appropriate sward mix to maximise yield. In Sweden, Nilsdotter-Linde (1998) has shown that with 4 cuts per year white clover (*Trifolium repens* L.) generally outyields birdsfoot trefoil (*Lotus corniculatus*) or red clover (*T pratense* L.) when grown in mixed grass swards. With two cuts per year the red clover mix was higher yielding in the early years but birdsfoot trefoil improved in later years. Two different grass mixes were used: white clover was grown with red fescue and smooth stalked meadow grass, a mixture suitable for grazing, red clover was grown with Timothy and meadow fescue which is a suitable mix for hay in Sweden, the trefoil was grown with both grass mixtures. For the birdsfoot trefoil mixes two cuts appeared to give higher yields than four, however the quality expressed as energy content was better with four cuts. Birdsfoot trefoil was a slow starter in the spring but gained an advantage later in the season. Botanical composition was more consistent with Birdsfoot trefoil. Bullard (1992) has studied the growth of birdsfoot trefoil under UK conditions, in both pure and mixed swards (with *Phleum pratense* and *Festuca pratensis*). Under monoculture, birdsfoot trefoil out-yielded both red and white clover. In mixed swards birdsfoot trefoil constituted a higher proportion of DM yield than other legumes. Marsh trefoil (*Lotus uliginosus*) did not perform well under high pH conditions.

7.2. Nutrient balances

The calculation of nutrient balances is well recognised as technique for studying the sustainability of organic rotations (Watson & Stockdale, 1997, Fortune *et al.*, 2000). Indeed, they are recommended by Lampkin (1990) as an essential precursor to conversion. However estimating the N fixation component can be difficult (Cuttle, 2002).

The following illustrates the nutrient balance created for ADAS High Mowthorpe prior to conversion in 1999. Although the system includes livestock, manures are not included in the balance on the premise that they are the outcome of feeding from inputs grown on the farm and are therefore merely a recycling of nutrients. An attempt was made to estimate the losses in livestock sold off the farm although some workers (Fillery, 2001) suggest these are insignificant in respect to N_2 fixation in improved pastures. The net balance/ha is negative for N, P and K. The deficit in N is largely due to estimates of leaching losses, which will be subject to seasonal variation related to rainfall. The issue of N leaching has been dealt with in more detail in Section 6.

Mäder *et al*. (2000) studied nutrient balance in 99 Swiss mixed dairy farms, which had been managed organically for up to 60 years. Although nutrient balances were often negative, only soluble K showed signs of decline. Also in Switzerland, Oberson *et al*. (2000) have found that increased biological activity is at least in part compensating for lower available inorganic P in organically managed soils. However P budgets were negative so there was a risk of P mining. In Denmark Høgh-Jensen (2000) found that in a low soil PK situation white clover facilitated the uptake of P and K in ryegrass especially in the first year after establishment. UK farmers involved in the current fertility-building project (OF0316) expressed concerns about falling soil K levels.

Some crops are believed to be deep rooting and able to extract nutrients from depth, thereby enhancing the fertility of the topsoil when incorporated but there is little documented evidence to support this claim.

Serious deficiency of any nutrient may affect the ability of legumes to fix N. For example, Haglund *et al*. (2000) working in Norway found that generally organically grown grass was low in sulphur and that this often coincided with low N. They advised investigating whether this was related to reduced N fixation. Other workers (Eriksen *et al*., 1999) have calculated sulphur balances and found that these are commonly negative, especially in stockless systems and those with a high proportion of vegetables. They recommend use of catch crops to reduce sulphate leaching at the same time as reducing nitrate losses.

Assessment of the contribution of legumes to the overall N balance is difficult. The variation in the amount of N fixed is discussed in more detail in Section 3, and it is also necessary to consider the amount removed in crop offtake (forage or grain). The net contribution to soil N from legume-rich pastures is usually higher than that from grain legumes (Peoples *et al*., 2001) as a much larger fraction of the total plant N is removed when pulses are harvested for grain than that removed or lost from grazed pastures. The potential variation in grain legume contributions to soil N is well illustrated in work in SE Australia by Evans *et al*. (2001b). They reported that the amount of N added (the difference between N fixed and N removed in grain) to the rotation varied considerably for different crops: lupin –29 to +247 kg N/ha (mean 80); pea –46 to +181 kg N/ha (mean 40); chickpea –67 to +102 kg N/ha (mean 6); and faba bean +8 to +271 kg N/ha (mean 113). The amount of N added was found to be related to the amount of N fixed and proportion of crop N derived from N_2 fixation but not to legume grain yield. Biederbeck *et al.* (1996) reported that chickling vetch (*Lathyrus sativus L.*) and feedpea (*Pisum sativum L.*) were more successful at replacing the N removed in the preceding wheat crop than black lentil (*Lens culinaris Medik.*) or Tangier flatpea (*Lathyrus tingitanus L.*)

In the UK and Germany, Schmidt *et al*., (1999) obtained a positive N balance in two of three different 4-year stockless rotations based on a one year green manure of clover. The risk of rotation failure was illustrated in this work when weather and pest attack damaged the clover in the third rotation resulting in a net N deficit.

Table 7.2. Nutrient Balance Sheet for High Mowthorpe

Rotation course	Crop	Area (ha)	Yield (t/ha)	Nutrients imported/fixed (kg)			Nutrients removed/offtakes (kg)		
				N	Phosphate	Potash	N	Phosphate	Potash
1	Ryegrass/clover	16		1600					
2	Ryegrass/clover	16		1600					
3	Seed potatoes	16	20				333	72	581
4	Winter wheat	16	5.5	90	14	19	1563	242	327
5a	Sp. Beans	8	2	90	14	29	545	85	176
5b	Sp. Barley	8	4.5	61	12	17	489	92	138
6	Undersown Sp. Barley	16	4	61	12	17	870	163	245
	Permanent grass/clover	12		260					
Livestock	20 cows [1]						251	73	38
Deposition				2757	12	0			
Totals		109		**6487**	**64**	**82**	**4051**	**727**	**1505**
Leaching loss							4304	0	0
Total (kg)				6487	64	82	8355	727	1505
Balance (kg/ha)							**-17**	**-6**	**-13**

[1] 20 x 0-1 year, 20x1-2 year & 20 x breeding cows = 1.8 livestock units (stock rate = 1.4 LU/ha)

7.3. Constructing rotations

The cropping balance across the rotation needs to be considered. This is important not just to maintain adequate fertility in the soil but also to avoid undue build up of pest, disease and weed problems. Wijnands (1999) recommends that specific at risk crops should be grown no more frequently than 1 year in 6 and for phytopathologically related crops, no more than 1 in 3 years to avoid pest and disease problems. In Latvia (Zarina and Mikelsons, 1999) it is recommended that 20-30% of the rotation be fertility-building (grass/legume), 50-60% grain crops and 10-20% root crops. Strategies to create rotations which maintain long term soil N fertility depend on an understanding of the dynamics of soil N processes (Koopmans and Bokhorst, 2000) and in the absence of practical means of direct measurement simulation modelling may be useful.

Pest and disease issues have been dealt with in Section 2. Disease was also reviewed in detail an earlier Defra funded project (OF0168) and the results are available in the DOVE report (Gladders *et al*., 2001).

Weed control in organic farming is currently under review in a new Defra funded project (OF0315) which has its own website for information:
(http://www.hdra.org.uk/research/ir_weed_management.htm).

Elsewhere, Cagaš and Machác (2002) have reported that in Czechoslovakia, red and white clover grown in mixture with grass were better at suppressing weeds (mainly dandelion) than black medick. Perennial weeds (grass and creeping thistle) have become a problem in stockless organic systems at Elm Farm and ADAS (Welsh *et al*., 2002). In discussion, UK farmers reported charlock, docks and cleavers as the main problems. Some use longer strawed varieties of cereals to aid weed control. There can also be problems with self-sown fertility builders for example vetch flowers early in Cornwall so must be incorporated earlier than in the north to prevent seeding and volunteer growth. Rasmussen *et al.* (1999) found weed populations varied with soil type and were affected by the crops in the rotation where these influenced the ability to used mechanical mean of weeding. Brandsæter & Riley (1999) reported that mulching with cut material from legume fertility builders from elsewhere in the rotation was a useful means of controlling weeds in vegetables.

UK farmers have expressed concern about managing straw disposal in stockless systems, they are worried about nutrient lock up during straw break down and about build up of slug populations. There is evidence from the work done following the straw burning ban that during the early years of straw incorporation there may be a temporary lock up of N (Silgram & Chambers, 2002). However once microbial populations became established the problem disappeared. There is no reason to expect organic rotations to behave differently from organic ones in terms of microbial activity (Oberholzer *et al*., 2000).

Farmer experience in the UK shows that undersowing is a successful way of establishing legumes. In Denmark, Tersbøl & Thorup-Kristensen (2000) showed that undersown legumes can be used as green manure with modest yield loss in the nurse crop and substantial extra yield in the succeeding crop. They found no material difference in legume species although some yielded less in the establishment year. Birdsfoot trefoil (*Lotus corniculatus*) and black medic (*Medicago lupulina*) had most adverse effect on the nurse crop. To avoid yield losses in the nurse crop, it was important not use excessive seed rates for the legume. (They also found that the legumes lowered the soil mineral N in the subsoil during autumn, which would help reduce over-winter leaching if replicated in UK conditions.) However undersowing cannot be used too frequently in the rotation as this has implications for weed build-up, notably of perennial weeds such as couch grass and thistle (Holle & Untiedt, 1999).

For over-winter covers, farmers prefer crops which can be established in September and killed in March. Destruction of the cover can be a significant problem, both rye and vetch are reported to be difficult, however there is limited documented evidence of this. Changes to cultivation practices (eg deep ploughing) may help. The results from the OF0315 project should contribute to this debate.

Maintaining soil physical condition through the rotation is also important. Alternating root crops with combineable crops is recommended (Wijnands 1999) to aid maintenance of soil structure. The choice of legume may also have an impact. Larsson (1999) grew different leguminous crops for two years followed by sugar beet. Investigations were done on physical parameters like water infiltration and soil resistance with a penetrometer. Spade diagnosis was used for the description of roots and soil structure after the different crops. This showed high earthworm activity in *Medicago sativa, Trifolium pratens*e, *Melilotus officinalis* and *Trifolium pratens*e. In the subsoil the best penetration of roots was found with *Medicago sativ*a, *Melilotus officinalis* and *Trifolium pratens*e. Very good aggregation of the soil was found with *Medicago sativ*a, *Melilotus officinali*s, *Trifolium pratense* and *Trifolium repens.*

As indicated above practical considerations are also important in determining crop rotations. Crops that are harvested late do not lead well into a following crop that requires early establishment. The benefits of stale seedbeds may need to be balanced against the disadvantages of increased N leaching. The crop-weed-nitrogen triangle is also a common dilemma (e.g. Askegaard *et al.*, 1999).

Weather can also play an important part, with adverse conditions affecting even the most carefully laid plans. The example rotations discussed in earlier in this chapter were clearly regarded as flexible by the farmers involved in the discussion. Over the course of a 6 to 7 year rotation there is plenty of scope for adjustment: vegetables instead of potatoes, oats instead of wheat and so on. Wijnands (1999) reported that in the Netherlands only about 60% of organic farmers have clear rotation plans and that 18% of these fail to stick to the 1 year in 6 guidelines. One of the reasons g[illegible] for this failure is market forces.

7.4. Companion Cropping ('bi-cropping')

The economic viability of conventional rotations in organic farming tends to be reduced by the need to have crops within the rotation purely for fertility-building and not for their cash value, particularly where there are no livestock to utilise grass/clover and forage legume crops. The use of permanent beds of companion crop grown alongside the vegetable crops has been developed under various conditions around the world and is perceived as a possible alternative in organic husbandry in the UK (Wolfe *et al*., 2000). Such systems may allow both cash crops and fertility crops to be grown every year. Companion crops also have the potential to reduce the impact of pests and weeds. The big disadvantage of companion crops is competition with crop plants for space, light, water and nutrients. The companion crop, therefore, is likely to have to be mown or grazed to control competition and encourage nutrient transfer. In a recent Defra project (OF0182) vegetables were grown in single rows alternating with semi-permanent, frequently mown white clover strips. Competition was severe, leading to failure of some crops and uneconomic yields of others. A much less intimate mixing (in space and/or time) of companion and cash crops is likely to be required for commercial success. However, such a system is likely to be of less benefit for weed, pest and disease control.

Agroforestry is an extreme form of companion cropping and is widely used in tropical agriculture but not as yet in temperate organic systems. Work in the UK on organic silvi-agriculture is now in progress (Wolfe & Pasiecznik, 2000). Systems under investigation include alley cropping systems with a mix of hardwood trees and apple trees to reduce the pest/disease intensity associated in orchards. As with conventional bi-cropping, crop competition can be a problem and all trees are high and root pruned to reduce this. As an alternative to tall hardwoods, hazel and willow are also being tested with regular coppicing to reduce crop competition.

7.5. Conclusions

- The optimum duration and type of legume sequences in a rotation is affected differently by the economic and production constraints of livestock and stockless organic systems.
- Rotation sequences need to be chosen with due regard to weed, pest and disease considerations as well as maintenance of soil N reserves
- Grain legumes and forage legumes grown as seed crops in stockless organic systems provide an opportunity to increase the number of cash crops within the rotation

8. CONCLUSIONS

Organic farming aims to be self-sufficient in nitrogen (N) through fixation of atmospheric N_2 by legumes, recycling of crop residues and application of manures or composts. Nitrogen in legumes comes from **uptake of soil N** and from **fixation of N from the atmosphere**. Only the fixed N represents a true import of N on to the farm. As well as legume based leys, organic rotations also often provide a supplementary boost of N during the fertility depleting phase by the growing of a leguminous crop, such as field beans or peas. Despite reliance on legumes for N, much remains to be understood about how to maximise N fixation and make most efficient use of the fixed N.

It was stated in the introduction that organic growers identified a number of key issues that they felt needed to be addressed:

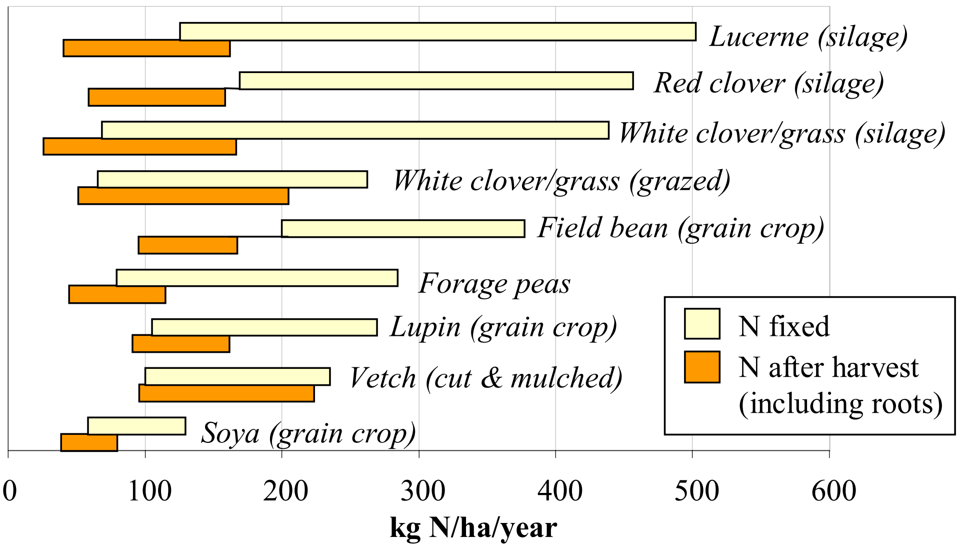
- Optimum crop sequence (including length of build up and break between legumes and/or green manures)
- Management of cover crops - options/timing
- Rate of release of N from green manures/covers and crop residues
- Management of swards (i.e. cutting/mulching/removal/grazing requirements) to optimise N accumulation and minimise losses
- N fixation ability of different legume species in UK conditions (including optimum mixes for mixed swards)
- Assessment of % clover in mixed swards
- N build-up/retention - Interactions with cultivations/seed bed preparation
- N build-up/retention - Interactions with pest and disease issues
- Bi-cropping
- N build-up/retention - Interactions with other nutrients
- Management of organic manures
- Cost implications
- Grain legumes for cash crops

We have tried to address these issues.

8.1. How much N is fixed under UK conditions?

The amount of N fixed by different legumes is determined by the inherent capacity of the crop/rhizobium symbiosis to fix N, modified by the crop's growing conditions (e.g. soil, climate, disease), crop management and length of time for which the crop is grown. Consequently, the influence of all of these factors means that a wide range of values have been reported by different researchers. However, for a particular legume species there is usually a close relationship between yield and the quantity of N fixed. Figure 8.1 indicates the **range** of fixation estimates quoted for a number of leguminous crops.

Figure 8.1. Provisional ranges for quantities of N fixed and remaining after harvest of legume crops.



8.2. Management to optimise N accumulation

The literature provides considerable evidence that management factors can influence N fixation by a legume. The presence of soil mineral N is generally thought to reduce fixation capacity (see box). Factors that will increase the soil mineral N pool include **manure application, cutting and mulching, grazing**. Fixation tends to decrease with **legume age**, mainly because the amount of soil N tends to increase. Consequently, there are many of these contradictions, which make management decisions difficult. For example, cutting and mulching is a standard practice in organic rotations, especially in stockless systems, yet it may be that such a practice is decreasing fixation and the amount of N imported into the rotation from the atmosphere.

Cutting	Grazing	Grain legumes
• Fixation is reduced for several days after cutting • If cut material is returned to the soil as a mulch this decreases fixation by increasing the soil N status • It is better to remove the material after cutting (e.g. as silage) but this has other management implications, especially on stockless farms	• Much of the ingested N is returned as excreta (as much as 90%) • Increases soil N pool and decreases fixation • There is a greater accumulation of N than under cutting	• Generally obtain a smaller proportion of their N by fixation • Harvesting of legume seed removes much of the fixed N from the field • Consequently, net effect on soil N status may be small • Greater benefit if seeds are fed on farm and N is returned as manure

Also, harvesting of forage or grain will remove much of the fixed N and reduce the benefit to following crops (see figure). The benefit will be further reduced if straw and other crop residues are also removed from the field. However, much of the fixed N will be retained within the farm if the forage and grain is fed to stock on the farm rather than being sold. Other aspects of management affecting N-fixation include position of the crop in the cropping rotation, duration of cropping and methods of cultivation. These are detailed later. Growing the legume in a mixture with a non-fixing crop can increase the proportion of N obtained from the atmosphere. For example, in grass/clover leys, the grass utilises soil-N and thus avoids the build-up of N that otherwise might inhibit fixation. However, the presence of a companion crop also reduces the number of N-fixing plants per unit area.

