GREEN MANURES

A review conducted by HDRA as part of **HDC Project FV 299:**

An investigation into the adoption of green manures in both organic and conventional rotations to aid nitrogen management and maintain soil structure

This review describes the evidence for the various beneficial effects of green manures, lists the relative merits of the main species that are suitable for use in the UK and considers some of the practical aspects of their use.

This review forms part of an HDC funded project led by Vegetable Consultancy Services Ltd with HDRA as a subcontractor. The practical work involves field trials at four sites in East Anglia (two conventional, one organic and one in conversion) to be conducted between 2006 and 2008. The field trials will investigate the performance of different fertility building crops and their effects on subsequent cash crop yield, nitrogen dynamics and pest, disease and weed problems.

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1. INTRODUCTION

Green manures, also referred to as fertility building crops, may be broadly defined as crops grown for the benefit of the soil. They have been used in traditional agriculture for thousands of years but conventional farming systems largely rejected them as the use of fertilizers and pesticides became more common. Although they have many roles they are still often under utilised by today's organic farmers. However, recent emphasis on reducing the environmental impact of all farming systems (stimulated by new legislation) has led to a growing interest from the conventional sector.

Green manuring can bring a number of advantages to the grower:

- Adding organic matter to the soil
- Increasing