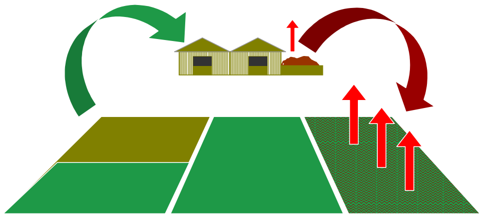
Thus, we know the factors that affect N build up. How are these translated into **practical advice? :-**

- In forage situations consider removal of cut material but don't cut too frequently
- Avoid returning cut and mulched material to legumes
- Accept that net input from grain legumes is lower and adjust rotation accordingly
- Don't apply high available N organic manures to legumes eg slurry and poultry manures

8.3. Rate of release of fixed N and minimising losses

Before N from the legumes can be used by the next crop, it has to be 'mineralised' into plant available forms (nitrate and ammonium). Some will already be in this form, due to transformations during the life of the crop. Most, however, will need to be mineralised by microbial action after cultivation. Since mineralisation is a microbial process, the rate depends on environmental conditions (soil moisture, temperature, etc), soil texture (potentially slower in clays than sands) and also the composition of the crop material (fresh green residues decompose more rapidly than old 'stemmy' materials). The dynamics are therefore complex and we are using computer models to develop guidelines on the rates of breakdown.

Once mineralised, N is also susceptible to loss and it is important that as much as possible is retained for use by the crop. Losses occur mainly through nitrate leaching and, sometimes, ammonia volatilisation. Nitrate leaching can be minimised by ploughing the ley as late as possible in the autumn or preferably in the spring. However, this advice does not always fit with more practical considerations of preparing the soil for the next crop. Nitrate leaching after ploughing the ley probably represents the greatest N loss from the rotation. Ammonia volatilisation can occur from the cut foliage, but amounts are thought to be small. The main loss of ammonia is from manure (during grazing or after application). Whereas grazing losses are difficult to control, rapid incorporation of manure after application will reduce volatilisation losses.



It is important to think at the farm scale

- if fed to livestock, N fixed in one field can be returned to other fields as manure

- but take care to avoid N losses

8.4. Other Considerations

Management of cover crops - options/timing

- To reduce N leaching risk cover crops need to be established early in the autumn to ensure good crop growth and hence N uptake. Establishment techniques need to ensure conservation of soil moisture and ensure a good seed/soil contact.
- Covers should be chosen with due regard for the cash crops in the rotation so as to minimise the risk of pest/disease build-up. For example stubble turnips are not suitable for use in brassica rotations.
- Some covers are difficult to destroy in the spring and thus interfere with establishment of the cash crop.
- Some covers do not release N quickly enough to be utilised by the following crop. If the N is released too slowly and not fully used by the cash crop it is at risk of being leached in the following season. Mustard releases N very quickly, phacelia may be slow to release N.

Crop sequences

- Various aspects of soil management can influence N-fixation. In many cases this will be through their effect on the soil mineral-N levels experienced by the legume, with the legume obtaining a greater proportion of its N from the atmosphere in low-N soils. Thus, as in most organic rotations, more N is likely to be fixed where legumes follow crops that have previously depleted soil-N levels.
- There will be differences in N-availability in different soils; for example, between soils on stockless farms and on predominantly livestock farms which are able to include a greater proportion of leys in the rotation or between soils of contrasting textures. However, it is possible that soil-N status has less effect on fixation in mixed swards than where the legume is grown alone. In high-N soils, N uptake by the non-legume component of mixtures may reduce mineral-N concentrations sufficiently to avoid the inhibitory effects on fixation.
- The optimum build up period for white clover swards is about three years.
- Some legumes are less suitable as annual build-up crops due to slow establishment and growth.

Bi-cropping

- The use of permanent beds of a legume grown alongside a cash crop has potential as an alternative technique in organic farming. Such systems may allow both cash crops and fertility-building crops to be grown every year. Companion crops also have the potential to reduce the impact of pests and weeds. The big disadvantage of companion crops is competition with crop plants for space, light, water and nutrients. The companion crop, therefore, is likely to have to be mown or grazed to control competition and encourage nutrient transfer. In a recent Defra project (OF0182) growing vegetables in single rows alternating with semi-permanent white clover strips mown frequently, competition was severe leading to failure of some crops and uneconomic yields of others. A much less intimate mixing (in space and / or time) of companion and cash crops is likely to be required for commercial success. However, such a system is likely to be of less benefit for weed, pest and disease control.

Costs

- The economic viability of conventional rotations in organic farming tend to be reduced by the need to have crops within the rotation purely for fertility-building and not for their cash value, particularly where there are no livestock to utilise grass/clover and forage legume crops. The use of marketable grain legumes in stockless rotations enables some income to be derived from the fertility builder. The potential income is dependent on the market end point

Interactions with cultivations/seed bed preparation

- Cultivation practices that increase mineralisation of soil organic matter will lead to increased levels of soil-N with the result that following legume crops obtain less of their N from the atmosphere. A number of studies have demonstrated greater fixation in minimum tillage systems.
- Weed control requirements for bare ground and stale seedbeds increase the risk of soil N loss through leaching.
- Repeated cultivations for weed control increase mineralisation of N which increases the potential for N leaching losses.
- Fertility builders which are not easily destroyed by cultivation and seedbed preparation may become weeds in the following cash crop.

Interactions with pest and disease

- Fertility-building crops are subject to pest and diseases that can reduce their effectiveness at increasing soil N supply, there is also a risk of carryover into the following cash crop.
- Consider cropping history and previous pest and disease problems before selecting fertility-building crops.
- Pest and disease risk is increased by selecting fertility-building crops of the same ‘type’ as arable or vegetable cash crops. i.e. cruciferous legumes in rotations with brassica cropping.
- Maintaining a green cover in the autumn (either through early drilling or use of cover crops) to minimise leaching losses increases the risk of some pests and diseases – the ‘green bridge’ effect.
- Good soil management and drainage are important factors in reducing threat from soil-borne diseases and cultivation techniques can minimise the impact of some soil pests such a slugs.
- Bi-cropping can reduce pest and disease severity.

Interactions with other nutrients

- Where growth of legumes is affected by nutrient deficiency (or acidity) the potential for soil N build up is reduced. Phosphorus and some trace elements (e.g. molybdenum) are particularly important.
- The risk of sulphur deficiency is now widespread in the UK due to reduced pollution from industry.
- Clover competes poorly with grass for soil nutrients and therefore needs a plentiful supply of soil nutrients when grown in a mixture.
- High soil N reduces the fixation capacity of legumes.
- There is some evidence that mycorrhizal fungi are more common in organic farming systems and may increase the availability of other soil nutrients.

Organic manures

- It is necessary to supply adequate P and K to ensure satisfactory growth of legumes, particularly where there are large offtakes of soil nutrients, as in silage crops, root crops or intensive field scale vegetable production.
- On organic farms, these nutrients are most likely to be supplied as animal manures. As these materials also contain N, their use may inhibit N–fixation in the short-term and reduce clover contents in the longer term.
- These effects will be less with FYM and composts than with slurry and poultry manure which generally contains a higher proportion of readily-available N.

Advantages/disadvantages of the main legumes

Crop	Forage or cash crop potential	Vigour	Soil type	Climate	Seed rate kg/ha	Cost £/kg
Red clover	Large biomass for forage; high protein content forage; can cause bloat.	Deep rooting; vigorous growth; Can disappear in grazed swards; susceptible to stem nematode; typical productive life of 3 years; can be very competitive when undersown; erect growth habit.	Most soils, difficult on soil with high organic matter content.	Difficult to establish in autumn in the north.	10-15 + grass	6-7
White clover	Withstands heavy grazing; lower biomass productivity.	Viable for 5-9 years; good regeneration after drought; resistant to stem nematode; suitable for undersowing/ bi-cropping; prostrate growth has good ground cover; Slow establishment, best established in spring.	Most soils, difficult on soil with high organic matter content.	Dislikes waterlogged/ droughty conditions.	4 – 6 + grass	20-30
Crimson clover	Forage can be stemmy.	Resistant to clover rot; erect growth habit; unsuited to bi-cropping; autumn establishment difficult.	Tolerates a wide range of soil pH; dislikes heavy soils.	Dislikes waterlogged conditions.	15 + grass	6-7
Subterranean clover	Suitable for grazing and/or forage.	Can be undersown.	Neutral to acid soils.	Warm, moist winters and dry summers.	Not available	Not available
Lucerne/alfalfa	Fodder potential; has higher bloat risk as fresh forage.	Deep rooting; drought tolerant; Requires inoculum to establish; slow to establish; resistant to stem nematode; can be undersown; productive for up to 5 years.	Requires soil pH of 6+ in topsoil and subsoil.	Risk of winter loss/die back.	20 + inoculant	5
Vetch -	Highly productive biomass.	Late sowing possible; Very competitive; long flowering period. May be difficult to kill in spring; viable seeds can become weeds in subsequent crops.	Difficult to establish on heavy clay.	Dislikes waterlogged conditions.	60-120	1-1.50

Sainfoin	High protein forage; bloat free; high palatability.	Highly productive.	Intolerant of acid soils.	Not suited to autumn sowing; intolerant of waterlogging.	60-90	2
Birdsfoot trefoil	Low bloat risk; Lower biomass production.	Prostrate growth habit; can be undersown; tolerant of shade.	Thrives on poorly drained soils.	Tolerant of cold and wet.	9-12	4.75-5
White-flowering lupin	Fodder and seed crop potential.	Poor yield; not very competitive; winter lupins not recommended in Scotland.	Intolerant of high pH needs high PK status.	Needs dry winters; late harvest.	225 + inoculant	0.71
Peas (fresh or dried)	Potential as cash crop, and animal feed.	Can be difficult to harvest (especially in wet conditions) as very prone to lodging; not very competitive, susceptible to weeds; risk of bird damage; much of fixed N removed in harvested crop.	Prefers free draining soil.	Dislikes waterlogged conditions.	350	0.50
Field Beans	Animal feed.	Easier to harvest than peas but may have lower yield; much of fixed N removed in harvested crop.	Suited to many soils.	Late harvest.	Winter 210 Spring 250	Winter 0.46 Spring 0.47

9. BIBLIOGRAPHY

ADGO, E. & SCHULZE, J. (2002). Nitrogen fixation and assimilation efficiency in Ethiopian and German pea varieties. *Plant and Soil*, **239**, 291-299.

ALMEIDA, J.P.F., HARTWIG, U.A., FREHNER, M., NÖSBERGER, J. & LUSCHER, A. (2000). Evidence that P deficiency induces N feedback regulation of symbiotic N_2 fixation in white clover (*Trifolium repens* L.). *Journal of Experimental Botany* , **51**, 1289-1297.

AMARGER, N. (2001). Rhizobia in the field. *Advances in Agronomy,* **73**, 109-168.

ANDERSON, G.C., FILLERY, I.R.P., DOLLING, P.J. & ASSENG, S. (1998). Nitrogen and water flows under pasture-wheat and lupin-wheat rotations in deep sands in Western Australia - 1. Nitrogen fixation in legumes, net N mineralisation, and utilisation of soil-derived nitrogen. *Australian Journal of Agricultural Research*, **49**, 329-343.

ANDERSON, J.M. (1973). The breakdown and decomposition of sweet chestnut and beech leaf litter in two deciduous woodland soils. II. Changes in C, N and polyphenol content. *Oecologia,* **12**, 275-388

ANON. (1985). Control of pests and diseases of grass and forage crops. MAFF/ADAS B2045. HMSO 84 pp.

ANON. (1997) Elaboration of standards for site-specified fertilization systems in organic farming in Europe based on long term field experiments. (Concerted Action report AIR3-CT94-1940 on website of idbf.de).

ARMSTRONG, E.L., PATE, J.S. & UNKOVICH, M.J. (1994). Nitrogen balance of field pea crops in south western Australia, studied using the ^{15}N natural abundance technique. *Australian Journal of Plant Physiology*, **21**, 533-549.

ASKEGAARD, M., OLESEN, J. E. & RASMUSSEN, I. A. (1999). Agronomic considerations and dilemmas in Danish crop rotation experiment. In: Designing and testing crop rotations for organic farming. Proceedings from an international workshop. DARCOF report No 1. (Eds J E Olesen, R Eltun, M J Gooding, E S Jensen U Köpke.) pp. 63-70.

ATALLAH, T. & LOPEZ-REAL, J.M. (1991). Potential of green manure species in recycling nitrogen, phosphorus and potassium. *Biological Agriculture and Horticulture* **8**, 53-65.

ATKINSON, D., WATSON, C.A., HOOKER, J.E. & BLACK, K.E. (1995). Nutrient conservation in organic crop production systems: implications for root systems. In: H.F Cook & H.C. Lee (Eds) *Soil Management in Sustainable Agriculture.* Proceedings Third International Conference on Sustainable Agriculture, Wye College, University of London, UK, 31 August - 4 September 1993. Wye College Press, Ashford, UK. pp. 54-60.

BAARS, T. (2000). Effective use of manure and fertiliser in organically grown grass/clover swards. In *Grassland Science in Europe. Vol. 5. Grassland Farming - Balancing Environmental and Economic Demands*. Proceedings of the 18th General Meeting of the European Grassland Federation. Aalborg, Denmark, 22-25 May 2000. (Eds K. Søegaard, C. Ohlsson, J. Sehested, N.J. Hutchings & T. Kristensen), pp. 524-526. Tjele, Denmark; Danish Institute of Agricultural Sciences.

BAARS, T. (2002). N-fixation of white clover affected by clover yield and type of manure. In *Grassland Science in Europe. Vol. 7. Multi-function Grasslands. Quality Forages, Animal Products and Landscapes.* Proceedings of the 19th General Meeting of the European Grassland Federation. La Rochelle, France, 27-30 May 2002. (Eds. J.L. Durand, J.C. Emile, C. Huyghe & G. Lemaire), pp. 654-655. Versailles, France; AFPF.

BAGGS, E., WATSON, C., REES, R.M. & SMITH, K.A. (1996). The fate of nitrogen from incorporated crop residues. In: D. Younie (ed.) *Legumes in Sustainable Farming Systems*. Occasional Symposium No. 30, British Grassland Society, Reading. pp. 113-118.

BAILEY, J.S. & LAIDLAW, A.S. (1999). The interactive effects of phosphorus, potassium, lime and molybdenum on the growth and morphology of white clover (*Trifolium repens* L.) at establishment. *Grass and Forage Science*, **54**, 69-76.

BALL, P.R. & KEENEY, D.R. (1981). Nitrogen losses from urine-affected areas of a New Zealand pasture, under contrasting seasonal conditions. *Proceedings 12th International Grassland Congress, Kentucky*, 342-344.

BANNON, F. J. & COOKE, B. M. (1998). Studies on dispersal of *Septoria tritici* pycnidiospores in wheat-clover bicrops. *Plant Pathology* **47**, 49-56.

BARRACLOUGH, D., JARVIS, S.C., DAVIES, G.P. & WILLIAMS, J. (1992). The relation between fertilizer nitrogen applications and nitrate leaching from grazed grassland. *Soil Use and Management* **8**, 51-56.

BARRACLOUGH, P.B. (1986). The growth and activity of winter wheat roots in the field: nutrient inflows of high yielding crops. *Journal of Agricultural Science, Cambridge* **106**, 53-59.

BARRY, D.A.J., GOORAHOO, D. & GOSS, M.J. (1993). Estimation of nitrate concentrations in groundwater using a whole farm nitrogen budget. *Journal of Environmental Quality*, **22**, 767-775.

BECHER, M., SCHEPL, U. & SCHUBERT, S. (1997). N_2 fixation during different physiological stages of *Phaseolus vulgaris* OAC Rico and its supernodulating mutant R32BS15: The role of assimilate supply to and export from nodules. *Journal of Plant Physiology*, **150**, 31-36.

BELL, F. & NUTMAN, P.S. (1971). Experiments on nitrogen fixation by nodulated lucerne. *Plant and Soil*, Special volume, 231-264.

BENDING, G.D., TURNER, M.K. & BURNS, I.G., (1998). Fate of nitrogen from crop residues as affected by biochemical quality and the microbial biomass. *Soil Biology Biochemistry,* **30**, 2055-2065

BENGTSSON, A. (1991). Field experiments with inoculation and nitrogen fertilization of kidney beans (*Phaseolus vulgaris* L). *Swedish Journal of Agricultural Research*, **21**, 63-66.

BERG, B. (1986) Nutrient release from litter and humus in coniferous forest soils - a mini review. *Scandinavian Journal of Forest Research,* **1**, 359-369

BERG, R.K.J. & LYND, J.Q. (1985). Soil fertility effects on growth, yield, nodulation and nitrogenase activity of Austrian winter pea. *Journal of Plant Nutrition*, **8**, 131-145.

BERGERSEN, F.J. & TURNER, G.L. (1983). An evaluation of ^{15}N methods for estimating nitrogen fixation in a subterranean clover - perennial ryegrass sward. *Australian Journal of Agricultural Research*, **34**, 391-401.

BERGERSEN, H.F., HELY, F.W. & COSTIN, A.B. (1963). Overwintering of clover nodules in alpine conditions. *Australian Journal of Biological Science*, **10**, 920-921.

BERRY P M, PHILLIPS L, SYLVESTER-BRADLEY R (2000) An expert group approach to improving nitrogen use and performance of arable crops on organic farms in the UK. The World grows organic. Proceedings 13th IFOAM scientific conference. (Eds: Alföldi T, Lockeretz W, Niggli U.) Basel 28-31 August 2000 p 80.

BHOGAL, A. & HARRISON, R. (1999). The effect of temperature on microbially mediated soil N transformations. Review for MAFF, *Report No. NT2101*. 70pp.

BIDDLE, A. J. and WHALLEY, W. M. (1996). Cross pathogenicity of *Fusarium solani* and *Phoma medicaginis* var. *pinodella* isolates on peas, field and dwarf green beans. *Aspects of Applied Biology* **47**, *Rotations and cropping systems*, 179-183.

BIDDLE, A.J. (1984). A prediction test for pea foot rot and the effects of previous legumes. *Proceedings of the British Crop Protection Conference – Pests & Diseases* **3**, 773-777.

BIEDERBECK, V. O., BOUMAN, O.T., CAMPBELL, C. A., BAILEY, L. D. & WINKLEMAN, G. E. (1996). Nitrogen benefits from four green-manure legumes in dryland cropping systems. *Canadian Journal of Plant Science*, **76,** 307-315.

BIEDERBECK, V.O., BOUMAN, O.T., CAMPBELL, C.A., BAILEY, L.D. & WINKLEMAN, G.E. (1996). Nitrogen benefits from four green-manure legumes in dryland cropping systems. *Canadian Journal of Plant Science*, **76**, 307-315.

BIEDERBECK, V.O., BOUMAN, O.T., LOOMAN, J., SLINKARD, A.E., BAILEY, L.D., RICE, W.A. & JANZEN, H.H. (1993). Productivity of four annual legumes as green manure in dryland cropping systems. *Agronomy Journal*, **85**, 1035-1043.

BLISS, F.A. (1993). Utilizing the potential for increased nitrogen fixation in common bean. *Plant and Soil*, **152**, 157-160.

BOLGER, T.P. (1989). Water use, yield, quality and dinitrogen fixation of sainfoin and alfalfa under gradient irrigation. *Dissertation Abstracts International B Sciences & Engineering*, **50**, 376B.

BOLGER, T.P., PATE, J.S., UNKOVICH, M.J. & TURNER, N.C. (1995). Estimates of seasonal nitrogen fixation of annual subterranean clover-based pastures using the ^{15}N natural abundance technique. *Plant and Soil*, **175**, 57-66.

BOLLER, B.C. & NÖSBERGER, J. (1987). Symbiotically fixed nitrogen from field-grown white and red clover mixed with ryegrasses at low levels of ^{15}N-fertilization. *Plant and Soil*, **104**, 219-226.

BOLLER, B.C. & NÖSBERGER, J. (1994). Differences in nitrogen fixation among field-grown red clover strains at different levels of ^{15}N-fertilization. *Euphytica*, **78**, 167-174.

BOUCHART, V., MACDUFF, J.H., OURRY, A., SVENNING, M.M., GAY, A.P., SIMON, J.C. & BOUCAUD, J. (1998). Seasonal pattern of accumulation and effects of low temperatures on storage compounds in *Trifolium repens*. *Physiologia Plantarum*, **104**, 65-74.

BOWMAN, A.M., PEOPLES, M.B., SMITH, W. & BROCKWELL, J. (2002). Factors affecting nitrogen fixation by dryland lucerne in central-western New South Wales. *Australian Journal of Experimental Agriculture*, **42**, 439-451.

BRADBURY, N.J., WHITMORE, A.P., HART, P.B.S. & JENKINSON, D.S. (1993). Modelling the fate of nitrogen in crop and soil in the years following application of ^{15}N-labelled fertiliser to winter wheat. *Journal of Agricultural Science,* **121**, 363-379.

BRANDSÆTER, L. O. & RILEY, H. (1999). Plant residues for weed management in vegetables. In: Designing and testing crop rotations for organic farming. Proceedings from an international workshop. DARCOF report No 1. (Eds J E Olesen, R Eltun, M J Gooding, E S Jensen U Köpke.) pp 331-336

BREMER, E., GEHLEN, H., SWERHONE, G.D.W. & VANKESSEL, C. (1993). Assessment of reference crops for the quantification of N_2 fixation using natural and enriched levels of ^{15}N abundance. *Soil Biology & Biochemistry*, **25**, 1197-1202.

BROPHY, L.S., HEICHEL, G.H. & RUSSELLE, M.P. (1987). Nitrogen fixation transfer from forage legumes to grass in a systematic planting design. *Crop Science*, **27**, 753-758.

BRYSON, R.J., SYLVESTER-BRADLEY, R., SCOTT, R.K. and PAVELEY, N.D. (1995). Reconciling the effects of yellow rust on yield of winter wheat through measurements of green leaf area and radiation interception. *Aspects of Applied Biology* **42**, 9-18.

BULLARD, M. J. (1992) The potential of Birdsfoot trefoil (*Lotus corniculatus L.*) for UK agriculture. PhD Thesis. University of York, Department of Biology.

BULLIED, W.J., ENTZ, M. H., SMITH, S. R. & BAMFORD, K. C. (2002). Grain yield and N benefits to sequential wheat and barley crops from single-year alfalfa, berseem and red clover, chickling vetch and lentil. *Canadian Journal of Plant Science*, **82,** 53-65.

BUTLER, G.W., GREENWOOD, R.M. & SOPER, K. (1959). Effects of shading and defoliation on the turnover of root and nodule tissue of plants of *Trifolium repens*, *Trifolium pratense*, and *Lotus uliginosus*. *New Zealand Journal of Agricultural Research*, **2**, 415-426.

BUTTERY, B.R., PARK, S.J. & HUME, D.J. (1992). Potential for increasing nitrogen fixation in grain legumes. *Canadian Journal of Plant Science*, **72**, 323-349.

CAGAŠ B, MACHÁC R (2002) The effect of grasses grown for seed in mixture with legumes on the incidence of weeds and soil nitrogen content In: Powell et al. (eds), *UK Organic Research 2002: Proceedings of the COR Conference, 26-28 th March 2002, Aberystwyt*h, pp. 53-54.

CAMERON, K.C. & WILD, A. (1984). Potential aquifer pollution from nitrate leaching following the ploughing of temporary grassland. *Journal of Environmental Quality* **13**, 274-278.

CARRANCA, C., DE VARENNES, A. & ROLSTON, D. (1999). Biological nitrogen fixation by fababean, pea and chickpea, under field conditions, estimated by the ^{15}N isotope dilution technique. *European Journal of Agronomy*, **10**, 49-56.

CHALIFOUR, F.P. & NELSON, L.M. (1988a). Effects of time nitrate application on nitrate reductase activity, nitrate uptake, and symbiotic dinitrogen fixation in faba bean and pea. *Canadian Journal of Botany-Revue Canadienne de Botanique*, **66**, 1646-1652.

CHALIFOUR, F.P. & NELSON, L.M. (1988b). Short-term effects of nitrate on nitrate reductase activity and symbiotic dinitrogen fixation in faba bean and pea. *Canadian Journal of Botany-Revue Canadienne de Botanique*, **66**, 1639-1645.

CHALK, P.M., SMITH, C.J., HOPMANS, P. & HAMILTON, S.D. (1996). A yield-independent, ^{15}N isotope dilution method to estimate legume symbiotic dependence without a non-N_2 fixing reference plant. *Biology and Fertility of Soils*, **23**, 196-199.

CHAPMAN, R. & HEATH, S.B. (1987). The effect of cattle slurry on clover in grass/clover swards. In *Animal Manure on Grassland and Fodder Crops: Fertilizer or Waste?* (Eds H.G. van der Meer, R.J. Unwin, T.A. van Dijk & G.C. Ennik), pp. 337-340. Dordrecht; Martinus Nijhoff.

CLEMENTS R O, MARTYN T, DONALDSON G. 2002. Clover: Cereal bi-cropping, IGER Information Leaflet, 4 pages.

CLEMENTS, R.O., MARTYN, T.M., DONALDSON, G. & WOLFE, M. (2000). Clover:cereal bi-cropping for organic farms. *Aspects of Applied Biology*, **62**, 181-185.

CLOUGH, T.J., JARVIS, S.C. & HATCH, D.J. (1998). Relationships between soil thermal units, nitrogen mineralisation and dry matter production in pastures. *Soil Use and Management,* **15**, 137-144.

COCHRAN, V.L. & SCHLENTNER, S.F. (1995). Intercropped oat and fababean in Alaska – dry matter production, dinitrogen fixation, nitrogen transfer, and nitrogen fertilizer response. *Agronomy Journal*, **87**, 420-424.

COLBOURN, P. (1985). Nitrogen losses from the field: denitrification and leaching in intensive winter cereal production in relation to tillage method of a clay soil. *Soil Use & Management* **1**, 117-120.

COLLINS, M. & LANG, D.J. (1985). Shoot removal and potassium fertilization effects on growth, nodulation and dinitrogen fixation of red clover and birdsfoot trefoil under greenhouse conditions. *Field Crops Research*, **10**, 251-256.

COOK, R. J. & BAKER, K. F. (1996). The nature and practice of biological control of plant pathogens. APS Press, St Paul, MN, USA, 539 pp.

COOKE, G.W. (1982). *Fertilizing for Maximum Yield*. 3rd Edition. Granada, London.

COOKSON, P., GOH, K.M., SWIFT, R.S. & STEELE, K.W. (1990). Effects of frequency of application of ^{15}N tracer and rate of fertilizer nitrogen applied on estimation of nitrogen fixation by an established mixed grass clover pasture using the ^{15}N enrichment technique. *New Zealand Journal of Agricultural Research*, **33**, 271-276.

CORRE, N., BOUCHART, V., OURRY, A. & BOUCAUD, J. (1996). Mobilization of nitrogen reserves during regrowth of defoliated *Trifolium repens* L and identification of potential vegetative storage proteins. *Journal of Experimental Botany*, **47**, 1111-1118.

COVENTRY, D.R., HIRTH, J.R. & FUNG, K.K.H. (1987). Nutritional restraints on subterranean clover grown on acid soils used for crop-pasture rotation. *Australian Journal of Agricultural Research*, **38**, 163-176.

COWELL, L.E., BREMER, E. & VAN KESSEL, C. (1989). Yield and N_2 fixation of pea and lentil as affected by intercropping and N application. *Canadian Journal of Soil Science*, **69**, 243-251.

COWIE, A.L., JESSOP, R.S. & MACLEOD, D.A. (1990). Effect of soil nitrate on the growth and nodulation of winter crop legumes. *Australian Journal of Experimental Agriculture*, **30**, 651-654.

COWLING, D.W. (1982). Biological nitrogen fixation and grassland production in the United Kingdom. *Philosophical Transactions of the Royal Society London*, **B296**, 397-404.

CRAIG, L.D.A., WIEBOLD, W.J. & McINTOSH, M.S. (1981). Nitrogen fixation rates of alfalfa and red clover grown in mixture with grasses. *Agronomy Journal*, **73**, 996-998.

CROOK D G, ELLIS R H, Summerfield R J (1999) Winter sown lentil and its impact on a subsequent cereal crop. *Aspects of Applied Biology* **56**, *Protection and production of combinable break crops*. Pp. 241-248.

CROOK D G, Summerfield R J, Ellis R H, Smith N O (1998) Plant population density in autumn affects winter survival in lentil. Proceedings of the 3rd European conference on grain legumes. Pp 154-155.

CROUCHLEY, G. (1979). Nitrogen fixation in pasture. VIII. Wairarapa plains dryland, Masterton. *New Zealand Journal of Experimental Agriculture*, **7**, 31-33.

CRUSH, J.R., COSGROVE, G.P. & BROUGHAM, R.W. (1982). The effect of nitrogen fertilizer on clover nitrogen fixation in an intensively grazed Manawatu pasture. *New Zealand Journal of Experimental Agriculture*, **10**, 395-399.

CULVENOR, R.A. & SIMPSON, R.J. (1991). Mobilization of nitrogen in swards of *Trifolium subterraneum* L. during regrowth after defoliation. *New Phytologist*, **117**, 81-90.

CUTTLE S P (2002) Nutrient budgets as a tool for researchers and farmers. In: Powell et al. (eds), *UK Organic Research 2002: Proceedings of the COR Conference, 26-28 th March 2002, Aberystwyt*h, pp 169-172

CUTTLE, S.P. (2003). *Influence of the level of self-sufficiency on the nutrient budgets of an organic dairy farm*. Defra Project OF0180: Final Report. Aberystwyth, Institute of Grassland & Environmental Research.

CUTTLE, S.P., SCURLOCK, R.V. & DAVIES, B.M.S. (1998). A 6-year comparison of nitrate leaching from grass/clover and N-fertilized grass pastures grazed by sheep. *Journal of Agricultural Science, Cambridge* **131**, 39-50.

CUTTLE, S.P., SCURLOCK, R.V. & DAVIES, B.M.S. (2001). Comparison of fertilizer strategies for reducing nitrate leaching from grazed grassland, with particular reference to the contribution from urine patches. *Journal of Agricultural Science, Cambridge*, **136**, 221-230.

DALAL, R.C. (1979). Mineralization of carbon and phophorus from carbon-14 and phosphorus-32 labelled plant material added to soil. *Soil Science Society of America Journal* **43**, 913-916.

DANSO, S.K.A., LABANDERA, C., PASTORINI, D. & CURBELO, S. (1988). Nitrogen fixation in a 2-year old white clover fescue pasture - influence of nitrogen fertilization. *Soil Biology & Biochemistry*, **20**, 261-262.

DANSO, S.K.A., PALMASON, F. & HARDARSON, G. (1993). Is nitrogen transferred between field crops? Examining the question through a sweet blue lupin (*Lupinus angustifolius* L.)-oats (*Avena sativa*) intercrop. *Soil Biology & Biochemistry*, **25**, 1135-1137.

DANSO, S.K.A., ZAPATA, F., HARDARSON, G. & FRIED, M. (1987). Nitrogen fixation in faba bean as affected by plant population density in sole or intercropped systems with barley. *Soil Biology and Biochemistry*, **19**, 411-415.

DART, P.J. & DAY, J.M. (1971). Effects of incubation temperature and oxygen tension on nitrogenase activity of legume root nodules. *Plant and Soil*, Special volume, 167-184.

DAVEY, A.G. & SIMPSON, R.J. (1989). Nitrogen fixation by subterranean clover (*Trifolium subterraneum* L) in an acid soil in response to moisture deficits. *Soil Biology & Biochemistry*, **21**, 9-14.

DAVIDSON, I.A. & ROBSON, M.J. (1986a). Effect of contrasting patterns of nitrate application on the nitrate uptake, N_2 fixation, nodulation and growth of white clover. *Annals of Botany*, **57**, 331-338.

DAVIDSON, I.A. & ROBSON, M.J. (1986b). Interactions between nitrate uptake and N_2 fixation in white clover. *Plant and Soil*, **91**, 401-404.

DAVIES, D.A. & HOPKINS, A. (1996). Production benefits of legumes in grassland. In: D. Younie (ed.) *Legumes in Sustainable Farming Systems.* Occasional Symposium No. 30, British Grassland Society, Reading. pp. 234-246.

DAVIES, W.E. (1964). The yields and composition of lucerne, grass and clover under different systems of management. *Journal of the British Grassland Society*, **19**, 263-270.

DAVIS A J. 1989. Effects of soil compaction on damage to wheat seeds by three pest species of slug. *Crop Protection* **8**, 118-121.

De NEVE, S., PANNIER, J. & HOFMAN, G. (1994). Fractionation of vegetable crop residues in relation to in situ N mineralisation. *European Journal of Agronomy,* **3**, 267-272

DEADMAN, M. L., SLOEIMANI, M. J., NKEMKA, P. N.,CLEMENTS, R.O. and GEORGE, S. (1996). Wheat disease and cereal clover bicroops –attempting to resolve the enigma. *Aspects of Applied Biology* **47***, Rotations and cropping systems*, 173-178.

DEANS, J.R., MOLINA, J.A.E. & CLAPP, C.E. (1986). Models for predicting potentially mineralisable nitrogen and decomposition rates, *Soil Science Society of America Journal,* **50**, 323-326.

DEAR, B.S., COCKS, P.S., PEOPLES, M.B., SWAN, A.D. & SMITH, A.B. (1999). Nitrogen fixation by subterranean clover (*Trifolium subterraneum* L.) growing in pure culture and in mixtures with varying densities of lucerne (*Medicago sativa* L.) or phalaris (*Phalaris aquatica* L.). *Australian Journal of Agricultural Research*, **50**, 1047-1058.

DESPERRIER, N., BACCOU, J.C. & SAUVAIRE, Y. (1986). Nitrogen fixation and nitrate assimilation in field-grown fenugreek (*Trigonella foenum graecum* L.). [French]. *Plant & Soil*, **92**, 189-199.

DEWES, T. & HÜNSCHE, E. (1999). Composition and microbial degradability in the soil of farmyard manure from ecologically-managed farms. *Biological Agriculture & Horticulture*, **16**, 251-268.

DOUGLAS, J.A. (1986). The production and utilization of lucerne in New Zealand (Review Paper). *Grass and Forage Science*, **41**, 81-128.

DOYLE, C.J. & THOMSON, D.J. (1985). The future of lucerne in British agriculture: an economic assessment. *Grass and Forage Science*, **40**, 57-68.

DOYLE, C.J., THOMSON, D.J. & SHEEHY, J.E. (1984). The future of sainfoin in British agriculture: an economic assessment. *Grass and Forage Science*, **39**, 43-51.

DUBACH, M. & RUSSELLE, M.P. (1994). Forage legume roots and nodules and their role in nitrogen transfer. *Agronomy Journal*, **86**, 259-266.

EASTON, H.S. (1976). Examples of utilization of grass/legume mixtures: a summary of experience in New Zealand. *Fourrages*, **66**, 103-110.

EBELHAR, S.A., FRYE, W.W. & BLEVINS, R.L. (1984). Nitrogen from legume cover crops for no-tillage corn. *Agronomy Journal*, **76**, 51-55.

EDMEADES, D.C. & GOH, K.M. (1978). Symbiotic nitrogen fixation in a sequence of pastures of increasing age measured by a ^{15}N dilution technique. *New Zealand Journal of Agricultural Research*, **21**, 623-628.

EDWARDS, C.A., LAL, R., MADDEN, P., MILLER, R.H. & HOUSE, G. (1990). Research on integrated arable farming and organic mixed farming in the Netherlands. Sustainable agricultural systems. Soil and Water Conservation Society, Ankeny, Iowa 50021-9764, USA: 287-296.

EKWUE, E.I. (1992). Effect of organic and fertilizer treatments on soil physical properties and erodibility. Soil Tillage Research **22**, 199-209.

ELGERSMA, A. & HASSINK, J. (1997). Effects of white clover (*Trifolium repens* L.) on plant and soil nitrogen and soil organic matter in mixtures with perennial ryegrass (*Lolium perenne* L.). *Plant and Soil*, **197**, 177-186.

ELGERSMA, A. & SCHLEPERS, H. (1997). Performance of white clover perennial ryegrass mixtures under cutting. *Grass and Forage Science*, **52**, 134-146.

ELGERSMA, A., SCHLEPERS, H. & NASSIRI, M. (2000). Interactions between perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.) under contrasting nitrogen availability: productivity, seasonal patterns of species composition, N_2 fixation, N transfer and N recovery. *Plant and Soil*, **221**, 281-299.

ELTUN, R. (1995). Comparisons of nitrogen leaching in ecological and conventional cropping systems. *Biological Agriculture and Horticulture* **11**, 103-114.

ENGIN, M. & SPRENT, J.I. (1973). Effects of water stress on nitrogen fixing activity of *Trifolium repens*. *New Phytologist*, **72**, 117-126.

ENNIK, G.C. (1983). Herbage production without fertilizer nitrogen. *Bedrijfsontwikkeling*, **14**, 959-960.

ERIKSEN J, ASKEGAARD M, OLESEN J E, THORUP-KRISTENSEN K (1999) The sulphur balance of organic crop rotations in Denmark. In: Designing and testing crop rotations for organic farming. Proceedings from an international workshop. DARCOF report No 1. Eds J E Olesen, R Eltun, M J Gooding, E S Jensen U Köpke. pp 251-256

ERIKSEN, J. & HØGH-JENSEN, H. (1998). Variations in the natural abundance of ^{15}N in ryegrass/white clover shoot material as influenced by cattle grazing. *Plant and Soil*, **205**, 67-76.

ERIKSEN, J., ASKEGAARD, M. & VINTHER, F.P. (1999). Nitrate leaching in an organic dairy/crop rotation as affected by organic matter type, livestock density and crop. *Soil Use and Management* **15**, 176-182.

EVANS, J. & HEENAN, D.P. (1998). Simplified methods for assessing quantities of N_2 fixed by *Lupinus* *angustifolius* L. and its benefits to soil nitrogen status. *Australian Journal of Agricultural Research*, **49**, 419-425.

EVANS, J., CHALK, P.M. & O'CONNOR, G.E. (1995). Potential for increasing N_2 fixation of field pea through soil management and genotype. *Biological Agriculture and Horticulture*, **12**, 97-112.

EVANS, J., LEWIS, M. R. & ANDREWS, M. (2001a) The economics of lentil as a grain legume in the UK. *Aspects of Applied Biology* **63,** *Plant Microbial Interactions: Positive interactions in relation to crop production and utilisation*. pp 97-100.

EVANS, J., MCNEILL, A. M., UNKOVICH, M. J., FETTELL, N. A. & HEENAN, D. P. (2001b). Net nitrogen balances for cool-season grain legume crops and contributions to wheat nitrogen uptake: a review. *Australian Journal of Experimental Agriculture*, **41,** pp 347-359.

EVANS, J., McNEILL, A.M., UNKOVICH, M.J., FETTELL, N.A. & HEENAN, D.P. (2001). Net nitrogen balances for cool-season grain legume crops and contributions to wheat nitrogen uptake: a review. *Australian Journal of Experimental Agriculture*, **41**, 347-359.

EVANS, J., TURNER, G.L., O'CONNOR, G.E. & BERGERSEN, F.J. (1987). Nitrogen fixation and accretion of soil nitrogen by field-grown lupins (*Lupinus angustifolius*). *Field Crops Research*, **16**, 309-322.

FALK, B. (1982). Nitrogen uptake in legumes in mixed culture with grass in pure stands - an investigation with a new ^{15}N technique. *Dissertation Abstracts International*, **42**, 44.

FARNHAM, D.E. & GEORGE, J.R. (1993). Dinitrogen fixation and nitrogen transfer among red clover cultivars. *Canadian Journal of Plant Science*, **73**, 1047-1054.

FARNHAM, D.E. & GEORGE, J.R. (1994a). Dinitrogen fixation and nitrogen transfer in birdsfoot trefoil orchardgrass communities. *Agronomy Journal*, **86**, 690-694.

FARNHAM, D.E. & GEORGE, J.R. (1994b). Harvest management effects on dinitrogen fixation and nitrogen transfer in red clover orchardgrass mixtures. *Journal of Production Agriculture*, **7**, 360-364.

FARRINGTON, P., GREENWOOD, E.A.N., TITMANIS, Z.V., TRINICK, M.J. & SMITH, D.W. (1977). Fixation, accumulation and distribution of nitrogen in a crop of *Lupinus angustifolius* cv. Unicrop. *Australian Journal of Agricultural Research*, **28**, 237-248.

FAULKNER, J.S. (1985). A comparison of faba beans and peas as whole-crop forages. *Grass and Forage Science*, **40**, 161-169.

FILLERY, I. R. P. (2001). The fate of biologically fixed nitrogen in legume-based dryland farming systems: a review. *Australian Journal of Experimental Agriculture*, **41,** pp 361-381.

FISHER, N.M. (1996). The potential of grain and forage legumes in mixed farming systems. In *Legumes in Sustainable Farming Systems. BGS Occasional Symposium No. 30*. (Ed. D. Younie), pp. 290-299. Reading: British Grassland Society.

FLANAGAN, P.W. & van CLEVE, K. (1983). Nutrient cycling in relation to decomposition and organic matter quality in Taiga ecosystems. *Canadian Journal of Forest Research,* **13**, 795-817

FORTUNE, S., CONWAY, J. S., PHILIPPS, L., ROBINSON, J. S,, STOCKDALE, E. A. & WATSON, C. (2000). N, P and K for some UK organic farming systems – implications for sustainability. In: Soil Organic Matter and Sustainability. CABI Wallingford, pp286-293.

FOULKES M J, SYLVESTER BRADLEY R, SCOTT R K (1998) Evidence for differences between winter wheat cultivars in acquisition of soil mineral nitrogen and uptake and utilisation of applied fertilizer nitrogen. J Ag Sci 130 29-44

FRAME, J. & BOYD, A. (1987). The effect of fertilizer nitrogen rate, white clover variety and closeness of cutting on herbage productivity from perennial ryegrass/white clover swards. *Grass and Forage Science*, **42**, 85-96.

FRAME, J. & HARKESS, R. (1987). The productivity of four forage legumes sown alone and with each of five companion grasses. *Grass and Forage Science*, **42**, 213-223.

FRANCIS, G.S, HAYNES, R.J., SPARLING, G.P., ROSS, D.J. & WILLIAMS, P.H. (1992). Nitrogen mineralization, nitrate leaching and crop growth following cultivation of a temporary leguminous pasture in autumn and winter. *Fertilizer Research* **33**, 59-70.

FRANKOW-LINDBERG, B.E. (1989). The effect of nitrogen and clover proportion on yield of red clover-grass mixtures. *XVI International Grassland Congress, Nice, France*, 173-174.

FUJITA, K., OFOSU-BUDU, K.G. & OGATA, S. (1992). Biological nitrogen fixation in mixed legume-cereal cropping systems. *Plant and Soil*, **141**, 155-175.

GAIR R. 1982. *Cereal Pests*. ADAS Reference Book 186. London: HMSO. 115 pp.

GATES, R.P.G. & SILSBURY, J.H. (1987). Effects of temperature on growth and nitrogen fixation by swards of subterranean clover. *Annals of Botany*, **59**, 461-469.

GILL, K., JARVIS, S.C. & HATCH, D.J. (1995). Mineralization of nitrogen in long-term pasture soils: Effects of management*. Plant and Soil,* A2: 153-162.

GILLER, K.E., ORMESHER, J. & AWAH, F.M. (1991). Nitrogen transfer from phaseolus bean to intercropped maize measured using ^{15}N enrichment and ^{15}N isotope dilution methods. *Soil Biology & Biochemistry*, **23**, 339-346.

GLEN D M, MILSOM, N F, WILTSHIRE C W. 1990. Effect of seed depth on slug damage to winter wheat. *Annals of Applied Biology* **117**, 693-701.

GLEN D M, WILTSHIRE C W, GREEN D B, MOWAT D J, SPAULL A M. 1992. Slug forecasting in cereals. *HGCA Project Report No. 47.* London: Home-Grown Cereals Authority.

GLEN D M. 1993. Cultural control of pests and prospects for manipulating pest behaviour, predators and parasites. *Proceedings of the Home-Grown Cereals Authority 1993 Conference on Cereals Research and Development*, pp 123-139.

GLENDINING, M.J., BRADBURY, N.J. & COLEMAN, K.W. (1997). MINIM: A database of mineralization experiments (1997). Final Report on MAFF contract NT 1503, pp 31.

GOH, K.M. & RIDGEN, G.E. (1997). Comparison of understorey biological nitrogen fixation and biomass production in grassed-down conventional and organic apple orchards in Canterbury, New Zealand. *Communications in Soil Science and Plant Analysis*, **28**, 1103-1116.

GOH, K.M., BRUCE, G.E. & SEDCOLE, J.R. (2001). Comparison of biological nitrogen fixation in four pairs of conventional and alternative mixed cropping farms with three rotational stages of pasture establishment in Canterbury, New Zealand. *Communications in Soil Science and Plant Analysis*, **32**, 521-536.

GOH, K.M., RIDGEN, G.E. & DALY, M.J. (1995). Understorey biomass production and biological nitrogen fixation in an organic apple orchard in Canterbury, New Zealand. *Communications in Soil Science and Plant Analysis*, **26**, 3261-3273.

GOINS, G.D. & RUSSELLE, M.P. (1996). Fine root demography in alfalfa (Medicago sativa L.). *Plant and Soil*, **185**, 281-291.

GOODLASS, G. & SMITH, K.A. (1979). Effects of ethylene on root extension and nodulation of pea (*Pisum sativum*) and white clover (*Trifolium repens* L.). *Plant and Soil*, **51**, 387-395.

GOODMAN, P.J. (1988). Nitrogen fixation, transfer and turnover in upland and lowland grass clover swards, using ^{15}N isotope dilution. *Plant and Soil*, **112**, 247-254.

GOODMAN, P.J. (1991). Root turnover and nitrogen cycling in low input grass/clover ecosystems. In *Plant Root Growth - an Ecological Perspective: Special Publication Number 10 of the British Ecological Society*. (Ed. D. Atkinson), pp. 267-280. Oxford: Blackwell Scientific Publications.

GORDON, A.J., MACDUFF, J.H., RYLE, G.J.A. & POWELL, C.E. (1989). White clover N_2 fixation in response to root temperature and nitrate. 2. N_2 fixation, respiration, and nitrate reductase activity. *Journal of Experimental Botany*, **40**, 527-534.

GRATWICK M. 1992. *Crop Pests in the UK.* London: Chapman & Hall. 490 pp.

GRIFFIN P, ANDREWS M (2001) Effect of season, sowing date, population, additional N and inoculation with *Rhizobia* on yield of pinto bean (*Phaseolus vulagris*) in N England. In: Plant Microbial Interactions: Positive interactions in relation to crop production and utilisation. Aspects of Applied Biology 63 p 85-90

GRIFFIN, P. & ANDREWS, M. (2001). Effect of season, sowing date, population, additional N and inoculation with *Rhizobia* on yield of pinto bean (*Phaseolus vulgaris*) in N. England. *Aspects of Applied*

Biology, **63**, 85-89.

GRIGNANI, C. & LAIDLAW, A.S. (2002). Nitrogen economy in grasslands and annual forage crops: control of environmental impact. In *Grassland Science in Europe. Vol. 7. Multi-function Grasslands. Quality Forages, Animal Products and Landscapes*. Proceedings of the 19th General Meeting of the European Grassland Federation. La Rochelle, France, 27-30 May 2002. (Eds J.L. Durand, J.C. Emile, C. Huyghe & G. Lemaire), pp. 625-633. Versailles, France, AFPF.

GRUBER, L., STEINWENDER, R., GUGGENBERGER, T. & PLAKOLM, G. (2001). Comparison of organic and conventional farming on a grassland farm. Third Communication: nutrient balances on supply/withdrawal basis and import/export basis. *Bodenkultur*, **52**, 183-195.

GUO, R., SILSBURY, J.H. & GRAHAM, R.D. (1992). Effect of four nitrogen compounds on nodulation and nitrogen fixation in faba bean, white lupin and medic plants. *Australian Journal of Plant Physiology*, **19**, 501-508.

HAGENDORN, D. J. (Ed.) (1984). *Compendium of pea diseases*. The American Phytopathological Society, St. Paul, MN, USA, 57 pp.

HAGLUND S, EBBESVIK M, HANSEN S (2000) Is ley production in organic farming limited by sub-optimal sulphur supply. The World grows organic. Proceedings 13th IFOAM scientific conference. Eds: Alföldi T, Lockeretz W, Niggli U. Basel 28-31 August 2000 p31

HALLING, M.A., HOPKINS, A., NISSINEN, O., PAUL, C., TUORI, M.& SOELTER, U. (2002). Forage legumes - productivity and composition. In *Legume Silages for Animal Production - LEGSIL*. Proceedings of an International Workshop, Braunschweig, Germany, 8-9 July 2001. (Eds R.J. Wilkins & C. Paul), pp. 5-15. (Landbauforschung Volkenrode, Special Issue 234).

HANEL, L. & SIMEK, M. (1993). Soil nematodes and nitrogenase activity (symbiotic N_2 fixation) in red-clover (*Trifolium pratense* L). *European Journal of Soil Biology*, **29**, 109-116.

HANSEN, E.M., HØGH-JENSEN, H. & DJURHUUS, J. (2002). Biological nitrogen fixation in a grazed perennial grass/clover ley and correlation with herbage and soil variables. *European Journal of Agronomy*, **16**, 309-320.

HANSEN, J.P. & VINTHER, F.P. (2001). Spatial variability of symbiotic N_2 fixation in grass-white clover pastures estimated by the ^{15}N isotope dilution method and the natural ^{15}N abundance method. *Plant and Soil*, **230**, 257-266.

HARDING, S.C. & SHEEHY, J.E. (1980). Influence of shoot and root temperature on leaf growth, photosynthesis and nitrogen fixation of lucerne. *Annals of Botany*, **45**, 229-233.

HARDMAN, R. (1981). Fenugreek: a crop that could bring a rise in food supply and a fall in population growth. *World Farming*, 14-18.

HARPER, J.E. & GIBSON, A.H. (1984). Differential nodulation tolerance to nitrate among legume species. *Crop Science*, **24**, 797-801.

HARPER, L. A., HENDRIX, P. F., LANGDALE, G. W. & COLEMAN, D. C. (1995). Clover management to provide optimum nitrogen and soil-water conservation. *Crop Science*, **35,** 176-182.

HARTMANN, C. & ALDAG, R. (1989). N-2-fixation and yield structure of white lupin (*Lupinus albus* L) in comparison to *Vicia faba* L and *Glycine max* (L) Merr. on different sites. *Journal of Agronomy and Crop Science-Zeitschrift fur Acker und Pflanzenbau*, **163**, 201-211.

HARTWIG, U.A. & NÖSBERGER, J. (1994). What triggers the regulation of nitrogenase activity in forage legume nodules after defoliation? *Plant and Soil*, **161**, 109-114.

HARTWIG, U.A. & SOUSSANA, J.-F. (2001). Ecophysiology of symbiotic N_2 fixation in grassland legumes. In *Grassland Science in Europe. Vol. 6. Organic Grassland Farming.* Proceedings of the International Occasional Symposium of the European Grassland Federation, 10-12 July 2001, Witzenhausen, Germany. (Eds J. Isselstein, G. Spatz & M. Hofmann), pp. 1-10. Witzenhausen, Germany: European Grassland Federation.

HARTWIG, U.A. & TROMMLER, J. (2001). Increase in the concentrations of amino acids in the vascular tissue of white clover and white lupin after defoliation: an indication of a N feedback regulation of symbiotic N_2 fixation. *Agronomie*, **21**, 615-620.

HARTWIG, U.A., HEIM, I., LUSCHER, A. & NÖSBERGER, J. (1994). The nitrogen sink is involved in the regulation of nitrogenase activity in white clover after defoliation. *Physiologia Plantarum*, **92**, 375-382.

HATCH, D.J. & MACDUFF, J.H. (1991). Concurrent rates of N_2 fixation, nitrate and ammonium uptake by white clover in response to growth at different root temperatures. *Annals of Botany*, **67**, 265-274.

HATCH, D.J. & MURRAY, P.J. (1994). Transfer of nitrogen from damaged roots of white clover (*Trifolium repens* L.) to closely associated roots of intact perennial ryegrass (*Lolium perenne* L.). *Plant and Soil*, **166**, 181-185.

HAUGGAARD-NIELSEN, H., AMBUS, P. & JENSEN, E.S. (2001a). Interspecific competition, N use and interference with weeds in pea-barley intercropping. *Field Crops Research*, **70**, 101-109.

HAUGGAARD-NIELSEN, H., AMBUS, P. & JENSEN, E.S. (2001b). Temporal and spatial distribution of roots and competition for nitrogen in pea-barley intercrops - a field study employing ^{32}P technique. *Plant and Soil*, **236**, 63-74.

HAYNES, R.J. & NAIDU, R. (1998). Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. *Nutrient Cycling in Agroecosystems* **51**, 123-137.

HAYNES, R.J. & SWIFT, R.S. (1990). Stability of soil aggregates in relation to organic constituents and soil water content. *Journal of Soil Science* **41**, 73-84.

HAYNES, R.J. (1980). Competitive aspects of the grass-legume association. *Advances in Agronomy*, **33**, 227-261.

HAYNES, R.J., MARTIN, R.J. & GOH, K.M. (1993). Nitrogen fixation, accumulation of soil nitrogen and nitrogen balance for some field-grown legume crops. *Field Crops Research*, **35**, 85-92.

HAYNES, R.J., SWIFT, R.S. & STEPHEN, R.C. (1991). Influence of mixed cropping rotations (pasture-arable) on organic matter content, water stable aggregation and clod porosity in a group of soils. *Soil Tillage Research* **19**, 77-87.

HEENAN, D.P., McGHIE, W.J. & COLLINS, D. (1998). Impact of lupins, grazed or ungrazed subterranean clover, stubble retention, and lime on soil nitrogen supply and wheat nitrogen uptake, grain yields, and grain protein. *Australian Journal of Agricultural Research*, **49**, 487-494.

HEICHEL, G.H. & HENJUM, K.I. (1991). Dinitrogen fixation, nitrogen transfer, and productivity of forage legume-grass communities. *Crop Science*, **31**, 202-208.

HEICHEL, G.H., BARNES, D.K., VANCE, C.P. & HENJUM, K.I. (1984). N_2 fixation, and N and dry matter partitioning during a 4-year alfalfa stand. *Crop Science*, **24**, 811-815.

HEICHEL, G.H., VANCE, C.P., BARNES, D.K. & HENJUM, K.I. (1985). Dinitrogen fixation, and N and dry matter distribution during 4-year stands of birdsfoot trefoil and red clover. *Crop Science*, **25**, 101-105.

HERRIDGE, D.F. & DOYLE, A.D. (1989). The narrow-leafed lupin (*Lupinus angustifolius* L) as a nitrogen-fixing rotation crop for cereal production. 2. Estimates of fixation by field-grown crops. *Australian Journal of Agricultural Research*, **39**, 1017-1028.

HEUWINKEL, H. & LOCHER, F. (2000). An approach to describe the variability of nitrogen fixation by a clover-grass mixture within a field. In *IFOAM 2000 The World Grows Organic*. Proceedings 13th International IFOAM Scientific Conference, 28-31 August 2000, Basel, Switzerland. (Eds T. Alfoldi, W. Lockeretz & U. Niggli), p. 90. Zurich; Switzerland: vdf Hochschulverlag AG an der ETH Zurich.

HØGH-JENSEN H (1996) Symbiotic N2 fixation in clover-grass mixtures and nitrogen transfer from clovers to the accompanying grass. In: Symbiotic nitrogen fixation in crop rotations with manure fertilisation. Proceedings of the 3rd meeting: Fertilization systems in organic farming - Concerted Action AIR3-CT94-1940, Copenhagen 4-5 March 1996. Ed J Raupp. Publications of the Institute of Biodynamic research Vol 8. Darmstadt 1996.

HØGH-JENSEN H (2000) Clovers in legume-based grasslaznd maintain their ability for fixing atmospheric nitrogen under low phosphorus and potassium conditions but change the herbage quality. The World grows organic. Proceedings 13th IFOAM scientific conference. Eds: Alföldi T, Lockeretz W, Niggli U. Basel 28-31 August 2000 p91

HØGH-JENSEN, H. & KRISTENSEN, E.S. (1995). Estimation of biological N_2 fixation in a clover-grass system by the ^{15}N dilution method and the total-N difference method. *Biological Agriculture &*

Horticulture, **11**, 203-219.

HØGH-JENSEN, H. & SCHJOERRING, J.K. (1994). Measurement of biological dinitrogen fixation in grassland - comparison of the enriched ^{15}N dilution and the natural ^{15}N abundance methods at different nitrogen application rates and defoliation frequencies. *Plant and Soil*, **166**, 153-163.

HØGH-JENSEN, H. & SCHJOERRING, J.K. (1997a). Effects of drought and inorganic N form on nitrogen fixation and carbon isotope discrimination in *Trifolium repens. Plant Physiology and Biochemistry*, **35**, 55-62.

HØGH-JENSEN, H. & SCHJOERRING, J.K. (1997b). Interactions between white clover and ryegrass under contrasting nitrogen availability: N_2 fixation, N fertilizer recovery, N transfer and water use efficiency. *Plant and Soil*, **197**, 187-199.

HØGH-JENSEN, H. & SCHJOERRING, J.K. (2000). Below-ground nitrogen transfer between different grassland species: Direct quantification by ^{15}N leaf feeding compared with indirect dilution of soil ^{15}N. *Plant and Soil*, **227**, 171-183.

HØGH-JENSEN, H. (1996). Symbiotic N_2 fixation in grass-clover mixtures and nitrogen transfer from clovers to the accompanying grass.In *Symbiotic Nitrogen Fixation in Crop Rotations with Manure Fertilization*. Proceedings of the third meeting, 4-5 March 1996, Copenhagen, Denmark. (Ed. J. Raup), pp. 7-31. Darmstadt, Germany: Institute for Biodynamic Research.

HØGH-JENSEN, H. (2000). Clovers in legume-based grassland maintain their ability for fixing atmospheric nitrogen under low phosphorus and potassium conditions but change the herbage quality. In *IFOAM 2000 The World Grows Organic*. Proceedings 13th International IFOAM Scientific Conference, 28-31 August 2000, Basel, Switzerland. (Eds T. Alfoldi, W. Lockeretz & U. Niggli), p. 91. Zurich, Switzerland: vdf Hochschulverlag AG an der ETH Zurich.

HØGH-JENSEN, H., LOGES, R., JENSEN, E.S., JØRGENSEN, F.V. & VINTHER, F.P. (1998). Empirical model for quantifying legume biological nitrogen fixation. In *Nitrate Leaching and Balances in Conventional and Organic Production Systems. Report No. 2*. (Eds E.S. Kristensen & J.E. Olesen), pp. 69-86. Danish Research Centre for Organic Farming.

HOLLE R, UNTIEDT U (1999) Crop rotations on organic farms in Northern Germany and development of the wide row system. In: Designing and testing crop rotations for organic farming. Proceedings from an international workshop. DARCOF report No 1. Eds J E Olesen, R Eltun, M J Gooding, E S Jensen U Köpke. pp 159-162

HONEYCUTT, C.W., ZIBILSKE, L.M. & CLAPHAM, W.M. (1988). Heat units for describing carbon mineralisation and predicting net N mineralisation. *Soil Science Society of America Journal,* **52**, 1348-1350.

HUME, L.J. & WITHERS, N.J. (1985). Nitrogen fixation in sainfoin (*Onobrychis viciifolia*). 1. Responses to changes in nitrogen nutrition. *New Zealand Journal of Agricultural Research*, **28**, 325-335.

HUME, L.J. (1985). An investigation into the efficiency of nitrogen fixation in sainfoin (*Onobrychis viciifolia* Scop.). *Proceedings of the New Zealand Grassland Association*, **46**, 239.

HUME, L.J., WITHERS, N.J. & RHOADES, D.A. (1985). Nitrogen fixation in sainfoin (*Onobrychis viciifolia*). 2. Effectiveness of the nitrogen-fixing system. *New Zealand Journal of Agricultural Research*, **28**, 337-348.

HUTCHINGS, N.J. & KRISTENSEN, I.S. (1995). Modelling mineral nitrogen accumulation in grazed pasture: will more nitrogen leach from fertilized grass than unfertilized grass/clover? *Grass and Forage Science* **50**, 300-313.

IMSANDE, J. (1988). Interrelationship between plant developmental stage, plant growth rate, nitrate utilization and nitrogen fixation in hydroponically grown soybean. *Journal of Experimental Botany*, **39**, 775-785.

IRITANI, W.M., & ARNOLD, C.Y. (1960). Nitrogen release of vegetable crop residues during incubations as related to their chemical composition. *Soil Science,* **9**, 74-82

ISHII, K. (1980). High yield of soybean and soil fertility - a case of seed yield of 600 kg/10a. *Japan Agricultural Research Quarterly*, **14**, 137-142.

IZAURRALDE, R.C., McGILL, W.B. & JUMA, N.G. (1992). Nitrogen fixation efficiency, interspecies N transfer, and root growth in barley-field pea intercrop on a black chernozemic soil. *Biology and Fertility* *of Soils*, **13**, 11-16.

JAMES, E.K. & CRAWFORD, R.M.M. (1998). Effect of oxygen availability on nitrogen fixation by two Lotus species under flooded conditions. *Journal of Experimental Botany*, **49**, 599-609.

JARVIS S.C., STOCKDALE E.A., SHEPHERD M.A. & POWLSON D.S. (1996). Nitrogen mineralization in temperate agricultural soils: processes and measurements. *Advances in Agronomy,* **57**,187-235.

JARVIS, S.C. & HATCH, D.J. (1985). The effects of aluminum on the growth of white clover dependent upon fixation of atmospheric nitrogen. *Journal of Experimental Botany*, **36**, 1075-1086.

JENKINSON, D.S. & RAYNER, J.H. (1977) The turnover of soil organic matter in some of the Rothamsted classical experiments. *Soil Science,* **123**, 298-305.

JENSEN, E.S. (1986a). Symbiotic N_2 fixation in pea and field bean estimated by ^{15}N fertilizer dilution in field experiments with barley as a reference crop. *Plant and Soil*, **92**, 3-13.

JENSEN, E.S. (1986b). The influence of rate and time of nitrate supply on nitrogen fixation and yield in pea (*Pisum sativum* L). *Fertilizer Research*, **10**, 193-202.

JENSEN, E.S. (1987a). Seasonal patterns of growth and nitrogen fixation in field- grown pea. *Plant and Soil*, **101**, 29-37.

JENSEN, E.S. (1987b). Variation in nitrate tolerance of nitrogen fixation in the pea rhizobium symbiosis. *Plant Breeding*, **98**, 130-135.

JENSEN, E.S. (1995). Cycling of grain legume residue nitrogen. *Biological Agriculture & Horticulture*, **11**, 193-202.

JENSEN, E.S. (1996a). Barley uptake of N deposited in the rhizosphere of associated field pea. *Soil Biology & Biochemistry*, **28**, 159-168.

JENSEN, E.S. (1996b). Grain yield, symbiotic N_2 fixation and interspecific competition for inorganic N in pea-barley intercrops. *Plant and Soil*, **182**, 25-38.

JENSEN, E.S. (1998). Soil N management and N_2 fixation in field pea (*Pisum sativum*). In *Opportunities for High Quality, Healthy and Added-value Crops to Meet European Demands*. 3rd European Conference on Grain Legumes, 14-19 November 1998, Valladolid, Spain. (Ed. AEP), pp.132-133. Paris: AEP.

JOHANSEN, A. & JENSEN, E.S. (1996). Transfer of N and P from intact or decomposing roots of pea to barley interconnected by an arbuscular mycorrhizal fungus. *Soil Biology & Biochemistry*, **28**, 73-81.

JOHNSON, H.S. & HUME, D.J. (1972). Effects of nitrogen sources and organic matter on nitrogen fixation and yield of soyabeans. *Canadian Journal of Plant Science*, **52**, 991-996.

JOHNSTON, A.E., MCEWAN, J., LANE, P.W., HEWITT, M.V., POULTON, P.R. & YEOMAN, D.P. (1994). Effects of one to six year old ryegrass-clover leys on soil nitrogen and on the subsequent yields and fertilizer nitrogen requirements of the arable sequence winter wheat, potatoes, winter wheat, winter beans (*Vicia faba*) grown on a sandy loam soil. *Journal of Agricultural Science, Cambridge* **122**, 73-89.

JØRGENSEN, F.V. & JENSEN, E.S. (1997). Short-term effects of a dung pat on N_2 fixation and total N uptake in a perennial ryegrass/white clover mixture. *Plant and Soil*, **196**, 133-141.

JØRGENSEN, F.V. & LEDGARD, S.F. (1997). Contribution from stolons and roots to estimates of the total amount of N_2 fixed by white clover (*Trifolium repens* L.). *Annals of Botany*, **80**, 641-648.

JØRGENSEN, F.V., JENSEN, E.S. & SCHJOERRING, J.K. (1999). Dinitrogen fixation in white clover grown in pure stand and mixture with ryegrass estimated by the immobilized ^{15}N isotope dilution method. *Plant and Soil*, **208**, 293-305.

JOYCE A N, McKENZIE B A, ANDREWS M, MILBURN C E (2001) Potential yields, N inputs and management of lentil (*Lens culinaris*) in the UK. In: Plant Microbial Interactions: Positive interactions in relation to crop production and utilisation. Aspects of Applied Biology 63 p 141-150

JOYCE, A., McKENZIE, B., GRIFFIN, P.& ANDREWS, M. (2001a). Evaluation of the potential of spring grown lentil (*Lens culinaris*) in the UK with the use of a crop simulation model. In *Towards the Sustainable Production of Healthy Food, Feed and Novel Products.* 4th European Conference on Grain Legumes, 8-12 July 2001, Cracow, Poland. (Ed. AEP), pp. 50-51. Paris: AEP.

JOYCE, A.N., McKENZIE, B.A., ANDREWS, M. & MILBURN, C.E. (2001b). Potential yields, N inputs and management of lentil (*Lens culinaris*) in the UK. *Aspects of Applied Biology*, **63**, 141-149.

KAGE, H. (1995). Interaction of nitrate uptake and nitrogen fixation in faba beans. *Plant and Soil*, **176**, 189-196.

KARPENSTEIN-MACHAN, M. & STUELPNAGEL, R. (2000). Biomass yield and nitrogen fixation of legumes monocropped and intercropped with rye and rotation effects on a subsequent maize crop. *Plant and Soil*, **218**, 215-232.

KAUL, H.P., AUFHAMMER, W. & WAGNER, W. (1996). Dry matter and nitrogen accumulation and residues of oil and protein crops. *European Journal of Agronomy*, **5**, 137-147.

KESSLER, W. & NÖSBERGER, J. (1994). Factors limiting white clover growth in grass/clover systems. In *Grassland and Society*. Proceedings of the 15th General Meeting of the European Grassland Federation, 6-9 June 1994, Wageningen. (Eds L. 't Mannetje & J. Frame), pp. 525-538. Wageningen: European Grassland Federation.

KESSLER, W., BOLLER, B.C. & NÖSBERGER, J. (1990). Distinct influence of root and shoot temperature on nitrogen fixation by white clover. *Annals of Botany*, **65**, 341-346.

KILIAN, S., BERSWORDT-WALLRABE, P., STEELE ,H. & WERNER, D. (2001). Cultivar-specific dinitrogen fixation in *Vicia faba* studied with the nitrogen-15 natural abundance method. *Biology and Fertility of Soils*, **33**, 358-364.

KIM, T.H., OURRY, A., BOUCAUD, J. & LEMAIRE, G. (1993). Partitioning of nitrogen derived from N_2 fixation and reserves in nodulated *Medicago sativa* L. during regrowth. *Journal of Experimental Botany*, **44**, 555-562.

KIPENOLT, J.A. & GILLER, K.E. (1993). A field evaluation using the ^{15}N isotope-dilution method of lines of *Phaseolus vulgaris* L. bred for increased nitrogen fixation. *Plant and Soil*, **152**, 107-114.

KIRKEGAARD, J.A., WONG, P.T.W. and DESMARCHELLIER, J.M. (1996). *In-vitro* suppression of fungal root pathogens of cereals by *Brassica* tissues. *Plant Pathology* **45**, 593-603.

KOIVISTO, J.M., DEVINE, T.E., SAWYER, C.& LANE, G.P.F. (2002). Evaluation of forage soybeans (*Glycine max* L. Merr.) in the United Kingdom. In *Grassland Science in Europe. Vol. 7. Multi-function Grasslands. Quality Forages, Animal Products and Landscapes.* Proceedings of the 19th General Meeting of the European Grassland Federation. La Rochelle, France, 27-30 May 2002. (Eds J-L. Durand, J-C. Emile, C. Huyghe & G. Lemaire), pp. 432-433. Versailles, France: AFPF.

KOOPMANS, C. J. & BOKHORST, J. (2000). Optimising organic farming systems: nitrogen dynamics and long-term soil fertility in arable and vegetable production systems in the Netherlands. The World grows organic. Proceedings 13th IFOAM scientific conference. Eds: Alföldi T, Lockeretz W, Niggli U. Basel 28-31 August 2000, pp 69-72.

KORSAETH, A. & ELTUN, R. (2000). Nitrogen mass balances in conventional, integrated and ecological cropping systems and the relationship between balance calculations and nitrogen runoff in an 8-year field experiment in Norway. *Agriculture, Ecosystems and Environment*, **79**, 199-214.

KOTNIK T, KÖPKE U (2000) Efficient use of turnip (*Brassica rapa* L. var. *rapa*) for nitrogen management and enhancement of farm income. The World grows organic. Proceedings 13th IFOAM scientific conference. Eds: Alföldi T, Lockeretz W, Niggli U. Basel 28-31 August 2000 p 81

KRAFT, J. (1991). Pea diseases. *Aspects of Applied Biology, Production and protection of legumes*, **27**, 313-319.

KRALL, J.M. & DELANEY, R.H. (1982). Assessment of acetylene reduction by sainfoin and alfalfa over three growing seasons. *Crop Science*, **22**, 762-766.

KRALL, J.M. (1980). $N_2(C_2H_2)$ fixation patterns in sainfoin (*Onobrychis viciifolia* Scop.) and alfalfa (*Medicago sativa* L.) grown in 6 soils. *Dissertation Abstracts International, B*, **41**, 530.

KRISTENSEN, E.S., HØGH-JENSEN, H. & KRISTENSEN, I.S. (1995). A simple model for estimation of atmospherically-derived nitrogen in grass-clover systems. *Biological Agriculture and Horticulture*, **12**, 263-276.

KRISTENSEN, S.P., MATHIASEN, J., LASSEN, J., MADSEN, H.B. & REENBERG, A. (1994). A comparison of the leachable inorganic nitrogen content in organic and conventional farming systems.

Acta Agriculturae Scandinavica Section B-Soil & Plant Science **44**, 19-27.

KUCEY, R.M.N. (1989). Contribution of N_2 fixation to field bean and pea N uptake over the growing season under field conditions in southern Alberta. *Canadian Journal of Soil Science*, **69**, 695-699.

KUMAR, K. & GOH, K.M. (2000). Biological nitrogen fixation, accumulation of soil nitrogen and nitrogen balance for white clover (*Trifolium repens* L.) and field pea (*Pisum sativum* L.) grown for seed. *Field Crops Research*, **68**, 49-59.

KUNDU, S., MUNESHWAR, S., MANNA, M.C., TRIPATHI, A.K., TAKKAR, P.N. & SINGH, M. (1996). Effect of farmyard manure on nitrogen fixation in soybean (*Glycine max*) and its net potential contribution to N balance as measured by ^{15}N-tracer methodology. *Indian Journal of Agricultural Sciences*, **66**, 509-513.

KURDALI, F., AL AIN, F. & AL SHAMMA, M. (2002). Nodulation, dry matter production, and N_2 fixation by fababean and chickpea as affected by soil moisture and potassium fertilizer. *Journal of Plant Nutrition*, **25**, 355-368.

LAIDLAW, A.S. (1988). The contribution of different white clover cultivars to the nitrogen yield of mixed swards. *Grass and Forage Science*, **43**, 347-350.

LAIDLAW, A.S., CHRISTIE, P. & LEE, H.W. (1996). Effect of white clover cultivar on apparent transfer of nitrogen from clover to grass and estimation of relative turnover rates of nitrogen in roots. *Plant and Soil*, **179**, 243-253.

LAMPKIN N (1990) Organic Farming. Farming Press, Ipswich 715 pp

LAMPKIN, N. & MEASURES, M. (eds) (1999). *Organic Farm Management Handbook*. 3rd edition. Aberystwyth, University of Wales.

LAMPKIN, N. (1990). *Organic Farming*. Ipswich: Farming Press.

LAMPKIN, N. (1992). *Organic Farming.* Farming Press, UK.

Lampkin, N. (1992). *Organic Farming.* Farming Press, UK.

LANDI, L., BADALUCCO, L., POMARE, F. & NANNIPIERI, P. (1993) Effectiveness of antibiotics to distinguish the contribution of fungi and bacteria to net nitrogen mineralisation, nitrification and respiration. *Soil Biology & Biochemistry,* **25** 1771-1778.

LARSON, K.J., CASSMAN, K.G. & PHILLIPS, D.A. (1989). Yield, dinitrogen fixation, and above-ground nitrogen balance of irrigated white lupin in a Mediterranean climate. *Agronomy Journal*, **81**, 538-543.

LARSSON H (1999) Experiments with leguminous crops in a stockless organic farming system with sugar beets. In: Designing and testing crop rotations for organic farming. Proceedings from an international workshop. DARCOF report No 1. Eds J E Olesen, R Eltun, M J Gooding, E S Jensen U Köpke. pp 311-317

LEDGARD, S.F. & STEELE, K.W. (1992). Biological nitrogen fixation in mixed legume grass pastures. *Plant and Soil*, **141**, 137-153.

LEDGARD, S.F. (1991). Transfer of fixed nitrogen from white clover to associated grasses in swards grazed by dairy cows, estimated using ^{15}N methods. *Plant and Soil*, **131**, 215-223.

LEDGARD, S.F. (2001). Nitrogen cycling in low input legume-based agriculture, with emphasis on legume/grass pastures. *Plant and Soil*, **228**, 43-49.

LEDGARD, S.F., BRIER, G.J. & LITTLER, R.A. (1987). Legume production and nitrogen fixation in hill pasture communities. *New Zealand Journal of Agricultural Research*, **30**, 413-421.

LEDGARD, S.F., SPROSEN, M.S. & STEELE, K.W. (1996). Nitrogen fixation by nine white clover cultivars in grazed pasture, as affected by nitrogen fertilization. *Plant and Soil*, **178**, 193-203.

LEDGARD, S.F., SPROSEN, M.S., PENNO, J.W. & RAJENDRAM, G.S. (2001). Nitrogen fixation by white clover in pastures grazed by dairy cows: Temporal variation and effects of nitrogen fertilization. *Plant and Soil* , **229**, 177-187.

LEDGARD, S.F., STEELE, K.W. & SAUNDERS, W.H.M. (1982). Effects of cow urine and its major constituents on pasture properties. *New Zealand Journal of Agricultural Research*, **25**, 61-68.

LEGROS, T. & SMITH, D.L. (1994). Root-zone temperature sensitivity of nitrogen-fixing and nitrate-supplied soybean (*Glycine max* (L) Merr cv Maple arrow) and lupin (*Lupinus albus* L cv Ultra) plants. *Environmental and Experimental Botany*, **34**, 117-127.

LILLEY, J.M., BOLGER, T.P., PEOPLES, M.B. & GIFFORD, R.M. (2001). Nutritive value and the nitrogen dynamics of *Trifolium subterraneum* and *Phalaris aquatica* under warmer, high CO_2 conditions. *New Phytologist*, **150**, 385-395.

LINDSTRÖM, K. (1984). Analysis of factors affecting in situ nitrogenase (C_2H_2) activity of *Galega orientalis*, *Trifolium pratense* and *Medicago sativa* in temperate conditions. *Plant and Soil*, **79**, 329-341.

LLOYD, A. (1992). Nitrate leaching under arable land ploughed out from grass. Proceedings No. 330, The Fertiliser Society, Peterborough, 32 pp.

LODEIRO, A.R., GONZALEZ, P., HERNANDEZ, A., BALAGUE, L.J. & FAVELUKES, G. (2000). Comparison of drought tolerance in nitrogen-fixing and inorganic nitrogen-grown common beans. *Plant Science*, **154**, 31-41.

LOGES R, KASKE A, INGWERSEN K and TAUBE F (2000) Yield, forage quality, residue nitrogen and nitrogen fixation of different forage legumes. The World grows organic. Proceedings 13th IFOAM scientific conference. Eds: Alföldi T, Lockeretz W, Niggli U. Basel 28-31 August 2000 p 83

LOGES, R., INGWERSEN, K., KASKE, A.& TAUBE, F. (2000a). Methodological aspects of determining nitrogen fixation of different forage legumes. In *IFOAM 2000 The World Grows Organic*. Proceedings 13th International IFOAM Scientific Conference, 28-31 August 2000, Basel, Switzerland. (Eds T. Alfoldi, W. Lockeretz & U. Niggli), p. 92. Zurich, Switzerland: vdf Hochschulverlag AG an der ETH Zurich.

LOGES, R., KASKE, A., INGWERSEN, K.& TAUBE, F. (2000b). Yield, forage quality, residue nitrogen and nitrogen fixation of different forage legumes. In *IFOAM 2000 The World Grows Organic*. Proceedings 13th International IFOAM Scientific Conference, 28-31 August 2000, Basel, Switzerland. (Eds T. Alfoldi, W. Lockeretz & U. Niggli), p. 83. Zurich, Switzerland: vdf Hochschulverlag AG an der ETH Zurich.

LOGES, R., TAUBE, F.& KORNHER, A. (1997). Yield, N-fixing ability as well as crop residues after cutting of different red clover and red clover/grass stands. In *4th Scientific Meeting on Ecological Agriculture*, 3-4 March 1997, Rheinische Friedrich Wilhelms Universitat, Bonn, pp. 265-271. Bonn: Schriftenreihe Institut fur Organischen Landbau.

LOW, A.J & ARMITAGE, E.R. (1970). The composition of the leachate through cropped and uncropped soils in lysimeters compared with that of the rain. *Plant and Soil* **33**, 393-411.

LOW, A.J. & ARMITAGE, E.R. (1959). Irrigation of grassland. *Journal of Agricultural Science, Cambridge*, **52**, 256-262.

LYND, J.Q. & McNEW, R.W. (1983). Inoculation effects on growth, nodulation, cytosol components and nitrogen fixation of narrowleaf and hairy vetch. *Communications in Soil Science & Plant Analysis*, **14**, 411-426.

MACDONALD, A.J., POWLSON, D.S., POULTON, P.R. & JENKINSON, D.S. (1989). Unused fertilizer nitrogen in arable soils - its contribution to nitrate leaching. *Journal of the Science of Food and Agriculture* **49**, 407-419.

MACDUFF, J.H. & DHANOA, M.S. (1990). N_2 fixation and nitrate uptake by white clover swards in response to root temperature in flowing solution culture. *Annals of Botany*, **65**, 325-335.

MACDUFF, J.H., JARVIS, S.C. & ROBERTS, D.H. (1990). Nitrates: leaching from grazed grassland systems. In *Nitrates - Agriculture - Eau.* (Ed. R. Calvert), pp. 405-410. Paris: INRA.

MACDUFF, J.H., JARVIS, S.C. & ROBERTS, D.H. (1990). Nitrates: leaching from grazed grassland systems. In: R. Calvert (ed.) *Nitrates - Agriculture - Eau.* INRA, Paris. pp. 405-410.

MACHOVA, M. (1992). Nitrogenase activity of red clover during flowering, seed development and after cuts. *Rostlinna Vyroba*, **38**, 1023-1031.

MÄDER P, BERNER A, BOSSHARD C, OBERHOLZER H R, FITZE P (2000) Soil nutrients and yield of winter wheat grown in Swiss organic farms. The World grows organic. Proceedings 13th IFOAM scientific conference. Eds: Alföldi T, Lockeretz W, Niggli U. Basel 28-31 August 2000 p26

MAIDL, F.X., HAUNZ, F.X., PANSE, A. & FISCHBECK, G. (1996). Transfer of grain legume nitrogen within a crop rotation containing winter wheat and winter barley. *Journal of Agronomy and Crop Science-Zeitschrift fur Acker und Pflanzenbau*, **176**, 47-57.

MALARINO, A.P., WEDIN, W.F., PERDOMO, C.H., GOYENOLA, R.S. & WEST, C.P. (1990). Nitrogen transfer from white clover, red clover and birdsfoot trefoil to associated grass. *Agronomy Journal*, **82**, 790-795.

MARRIOTT, C.A. (1988). Seasonal variation in white clover content and nitrogen fixing (acetylene reduction) activity in a cut upland sward. *Grass and Forage Science*, **43**, 253-262.

MARSHALL A H, HUMPHREYS M O (2002) Challenges in organic forage seed production. In: Powell et al. (eds), *UK Organic Research 2002: Proceedings of the COR Conference, 26-28 th March 2002, Aberystwyt*h, pp. 95-96.

MATTHEWS, D.J. & HAYES, P. (1982). Effect of root zone temperature on early growth, nodulation and nitrogen fixation in soya beans. *Journal of Agricultural Science*, **98**, 371-376.

MATUS, A., DERKSEN, D.A., WALLEY, F.L., LOEPPKY, H.A. & VANKESSEL, C. (1997). The influence of tillage and crop rotation on nitrogen fixation in lentil and pea. *Canadian Journal of Plant Science*, **77**, 197-200.

McCALLUM, M.H., PEOPLES, M.B. & CONNOR, D.J. (1999). Contributions of nitrogen by field pea (*Pisum sativum* L.) in a continuous cropping sequence compared with a lucerne (*Medicago sativa* L.)-based pasture ley in the Victorian Wimmera. *Australian Journal of Agricultural Research*, **51**, 13-22.

McCORMICK, K.M., NORTON, R.M., PEOPLES, M.B.& EAGLES, H.A. (2001). Fenugreek (*Trigonella foenum graecum*) compared to five temperate legume species in Wimmera farming systems. Proceedings of the 10th Australian Agronomy Conference, Hobart, 2001.

MCKENZIE, B.A., HILL, G.D., GANESHAM, V. & YAMOAH, E. (2001). The role of legumes in improving nitrogen availability, soil fertility and growth in the following crop. *Aspects of Applied Biology* **47**, *Rotations and cropping systems*, 53-60.

McKENZIE, R.H., MIDDLETON, A.B., SOLBERG, E.D., DEMULDER, J., FLORE, N., CLAYTON, G.W. & BREMER, E. (2001). Response of pea to rhizobia inoculation and starter nitrogen in Alberta. *Canadian Journal of Plant Science*, **81**, 637-643.

McNEILL, A.M. & WOOD, M. (1990). ^{15}N estimates of nitrogen fixation by white clover (*Trifolium repens* L.) growing in a mixture with ryegrass (*Lolium perenne* L.). *Plant and Soil*, **128**, 265-273.

McNEILL, A.M., HOOD, R.C. & WOOD, M. (1994). Direct measurement of nitrogen fixation by *Trifolium repens* L. and *Alnus glutinosa* L. using $^{15}N_2$. *Journal of Experimental Botany*, **45**, 749-755.

McNEILL, A.M., ZHU, C.Y. & FILLERY, I.R.P. (1997). Use of in situ ^{15}N-labeling to estimate the total below-ground nitrogen of pasture legumes in intact soil-plant systems. *Australian Journal of Agricultural Research*, **48**, 295-304.

MEFTI, H., HARDARSON, G.& SESSITSCH, A. (1998). Time course study of nodulation, and biological nitrogen fixation at two P-levels in common bean (*Phaseolus vulgaris* L.). In *Opportunities for High Quality, Healthy and Added-value Crops to Meet European Demands*. 3rd European Conference on Grain Legumes, 14-19 November 1998, Valladolid, Spain. (Ed. AEP), pp. 413-414. Paris: AEP.

MELILLO, J.M., ABER, J.D., LINKINS, A.E., RICCA, A., FRY, B. & NADELHOFFER, K.J., (1989). Carbon and nitrogen dynamics along the decay continuum: Plant litter to soil organic matter. *Plant & Soil,* 115: 189-198

METZGER, L. & YARON, B. (1987). Influence of sludge organic matter on soil physical properties. *Advances in Soil Science* **7**, 141-163.

MOHARRAM, T.M., EL MOHANDES, M.A. & BADAWI, M.A. (1999). Effect of inoculation and organic manure application on symbiotic N_2 -fixation, microbial biomass and nutrients availability in sandy soils cultivated with soybean and peanut. *Annals of Agricultural Science Cairo*, **44**, 27-40.

MONAGHAN, R.M. & BARRACLOUGH, D. (1993). Nitrous oxide and dinitrogen emissions from urine-affected soil under controlled conditions. *Plant and Soil* **151**, 127-138.

MORRA, M. (1999). Chemicals released into soil by GSL-containing plants. *CSIRO Horticulture*

Biofumigation Update No. **10**, p. 1.

MORRIS M, PHILLIPS L (2000) The use of new clover varieties in grass clover leys for improving early spring grazing opportunities for organic farming systems. The World grows organic. Proceedings 13th IFOAM scientific conference. Eds: Alföldi T, Lockeretz W, Niggli U. Basel 28-31 August 2000 p85.

MOSIMANN E, TROXLER J (2000) Alfalfa –grass mixtures management. The World grows organic. Proceedings 13th IFOAM scientific conference. Eds: Alföldi T, Lockeretz W, Niggli U. Basel 28-31 August 2000 p84.

MUELLER, T. & THORUP-KRISTENSEN, K. (2001). N-fixation of selected green manure plants in an organic crop rotation. *Biological Agriculture & Horticulture*, **18**, 345-363.

MÜLLER, M.M. (1987). Leaching of subterranean clover-derived N from a loam soil. *Plant and Soil* **102**, 185-191.

MUNDY, G.N., JONES, H.R. & MASON, W.K. (1988). Nitrogen fixation activity by white clover pastures during flood irrigation cycles. *Australian Journal of Agricultural Research*, **39**, 409-414.

MUNOZ, A.E. & WEAVER, R.W. (1999). Competition between subterranean clover and rygrass for uptake of ^{15}N-labeled fertilizer. *Plant and Soil*, **211**, 173-178.

MURPHY, D.V., FORTUNE, S., WAKEFIELD, J.A. *et al.* (1999). Assessing the importance of soluble organic nitrogen in agricultural soils. In: W.S. Wilson, A.S. Ball & R.H. Hinton (eds) *Managing Risks of Nitrates to Humans and the Environment.* The Royal Society of Chemistry, Cambridge. pp. 65-86.

MURRAY, P.J. & HATCH, D.J. (1994). Sitona weevils (Coleoptera, Curculionidae) as agents for rapid transfer of nitrogen from white clover (*Trifolium repens* L) to perennial ryegrass (*Lolium perenne* L). *Annals of Applied Biology*, **125**, 29-33.

MURRAY, P.J., HATCH, D.J. & CLIQUET, J.B. (1996). Impact of insect root herbivory on the growth and nitrogen and carbon contents of white clover (Trifolium repens) seedlings. *Canadian Journal of Botany-Revue Canadienne de Botanique*, **74**, 1591-1595.

MYTTON, L.R., CRESSWELL, A. & COLBOURN, P. (1993). Improvement in Soil Structure Associated with White Clover. *Grass and Forage Science* **48**, 84-90.

NATHANSON, K., LAWN, R.J., DE JABRUM, P.L.M. & BLYTH, D.E. (1984). Growth, nodulation and nitrogen accumulation by soybean in saturated soil culture. *Field Crops Research*, **8**, 73-92.

NESHEIM, L. & BOLLER, B.C. (1991). Nitrogen fixation by white clover when competing with grasses at moderately low temperatures. *Plant and Soil*, **133**, 47-56.

NESHEIM, L. & OYEN, J. (1994). Nitrogen-fixation by red clover (*Trifolium pratense* L) grown in mixtures with timothy (*Phleum pratense* L) at different levels of nitrogen fertilization. *Acta Agriculturae Scandinavica Section B-Soil and Plant Science*, **44**, 28-34.

NESHEIM, L., BOLLER, B.C., LEHMANN, J. & WALTHER, U. (1990). The effect of nitrogen in cattle slurry and mineral fertilizers on nitrogen fixation by white clover. *Grass and Forage Science*, **45**, 91-97.

NESMITH, D.S. & McCRACKEN, D.V. (1994). Influence of tillage and sidedress nitrogen on snap bean following a hairy vetch cover crop. *Communications in Soil Science and Plant Analysis*, **25**, 2959-2970.

NEWBOULD, P. & RANGELEY, A. (1984). Effect of lime, phosphorus and mycorrhizal fungi on growth, nodulation and nitrogen fixation by white clover (*Trifolium repens*) grown in UK hill soils. *Plant and Soil*, **76**, 105-114.

NILSDOTTER-LINDE N 1998 Birdsfoot trefoil grown in mixtures with grasses in a temperate climate. Organic Agriculture: The credible solution for the 21st Century. Proceedings of the 12th International INFOAM Scientific Conference 1998 Argentina. p 171-175

NOMMSALU, H. & MERIPOLD, H. (1996). Forage production, quality and seed yield of fodder galega (*Galega orientalis* Lam.). In *Grassland Science in Europe. Vol. 1. Grassland and Land Use Systems.* Proceedings of the 16th General Meeting of the European Grassland Federation. Grado (Gorizia), Italy, 15-19 September 1996. (Eds G. Parente, J. Frame & S. Orsi) pp. 541-544. Gorizia, Italy: ERSA.

NUTMAN, P.S. (1976). I.B.P field experiments on nitrogen fixation by nodulated legumes. In *Symbiotic Nitrogen Fixation in Plants*. IBP Vol. 7. (Ed. P.S. Nutman), pp. 211-237. Cambridge: Cambridge University Press.

NYKÄNEN, A., GRANSTEDT, A., LAINE, A. & KUNTTU, S. (2000). Yields and clover contents of leys of different ages in organic farming in Finland. *Biological Agriculture & Horticulture*, **18**, 55-66.

O'ROURKE, C. J. (1976). Diseases of grass and forage legumes. An Foras Taluntais, Dublin, 115 pp.

OBERHOLZER H R, NOWAK K, MÄDER P (2000) Soil microbiological aspects in winter cereal fields of organic and integrated farms. The World grows organic. Proceedings 13th IFOAM scientific conference. Eds: Alföldi T, Lockeretz W, Niggli U. Basel 28-31 August 2000 p 15

OBERSON A, OEHL F, LANGMEIER M, FLEISSBACH A, DUBOIS D, MÄDER P BESSON J-M, FROSSARD E (2000) Can increased soil microbial activity help to sustain phosphorus availability. The World grows organic. Proceedings 13th IFOAM scientific conference. Eds: Alföldi T, Lockeretz W, Niggli U. Basel 28-31 August 2000 p27-28

O'CONNOR, G.E., EVANS, J., FETTELL, N.A., BAMFORTH, I., STUCHBERRY, J., HEENAN, D.P. & CHALK, P.M. (1993). Sowing date and varietal effects on the N_2 fixation of field pea and implications for improvement of soil nitrogen. *Australian Journal of Agricultural Research*, **44**, 151-163.

OENEMA, O., VELTHOF, G.L., YAMULKI, S. & JARVIS, S.C. (1997). Nitrous oxide emissions from grazed grassland. *Soil Use & Management* **13**, 288-295.

O'HARA, G.W. (2001). Nutritional constraints on root nodule bacteria affecting symbiotic nitrogen fixation: a review. *Australian Journal of Experimental Agriculture*, **41**, 417-433.

PALM, C.A. & ROWLAND, A.P., (1997). A minimum dataset for characterization of plant quality for decomposition. *Driven by Nature: Plant Litter Quality and Decomposition*, (eds. G Cadisch and KE Giller). CAB International. 379-392 (1997)

PALMASON, F., DANSO, S.K.A. & HARDARSON, G. (1992). Nitrogen accumulation in sole and mixed stands of sweet blue lupin (*Lupinus angustifolius* L.), ryegrass and oats. *Plant and Soil*, **142**, 135-142.

PAPASTYLIANOU, I. & DANSO, S.K.A. (1991). Nitrogen fixation and transfer in vetch and vetch-oats mixtures. *Soil Biology & Biochemistry*, **23**, 447-452.

PAPASTYLIANOU, I. (1988). The ^{15}N methodology in estimating N_2 fixation by vetch and pea grown in pure stand or in mixtures with oat. *Plant and Soil*, **107**, 183-188.

PAPASTYLIANOU, I. (1999). Estimation of nitrogen fixed by legumes in long-term vs. short- term cropping systems. *Agronomy Journal*, **91**, 329-334.

PARTON, W.J., SCHIMEL, D.S., COLE, C.V. & OJIMA, D.S. (1987). Analysis of factors controlling soil organic matter levels in great plains grasslands. *Soil Science Society of America Journal,* **51**, 1173-1179.

PAUL, E.A. & CLARK, F.E. (1996). *Soil Microbiology and Biochemistry.* 2nd Edition. San Diego, Academic Press.

PAUSTIAN, K., AGREN, G. & BOSATTA, E. (1997). Modelling litter quality effects on decomposition and soil organic matter dynamics. In, *"Driven by Nature."* Eds., Cadisch G. & Giller K.E. Publ. CAB International, Wallingford, UK. 313-336.

PELTZER, S.C., ABBOTT, L.K. & ATKINS, C.A. (2002). Effect of low root-zone temperature on nodule initiation in narrow-leafed lupin (*Lupinus angustifolius* L.). *Australian Journal of Agricultural Research*, **53**, 355-365.

PEÑA-CABRIALES, J.J., GRAGEDA-CABRERA, O.A., KOLA, V. & HARDARSON, G. (1993). Time course of N_2 fixation in common bean (*Phaseolus vulgaris* L.). *Plant and Soil*, **152**, 115-121.

PEOPLES, M. B., BOWMAN, A. M., GAULT, R. R., HERRIDGE, D. F., McCALLUM, M. H., McCORMICK, K. M., NORTON, R.M., ROCHESTER, I. J., SCAMMELL,G. J. & SCHWENKE, G. D. (2001). Factors regulating the contributions of fixed nitrogen by pasture and crop legumes to different farming systems of eastern Australia. *Plant and Soil*, **228,** pp 29-41.

PEOPLES, M.B., GAULT, R.R., SCAMMELL, G.J., DEAR, B.S., VIRGONA, J., SANDRAL, G.A., PAUL, J., WOLFE, E.C. & ANGUS, J.F. (1998). Effect of pasture management on the contributions of fixed N to the N economy of ley-farming systems. *Australian Journal of Agricultural Research*, **49**, 459-474.

PHILIPPS, L. & STOPES, C. (1995). The impact of rotational practice on nitrate leaching losses in organic farming systems in the United Kingdom. *Biological Agriculture and Horticulture* **11**, 123-134.

PHILIPPS, L., STOPES, C.E. & WOODWARD, L. (1995). The impact of cultivation practice on nitrate leaching from organic farming systems. In: H.F Cook & H.C. Lee (Eds) *Soil Management in Sustainable Agriculture.* Proceedings Third International Conference on Sustainable Agriculture, Wye College, University of London, UK, 31 August - 4 September 1993. Wye College Press, Ashford, UK. pp. 488-496.

PHILLIPS L, WELSH J P, BULSON H A J and WOODWARD L (1998). Agronomic viability and potential economic performance of three organic four-year rotations without livestock 1988-1998. Organic Agriculture: The credible solution for the 21st Century. Proceedings of the 12th International INFOAM Scientific Conference 1998 Argentina. p 109-116

PHILLIPS, L., HUXHAM, S.K., BRIGGS, S.R. & SPARKES, D.L. (2002). Rotation and nutrient management strategies. In *Organic Cereals and Pulses*. (Eds D. Younie, B.R. Taylor, J.P. Welsh & J.M. Wilkinson), pp. 51-76. Lincoln: Chalcombe Publications.

PONGSAKUL, P. & JENSEN, E.S. (1991). Dinitrogen fixation and soil-N uptake by soybean as affected by phosphorus availability. *Journal of Plant Nutrition*, **14**, 809-823.

POPESCU, A. (1998). Contributions and limitations to symbiotic nitrogen fixation in common bean (*Phaseolus vulgaris* L.) in Romania. *Plant and Soil*, **204**, 117-125.

PORT C M, PORT G R. 1986. The biology and behaviour of slugs in relation to crop damage and control. *Agricultural Zoology Reviews* **1**, 255-299.

POWER, J.F. & KOERNER, P.T. (1994). Cover crop production for several planting and harvest dates in eastern Nebraska. *Agronomy Journal*, **86**, 1092-1097.

POWER, J.F. & ZACHARIASSEN, J.A. (1993). Relative nitrogen utilization by legume cover crop species at three soil temperatures. *Agronomy Journal*, **85**, 134-140.

POWLSON, D.S. (1993). Understanding the soil nitrogen cycle. *Soil Use & Management* **9**, 86-94.

PRÉVOST, D. & BROMFIELD, E.S.P. (1991). Effect of low root temperature on symbiotic nitrogen fixation and competitive nodulation of *Onobrychis viciifolia* (sainfoin) by strains of arctic and temperate rhizobia. *Biology and Fertility of Soils*, **12**, 161-164.

PUGH, R., WITTY, J.F., MYTTON, L.R. & MINCHIN, F.R. (1995). The effect of waterlogging on nitrogen fixation and nodule morphology in soil grown white clover. *Journal of Experimental Botany*, **46**, 284-290.

RAHN, C.R & LILLYWHITE, R.D. (2002). A study of the quality factors affecting the short-term decomposition of field vegetable residues. *Journal of the science of Food and Agriculture,* **182**, 19-26.

RAHN, C.R. & LILLYWHITE, R. (2002). A study of quality factors affecting the short term decomposition of field vegetable residues. *Journal of the Science of Food and Agriculture,* **82**, 19-26

RASMUSSEN I A, ASKEGAARD M, OLESEN J E (1999) Plant protection in organic crop rotatio experiments for grain production. In: Designing and testing crop rotations for organic farming. Proceedings from an international workshop. DARCOF report No 1. Eds J E Olesen, R Eltun, M J Gooding, E S Jensen U Köpke. pp 331-336

RAUBER R, SCHMIDTKE K (1999) Nutzung der symbiontischen Stickstoff-Fixierleistung bei Leguminosen. Mitt. Ges. F Pflanzenbauwiss, 12, 1-6

RAYNS, F.W. & LENNARTSSON, E.K.M. (1995). The nitrogen dynamics of winter green manures. In: H.F. Cook & H.C. Lee (eds) *Soil Management in Sustainable Agriculture.* Proc. 3rd International Conference on Sustainable Agriculture, Wye College, 31 August-4 September 1993. Wye College Press, Wye, Ashford. pp. 308-311.

REDDEN, R.J. & HERRIDGE, D.F. (1999). Evaluation of genotypes of navy and culinary bean (*Phaseolus vulgaris* L.) selected for superior growth and nitrogen fixation. *Australian Journal of Experimental Agriculture*, **39**, 975-980.

REENTS H J, MÖLLER K (2000) Effect of different green manure catch crops grown after peas on nitrate dynamics in soils and on yield and quality of subsequent potatoes and wheat. The World grows organic. Proceedings 13th IFOAM scientific conference. Eds: Alföldi T, Lockeretz W, Niggli U. Basel 28-31 August 2000 p 73-76

REEVES, M. (1992). The role of VAM fungi in nitrogen dynamics in maize-bean intercrops. *Plant and Soil*,

144, 85-92.

REID, D. (1986). The effects of frequency of cutting and nitrogen application rates on the yields from perennial ryegrass plus white clover. *Journal of Agricultural Science, Cambridge*, **107**, 687-696.

REITER, K., SCHMIDTKE, K. & RAUBER, R. (2002). The influence of long-term tillage systems on symbiotic N_2 fixation of pea (*Pisum sativum* L.) and red clover (*Trifolium pratense* L.). *Plant and Soil*, **238**, 41-55.

REITER, K., SCHMIDTKE, K.& RAUBER, R. (2001). The influence of long-term tillage systems on N_2 fixation of pea (*Pisum sativum* L.). In *Towards the Sustainable Production of Healthy Food, Feed and Novel Products.* 4th European Conference on Grain Legumes, 8-12 July 2001, Cracow, Poland. (Ed. AEP), pp. 332-333. Paris: AEP.

RENNIE, R.J. & KEMP, G.A. (1981). Dinitrogen fixation in pea beans (*Phaseolus-vulgaris*) as affected by growth stage and temperature regime. *Canadian Journal of Botany-Revue Canadienne de Botanique*, **59**, 1181-1188.

RENNIE, R.J. & KEMP, G.A. (1983). N_2-fixation in field beans quantified by ^{15}N isotope-dilution. 2. Effect of cultivars of beans. *Agronomy Journal*, **75**, 645-649.

RENNIE, R.J. & KEMP, G.A. (1984). ^{15}N-determined time course for N_2 fixation in two cultivars of field bean. *Agronomy Journal*, **76**, 146-154.

RHODES, I. & HARRIS, W. (1979). The nature and basis of differences in sward composition and yield in ryegrass-white clover mixtures. In *Changes in Sward Composition and Productivity*. BGS Occasional Symposium No.10. (Eds A.H. Charles & R.J. Haggar), pp. 55-60. Reading: British Grassland Society.

RICHTER, G.M., HOFFMANN, A., NIEDER, R. & RICHTER, J. (1989). Nitrogen mineralization in loamy arable soils after increasing the ploughing depth and ploughing grasslands. *Soil Use and Management* **5**,169-173.

RIFFKIN, P.A., QUIGLEY, P.E., CAMERON, F.J., PEOPLES, M.B. & THIES, J.E. (1999a). Annual nitrogen fixation in grazed dairy pastures in south-western Victoria. *Australian Journal of Agricultural Research*, **50**, 273-281.

RIFFKIN, P.A., QUIGLEY, P.E., KEARNEY, G.A., CAMERON, F.J., GAULT, R.R., PEOPLES, M.B. & THIES, J.E. (1999b). Factors associated with biological nitrogen fixation in dairy pastures in south-western Victoria. *Australian Journal of Agricultural Research*, **50**, 261-272.

ROBSON, M.C., FOWLER, S.M., LAMPKIN, N.H., LEIFERT, C., LEITCH, M., ROBINSON, D., WATSON, C.A. & LITTERICK, A.M. (2002). The agronomic and economic potential of break crops for ley/arable rotations in temperate organic agriculture. *Advances in Agronomy*, **77**, 369-427.

ROCHESTER, I.J., PEOPLES, M.B., CONSTABLE, G.A. & GAULT, R.R. (1998). Faba beans and other legumes add nitrogen to irrigated cotton cropping systems. *Australian Journal of Experimental Agriculture*, **38**, 253-260.

ROSA, E.A.S. and RODRIGUES, P.M.F. (1999). Towards a more sustainable agricultural system: the effect of glucosinolates on the control of soil-borne diseases. *Journal of Horticultural Science and Biotechnology* **74(6)**, 667-674.

ROYAL SOCIETY (1983). *The Nitrogen Cycle of the United Kingdom*. London: The Royal Society. p.68.

RUSSELLE, M.P., ALLAN, D.L. & GOURLEY, C.J.P. (1994). Direct assessment of symbiotically fixed nitrogen in the rhizosphere of alfalfa. *Plant and Soil*, **159**, 233-243.

RUSSOW, R., KNAPPE, S. & RITZKOWSKI, E.M. (1997). Estimating plant-available ^{15}N and its impact on the ^{15}N dilution measurement of the symbiotic biological nitrogen fixation of red clover grown on different soils. *Isotopes in Environmental and Health Studies*, **33**, 337-348.

RYDEN, J.C., BALL, P.R. & GARWOOD, E.A. (1984). Nitrate leaching from grassland. *Nature (London)* **311**, 50-53.

RYLE, G.J.A., POWELL, C.E. & GORDON, A.J. (1985). Defoliation in white clover - regrowth, photosynthesis and N_2 fixation. *Annals of Botany*, **56**, 9-18.

SALON, C., MUNIER-JOLAIN, N.G., DUC, G., VOISIN, A.S., GRANDGIRARD, D., LARMURE, A., EMERY, R.J.N. & NEY, B. (2001). Grain legume seed filling in relation to nitrogen acquisition: A review and prospects with particular reference to pea. *Agronomie*, **21**, 539-552.

SANDERS I , WATSON C, REES R, ATKINSON D (2002) Nitrogen fixation and soil nitrogen in organic ley arable rotations. In: Powell *et al.* (eds), *UK Organic Research 2002: Proceedings of the COR Conference, 26-28 th March 2002, Aberystwyt*h, pp. 85-88.

SANDERS, I., WATSON, C., REES, R.& ATKINSON, D. (2000). Nitrogen fixation in first and second year grass/white clover leys of two organic rotations. In *IFOAM 2000 The World Grows Organic*. Proceedings 13th International IFOAM Scientific Conference, Basel, Switzerland. (Eds T. Alfoldi, W. Lockeretz & U. Niggli), pp. 94-96. Zurich, Switzerland: vdf Hochschulverlag AG an der ETH Zurich.

SANDERS, I., WATSON, C.A., REES, R., ATKINSON, D., ANDREWS, M., ANDREWS, M.E. & HUMPHRY, D.R. (2001). Effects of ley arable rotation on soil nitrogen and nitrogen fixation. *Aspects of Applied Biology*, **63**, 61-66.

SANFORD, P., PATE, J.S., UNKOVICH, M.J. & THOMPSON, A.N. (1995). Nitrogen fixation in grazed and ungrazed subterranean clover pasture in south-west Australia assessed by the ^{15}N natural abundance technique. *Australian Journal of Agricultural Research*, **46**, 1427-1443.

SANGAKKARA, U.R., HARTWIG, U.A. & NÖSBERGER, J. (1996a). Soil moisture and potassium affect the performance of symbiotic nitrogen fixation in faba bean and common bean. *Plant and Soil*, **184**, 123-130.

SANGAKKARA, U.R., HARTWIG, U.A. & NÖSBERGER, J. (1996b). Growth and symbiotic nitrogen fixation of *Vicia faba* and *Phaseolus vulgaris* as affected by fertiliser potassium and temperature. *Journal of the Science of Food and Agriculture*, **70**, 315-320.

SANTALLA, M., AMURRIO, J.M., RODINO, A.P. & DE RON, A.M. (2001). Variation in traits affecting nodulation of common bean under intercropping with maize and sole cropping. *Euphytica*, **122**, 243-255.

SAUNDERS, W.M.H. (1984). Mineral composition of soil and pasture from areas of grazed paddocks, affected and unaffected by dung and urine. *New Zealand Journal of Agricultural Research*, **27**, 405-412.

SCAGNOZZI, A., SAVIOZZI, A., LEVI-MINZI, R. & RIFFALDI, R. (1997). Nutrient release from decomposing crop residues in soil: a laboratory experiment. *American Journal of Alternative Agriculture* **12**, 10-13.

SCHELLER, E. & VOGTMANN, H. (1995). Case studies on nitrate leaching in arable fields of organic farms. *Biological Agriculture and Horticulture* **11**, 91-102.

SCHLUTER, W., HENNIG, A. & BRUMMER, G.W. (1997). Nitrogen transport in meadow soils under organic and conventional farming - analytical results, modelling and balances. [Nitrat-Verlagerung in Auenboden unter organischer und konventioneller Bewirtschaftung - Messergebnisse, Modellierungen und Bilanzen.] *Zeitschrift fur Pflanzenernahrung und Bodenkunde* **160**, 1, 57-65.

SCHMIDT, H., PHILIPPS, L., WELSH, J.P. & VON FRAGSTEIN, P. (1999). Legume breaks in stockless organic farming rotations: Nitrogen accumulation and influence on the following crops. *Biological Agriculture & Horticulture*, **17,** pp 159-170.

SCHMIDTKE, K. (1997). Self-regulation of N supply in ecological agriculture - a mechanism to protect groundwater. [Selbstregelung der N-Zufuhr im Okologischen Landbau - ein Wirkungsmechanismus zum Schutz des Grundwassers] *Schriftenreihe - Institut fur Organischen Landbau* **4**, 21-27.

SCHMITT, L. & DEWES, T. (1997). N-fixation and N-flows in and under a grass/clover stand on stockless and stocked farms. In *4th Scientific Meeting on Ecological Agriculture*, Rheinische Friedrich-Wilhelms-Universitat, Bonn, pp. 258-264. Bonn: Schriftenreihe Institut fur Organischen Landbau.

SCHOLEFIELD, D. & SMITH, J.U. (1996). Nitrogen flows in ley-arable systems. In *Legumes in Sustainable Farming Systems*, BGS Occasional Symposium No. 30. (Ed. D. Younie), pp. 96-104. Reading: British Grassland Society.

SCHUBERT, E., MENGEL, K. & SCHUBERT, S. (1990). Soil pH and calcium effect on nitrogen fixation and growth of broad bean. *Agronomy Journal*, **82**, 969-972.

SCHUBERT, S. (1995). Nitrogen assimilation by legumes - processes and ecological limitations. *Fertilizer Research*, **42**, 99-107.

SCHULZE, J., BESCHOW, H. & MERBACH, W. (1999). The effect of $^{15}NH_4{}^{15}NO_3$ fertilization at flowering on growth and nitrogen fixation of white and blue lupins. *Isotopes in Environmental and Health Studies*, **35**, 85-95.

SCHULZE, J., KUPIETZ, A. & MERBACH, W. (1998). N_2 fixation in different varieties of *Vicia faba* L. and *Pisum sativum* L. during pod-filling. *Agribiological Research-Zeitschrift fur Agrarbiologie Agrikulturchemie Okologie*, **51**, 261-269.

SCHWINNING, S. & PARSONS, A.J. (1996). Analysis of the coexistence mechanisms for grasses and legumes in grazing systems. *Journal of Ecology*, **84**, 799-813.

SEARS, P.D., GOODHALL, V.C., JACKMAN, R.H. & ROBINSON, G.S. (1965). Pasture growth and soil fertility. VIII. The influence of grasses, white clover, fertilisers, and the return of herbage clippings on pasture production of an impoverished soil. *New Zealand Journal of Agricultural Research*, **8**, 270-283.

SERESINHE, T., HARTWIG, U.A., KESSLER, W. & NÖSBERGER, J. (1994). Symbiotic nitrogen fixation of white clover in a mixed sward is not limited by height of repeated cutting. *Journal of Agronomy and Crop Science-Zeitschrift fur Acker und Pflanzenbau*, **172**, 279-288.

SHEARER, G. & KOHL, D.H. (1986). N_2-fixation in field settings: estimations based on natural ^{15}N abundance. *Australian Journal of Plant Physiology*, **13**, 699-756.

SHEPHERD, M.A. (1993). Measuremment of soil mineral nitrogen to predict the response of winter wheat to fertilizer nitrogen after application of organic manures or after ploughed-out grass. *Journal of Agricultural Science, Cambridge* **121**, 223-231.

SHEPHERD, M.A., HARRISON, R. & WEBB, J. (2002). Managing soil organic matter – implications for soil structure on organic farms. *Soil Use and Management* **18** (supplement), 284-292.

SIDIRAS, N., AVGOULAS, C., BILALIS, D. & TSOUGRIANIS, N. (1999). Effects of tillage and fertilization on biomass, roots, N accumulation and nodule bacteria of vetch (*Vicia sativa* cv. Alexander). *Journal of Agronomy and Crop Science-Zeitschrift fur Acker und Pflanzenbau*, **182**, 209-216.

SILGRAM, M. & CHAMBERS, B. J. (2000). Effects of long-term straw management and fertilizer nitrogen additions on soil nutrient supply and crop yields at two sites in eastern England. *J. Ag. Sci.* **139**, pp 115-127.

SILGRAM, M. & SHEPHERD, M.A. (1999). The effect of cultivation on soil nitrogen mineralization. *Advances in Agronomy,* **65**, 267-311.

SIMON, J. & SKRDLETA, V. (1983). Biomass production in peas (*Pisum sativum* L.) and broad beans (*Vicia faba* L.) and symbiotic dinitrogen fixation as affected by plowing or no-tillage and nitrogen fertilizer. *Soil & Tillage Research*, **3**, 367-375.

SIMPSON, J.R. (1976). Transfer of nitrogen from three pasture legumes under periodic defoliation in a field environment. *Australian Journal of Experimental Agriculture and Animal Husbandry*, **16**, 863-869.

SMETHAM, M.L. (2003). A review of subterranean clover (*Trifolium subterraneum* L.): its ecology and use as a pasture legume in Australasia. *Advances in Agronomy*, **79**, 304-351.

SMITH, C.J., CHALK, P.M., HAMILTON, S.D. & HOPMANS, P. (1992). Estimating N_2 fixation by field-grown lupins (*Lupinus angustifolius* L.) using soil and plant ^{15}N enrichment. *Biology and Fertility of Soils*, **13**, 235-241.

SMITH, J.U., SMITH, P., MONAGHAN, R. & MACDONALD, A.J. (2002). When is a measured soil organic matter fraction equivalent to a model pool? *European Journal of Soil Science,* **53**, 405-416.

SØEGAARD, K. (1994). Agronomy of white clover. In *Grassland and Society*. Proceedings of the 15th General Meeting of the European Grassland Federation. (Eds L. 't Mannetje & J. Frame), pp. 515-524. Wageningen: European Grassland Federation.

SOLBERG, S.O. (1995). Influence and crops and cultivation management on the nitrogen leaching potential on ecological farms in South East Norway. *Biological Agriculture and Horticulture* **11**, 115-121.

SPARROW, S.D., COCHRAN, V.L. & SPARROW, E.B. (1995). Dinitrogen fixation by 7 legume crops in Alaska. *Agronomy Journal*, **87**, 34-41.

SPATZ, G. & BENZ, J. (2001). Two ecological controls of nitrogen fixation in white clover (*Trifolium repens*). In *Grassland Science in Europe. Vol. 6. Organic Grassland Farming*. Proceedings of the International Occasional Symposium of the European Grassland Federation, Witzenhausen, Germany. (Eds J.

Isselstein, G. Spatz & M. Hofmann), pp. 11-16. Witzenhausen, Germany: European Grassland Federation.

SPIERTZ, J.H.J. & SIBMA, L. (1986). Dry matter production and nitrogen utilization in cropping systems with grass, lucerne and maize. 2. Nitrogen yields and utilization. *Netherlands Journal of Agricultural Science*, **34**, 37-47.

SPIESS, E. & BESSON, J-M. (1992). Potassium in animal manure and plant residues: efficiency and losses. In: *Potassium in Ecosystems. Biogeochemical fluxes of cations in agro-and forest-systems.* International Potash Institute, Basel, Switzerland. pp. 91-102.

SPRENT, J.I. & BRADFORD, A.M. (1977). Nitrogen fixation in field beans (*Vicia faba*) as affected by population density, shading and its relationship with soil moisture. *Journal of Agricultural Science, Cambridge*, **88**, 303-310.

SPRENT, J.I. & MANNETJE, L.'t. (1996). The role of legumes in sustainable farming systems: past, present and future. In *Legumes in Sustainable Farming Systems*. BGS Occasional Symposium No. 30. (Ed. D. Younie), pp. 2-14. Reading: British Grassland Society.

STANFORD, G. & SMITH, S.J. (1972). Nitrogen Mineralisation potentials of soils. *Soil Science Society of America Proceedings,* **36**, 465-472.

STEINSHAMN, H. (2001). Effects of cattle slurry on the growth potential and clover proportion of organically managed grass-clover leys. *Acta Agriculturae Scandinavica Section B-Soil and Plant Science*, **51**, 113-124.

STEPHENSON J W. 1975. Laboratory observations on the effects of soil consolidation on slug damage to winter wheat. *Plant Pathology* **24**, 9-11.

STOCKDALE, E.A., REES, R.M. & DAVIES, M.G. (1995). Nitrogen supply for organic cereal production in Scotland. In: H.F Cook & H.C. Lee (Eds) *Soil Management in Sustainable Agriculture*. Proceedings Third International Conference on Sustainable Agriculture, Wye College, University of London, UK, 31 August - 4 September 1993. Wye College Press, Ashford, UK. pp. 254-264.

STOPES, C. & PHILIPPS, L. (1992). Nitrate leaching from organic farming systems. Aspects of Applied Biology, No. 30, Nitrate and Farming Systems, 167-174.

STOPES, C., LORD, E.I., PHILIPPS, L. & WOODWARD, L. (2002). Nitrate leaching from organic farms and conventional farms following best practice. *Soil Use and Management*, **18**, 256-263.

STOPES, C., MILLINGTON, S. & WOODWARD, L. (1995). Dry matter and nitrogen accumulation by three leguminous green manure species and the yield of a following wheat crop in an organic production system. *Agriculture Ecosystems & Environment* **57**, 189-196.

STOPES, C., MILLINGTON, S. & WOODWARD, L. (1996). Dry matter and nitrogen accumulation by three leguminous green manure species and the yield of a following wheat crop in an organic production system. *Agriculture Ecosystems & Environment*, **57**, 189-196.

STOPES, C., MILLINGTON, S. & WOODWARD, L. (1996). Dry matter and nitrogen accumulation by three leguminous green manure species and the yield of a following wheat crop in an organic production system. *Agriculture Ecosystems & Environment*, **57,** 189-196.

STOUT, W.L. & WEAVER, S.R. (2001). Effect of early season nitrogen on nitrogen fixation and fertilizer-use efficiency in grass-clover pastures. *Communications in Soil Science and Plant Analysis*, **32**, 2425-2437.

SULLIVAN, P.G., PARRISH, D.J. & LUNA, J.M. (1991). Cover crop contributions to N supply and water conservation in corn production. *American Journal of Alternative Agriculture*, **6**, 106-113.

SWIFT, M.J., HEAL, O.W. & ANDERSON, J.M. (1979). Decomposition in Terrestial Ecosystems. *Studies in Ecology* **5**. Blackwell Scientific Publications, Oxford, UK

TANG, C. & THOMSON, B.D. (1996). Effects of solution pH and bicarbonate on the growth and nodulation of a range of grain legume species. *Plant and Soil*, **186**, 321-330.

TANG, C., ROBSON, A.D., LONGNECKER, N.E. & BUIRCHELL, B.J. (1995). The growth of lupinus species on alkaline soils. *Australian Journal of Agricultural Research*, **46**, 255-268.

TAYLOR, B.R. & CORMACK, W.F. (2002). Choice of species and varieties. In *Organic Cereals and Pulses*. (Eds D. Younie, B.R. Taylor, J.P. Welsh & J.M. Wilkinson), pp. 9-28. Lincoln: Chalcombe

Publications.

TAYLOR, B.R., PARKINSON, D. & PARSONS, W.F.J. (1989). Nitrogen and lignin content as predictors of litter decay rates: A microcosm test. *Ecology,* **70**, 97-104

TAYLOR, J.D., DAY, J.M. & DUDLEY, C.L. (1983). The effect of rhizobium inoculation and nitrogen-fertilizer on nitrogen-fixation and seed yield of dry beans (*Phaseolus vulgaris*). *Annals of Applied Biology*, **103**, 419-429.

TERSBØL M, THORUP-KRISTENSEN K (2000) Undersown legumes as green manure in cereal production. IFOAM 2000 – The World grows organic. Proceedings 13th IFOAM scientific conference. Eds: Alföldi T, Lockeretz W, Niggli U. Basel 28-31 August 2000 p78

THEUNISSEN J, OUDEN H den. 1980. Effects of intercropping with *Spergula arvensis* on pests of Brussels sprouts. *Entomologia Experimentalis et Applicata*. **27**, 260-268.

THEUNISSEN, J. and SCHELLING, G. (1996). Pest and disease management by intercropping: suppression of thrips and rust in leeks. *International Journal of Pest Management* **42**, 227-234.

THEUNISSEN, J. and SCHELLING, G. (2000). Undersowing of carrots with clover: suppression of carrot rust fly (*Psila rosae*) and cavity spot (*Pythium* spp.) infestation. *Biological Agriculture and Horticulture* **18**, 67-76.

THOMAS, H. & BOWLING, M.J. (1981). The effect of companion species on the reaction of grass and clover to drought. *Report of the Welsh Plant Breeding Station for 1980*. pp. 126-127. Aberystwyth, Welsh Plant Breeding Station.

THOMAS, R.J. & ASAKAWA, N.M. (1993). Decomposition of leaf litter from tropical forage grasses and legumes. *Soil Biology Biochemistry,* **25**, 1351-1361

THOMSEN, I.K. & CHRISTENSEN, B.T. (1999). Nitrogen conserving potential of successive ryegrass catch crops in continuous spring barley. *Soil Use and Management* **15**, 195-200.

THORNLEY, J.H.M., BERGELSON, J. & PARSONS, A.J. (1995). Complex dynamics in a carbon-nitrogen model of a grass legume pasture. *Annals of Botany*, **75**, 79-94.

THORUP-KRISTENSEN, K., MAGID, J. & JENSEN, L.S. (2003). Catch crops and green manures as biological tools in nitrogen management in temperate zones. *Advances in Agronomy*, **79**, 227-302.

TISDALL, J.M. & OADES, J.M. (1982). Organic matter and water-stable aggregates in soils. *Journal of Soil Science* **33**, 141-163.

TOFINGA, M.P., PAOLINI, R. & SNAYDON, R.W. (1993). A study of root and shoot interactions between cereals and peas in mixtures. *Journal of Agricultural Science*, **120**, 13-24.

TOPP, C.F.E., DOYLE, C.J.& McGECHAN, M.B. (2002). The potential for legumes in dairy production: legume yields and nitrogen excretion. In *Grassland Science in Europe. Vol. 7. Multi-function Grasslands. Quality Forages, Animal Products and Landscapes*. Proceedings of the 19th General Meeting of the European Grassland Federation. La Rochelle, France, 27-30 May 2002. (Eds J-L. Durand, J-C. Emile, C. Huyghe & G. Lemaire), pp. 1080-1081. Versailles, France: AFPF.

TOWNLEY-SMITH, L. J. (1989). Short-term productivity of legume green manure cropping systems in Saskatchewan. *Dissertation Abstracts International B Sciences and Engineering*, **50,** 2217-2218.

TOWNLEY-SMITH, L., SLINKARD, A.E., BAILEY, L.D., BIEDERBECK, V.O. & RICE, W.A. (1993). Productivity, water use and nitrogen fixation of annual-legume green-manure crops in the Dark Brown soil zone of Saskatchewan. *Canadian Journal of Plant Science*, **73**, 139-148.

TURPIN, J.E., HERRIDGE, D.F. & ROBERTSON, M.J. (2002). Nitrogen fixation and soil nitrate interactions in field-grown chickpea (*Cicer arietinum*) and fababean (*Vicia faba*). *Australian Journal of Agricultural Research*, **53**, 599-608.

TYSON, K.C., STONE, A.C., SCHOLEFIELD, D. AND JARVIS, S.C. (1996). A comparison of animal output and nitrogen leaching losses from grassland receiving 200 kg N/ha/annum and grass/clover receiving no fertilizer nitrogen. In: D. Younie (ed.) *Legumes in Sustainable Farming Systems.* Occasional Symposium No. 30, British Grassland Society, Reading. pp. 273-274.

UNKOVICH, M., SANFORD, P., PATE, J. & HYDER, M. (1998). Effects of grazing on plant and soil nitrogen relations of pasture-crop rotations. *Australian Journal of Agricultural Research*, **49**, 475-485.

UNKOVICH, M.J., PATE, J.S., ARMSTRONG, E.L. & SANFORD, P. (1995). Nitrogen economy of annual crop and pasture legumes in southwest Australia. *Soil Biology & Biochemistry*, **27**, 585-588.

VALLIS, I. (1978). Nitrogen relationships in grass/legume mixtures. In *Plant Relations in Pastures*. (Ed. J.R. Wilson), pp. 190-201. Canberra, Australia: CSIRO.

VALLIS, I., HENZELL, E.F. & EVANS, T.R. (1977). Uptake of soil nitrogen by legumes in mixed swards. *Australian Journal of Agricultural Research*, **28**, 413-425.

VAN DER WERFF, P.A., BAARS, A. & OOMEN, G.J.M. (1995). Nutrient balances and measurement of nitrogen losses on mixed ecological farms on sandy soils in the Netherlands. *Biological Agriculture & Horticulture* **11**, 41-50.

VAN KESSEL, C. & HARTLEY, C. (2000). Agricultural management of grain legumes: has it led to an increase in nitrogen fixation? *Field Crops Research*, **65**, 165-181.

VAN KESSEL, C. (1994). Seasonal accumulation and partitioning of nitrogen by lentil. *Plant and Soil*, **164**, 69-76.

VARIS, E. (1986). Goat's rue (*Galega orientalis* Lam.), a potential pasture legume for temperate conditions. *Journal of Agricultural Science in Finland*, **58**, 83-101.

VERNICHENKO, L.Y. & SZEGI, J. (1984). The effect of increasing levels of mineral nitrogen on the productivity of symbiotic nitrogen fixation. In *Soil Biology and Conservation of the Biosphere*. pp. 487-493. Budapest; Hungary: Akademiai Kiado.

VESSEY, J. & PATRIQUIM, D.G. (1984). *In situ* nitrogen fixation by white clover in mixed swards in Nova Scotia. *Canadian Journal of Plant Science*, **64**, 625-636.

VESTERAGER, J.M., OSTERBY, S., JENSEN, E.S. & SCHJOERRING, J.K. (1995). Symbiotic N_2-fixation by the cover crop *Pueraria phaseoloides* as influenced by litter mineralization. *Plant and Soil*, **177**, 1-10.

VINTHER, F.P. & AAES, O. (1996). Effects of urine on biological nitrogen fixation in a grass-clover pasture. In *Transactions of the 9th Nitrogen Workshop, Braunschweig, September 1996*. pp. 173-176. Braunschweig: Technische Universität.

VINTHER, F.P. & JENSEN, E.S. (2000). Estimating legume N_2 fixation in grass-clover mixtures of a grazed organic cropping system using two ^{15}N methods. *Agriculture Ecosystems & Environment*, **78**, 139-147.

VINTHER, F.P. (1998). Biological nitrogen fixation in grass-clover affected by animal excreta. *Plant and Soil*, **203**, 207-215.

VINTHER, F.P. (2000). Symbiotic nitrogen fixation and N-transfer in a grass-white clover mixture. In *Grassland Science in Europe. Vol. 5. Grassland Farming. Balancing environmental and economic demands*. Proceedings of the 18th General Meeting of the European Grassland Federation. Aalborg, Denmark, 22-25 May 2000. (Eds K. Søegaard, C. Ohlsson, J. Sehested, N.J. Hutchings & T. Kristensen), pp. 415-417. Tjele, Denmark: Danish Institute of Agricultural Sciences.

VOISIN, A.S., SALON, C., MUNIER-JOLAIN, N.G. & NEY, B. (2002). Effect of mineral nitrogen on nitrogen nutrition and biomass partitioning between the shoot and roots of pea (*Pisum sativum* L.). *Plant and Soil*, **242**, 251-262.

VON FRAGSTEIN, P. (1995). Manuring, manuring strategies, catch crops and N-fixation. *Biological Agriculture and Horticulture*, **11**, 275-287.

WANEK, W. & ARNDT, S.K. (2002). Difference in delta ^{15}N signatures between nodulated roots and shoots of soybean is indicative of the contribution of symbiotic N_2 fixation to plant N. *Journal of Experimental Botany*, **53**, 1109-1118.

WARDLE, D.A. & GREENFIELD, L.G. (1991). Release of mineral nitrogen from plant root nodules. *Soil Biology & Biochemistry*, **23**, 827-832.

WAREMBOURG, F.R., LAFONT, F. & FERNANDEZ, M.P. (1997). Economy of symbiotically fixed nitrogen in red clover (*Trifolium pratense* L.). *Annals of Botany*, **80**, 515-523.

WATERER, J.G. & VESSEY, J.K. (1993). Effect of low static nitrate concentrations on mineral nitrogen uptake, nodulation, and nitrogen-fixation in field pea. *Journal of Plant Nutrition*, **16**, 1775-1789.

WATERER, J.G., VESSEY, J.K., STOBBE, E.H. & SOPER, R.J. (1994). Yield and symbiotic nitrogen fixation in a pea-mustard intercrop as influenced by N fertilizer addition. *Soil Biology & Biochemistry*, **26**, 447-453.

WATSON C A; STOCKDALE E A (1997). Using nutrient budgets to evaluate the sustainability of farming systems. Newsletter of the European Network on Organic Farming, Number 5, October 1997, 16-19.

WATSON, C.A. & GOSS, M.J. (1997). Estimation of N_2 fixation by grass- white clover mixtures in cut or grazed swards. *Soil Use and Management*, **13**, 165-167.

WATSON, C.A., ATKINSON, D., GOSLING, P. JACKSON, L.R. & RAYNS, F. (2002). Managing soil fertility in organic farming systems. *Soil Use and Management* **18**, 239-247.

WATSON, C.A., FOWLER, S.M. & WILMAN, D. (1993). Soil inorganic-N and nitrate leaching onorganic farms. *Journal of Agricultural Science, Cambridge* **120**, 361-369.

WATSON, C.A., FOWLER, S.M. & WILMAN, D. (1994). Purchases and sales of N, P and K, soil inorganic N and nitrate leaching on an organic horticultural holding. *Biological Agriculture and Horticulture*. **10**, 189-195.

WELSH J P, PHILIPPS L CORMACK W F (2002) The long-term agronomic performance of organic stockless rotations. In: Powell et al. (eds), *UK Organic Research 2002: Proceedings of the COR Conference, 26-28 th March 2002, Aberystwyt*h, pp. 47-50.

WHEELER, D.M., EDMEADES, D.C. & MORTON, J.D. (1997). Effect of lime on yield, N fixation, and plant N uptake from the soil by pasture on three contrasting trials in New Zealand. *New Zealand Journal of Agricultural Research*, **40**, 397-408.

WHITEHEAD, D.C. (1995) *Grassland Nitrogen*. C.A.B International, Wallingford.

WHITEHEAD, D.C. & JONES, E.C. (1969). Nutrient elements in the herbage of white clover, red clover, lucerne and sainfoin. *Journal of the Science of Food & Agriculture*, **20**, 584-591.

WHITEHEAD, D.C. (1982). Yield of white clover and its fixation of nitrogen as influenced by nutritional and soil factors under controlled environment conditions. *Journal of the Science of Food and Agriculture*, **33**, 1227-1234.

WHITEHEAD, D.C. (1995). *Grassland Nitrogen*. Wallingford: C.A.B. International.

WHITMORE, A.P. (1996). Describing the mineralization of carbon added to soil in crop residues using second-order kinetics. *Soil Biology and Biochemistry,* **28**, 1435-1442.

WHITMORE, A.P. & GROOT, J.J.R. (1994). The mineralisation of N from finely or coarsely chopped crop residues: measurements and modelling. *European Journal of Agronomy,* **3**, 367-373

WIJNANDS F W T (1999) Crop rotation in organic farming theory and practice. In: Designing and testing crop rotations for organic farming. Proceedings from an international workshop. DARCOF report No 1. Eds J E Olesen, R Eltun, M J Gooding, E S Jensen U Köpke. pp 21-36.

WIJNANDS, F.G. & KROONEN-BACKBIER, B. (1991). *Report for 1986. Experimental Farm, Development of Farming Systems*. OBS Publikatie Ontwikkeling Bedrijfs Systemen Netherlands 7. Lelystad; Netherlands, Proefstation voor de Akkerbouw en de Groenteteelt in de Vollegrond. OBS-Publikatie-Ontwikkeling-Bedrijfs-Systemen-Netherlands.

WILLIAMS, R.J.B. & COOKE, G.W. (1972). Experiments on herbage crops at Saxmundham, 1967-71. *Rothamsted Experimental Station. Report for 1971*, part 2. 95-121.

WILLUMSEN, J. & 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. *Biological Agriculture & Horticulture*, **18**, 365-384.

WILLUMSEN, J.& 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. *Biological Agriculture & Horticulture*, **18,** 365-384.

WOLFE, M. S. & PASIECZNIK, N. M. (2000). The potential for organic agroforestry: management of trees on organic farms. The World grows organic. Proceedings 13th IFOAM scientific conference. Eds: Alföldi T, Lockeretz W, Niggli U. Basel 28-31 August 2000 p431.

WOLFE, M. S., CLEMENTS, R. O. & DONALDSON, G. (2000). Clover:cereal bi-cropping for organic farms. The World grows organic. Proceedings 13th IFOAM scientific conference. Eds: Alföldi T, Lockeretz

W, Niggli U. Basel 28-31 August 2000 p147.

WOOD, M. (1996). Nitrogen fixation: How much and at what cost? In *Legumes in Sustainable Farming Systems. BGS Occasional Symposium No. 30*. (Ed. D. Younie), pp. 26-35. Reading: British Grassland Society.

WOOD, M., COOPER, J.E. & CAMPBELL, D.S. (1985). A survey of clover and *Lotus* rhizobia in Northern Ireland pasture soils. *Journal of Soil Science*, **36**, 357-365.

WOOD, M., COOPER, J.E. & HOLDING, A.J. (1984). Soil acidity factors and nodulation of *Trifolium repens*. *Plant and Soil*, **77**, 367-379.

WU, L. & McGECHAN, M.B. (1999). Simulation of nitrogen uptake, fixation and leaching in a grass-white clover mixture. *Grass and Forage Science*, **54**, 30-41.

YOSHIDA, S. (1979). Effect of farmyard manure on the nitrogen nutrition of soyabean. *Japanese Journal of Crop Science*, **48**, 17-24.

YOUNIE, D. & WATSON, C.A. (1992). Soil nitrate-N levels in organically and intensively managed grassland systems. *Aspects of Applied Biology*, No. 30, *Nitrate and Farming Systems*, 235-238.

ZACHARIASSEN, J.A. & POWER, J.F. (1991). Growth-rate and water-use by legume species at three soil temperatures. *Agronomy Journal*, **83**, 408-413.

ZAPATA, F., DANSO, S.K.A., HARDARSON, G. & FRIED, M. (1987). Time course of nitrogen fixation in field-grown soybean using nitrogen-15 methodology. *Agronomy Journal*, **79**, 172-176.

ZARINA, L. & MIKELSONS, V. (1999) Long-term crop rotations experiments in Latvia. In: Designing and testing crop rotations for organic farming. Proceedings from an international workshop. DARCOF report No 1. Eds J E Olesen, R Eltun, M J Gooding, E S Jensen U Köpke. pp 107-111

ZHANG, F., LYNCH, D.H. & SMITH, D.L. (1995). Impact of low root temperatures in soybean (*Glycine max.* (L.) Merr.). *Environmental and Experimental Botany*, **35**, 279-285.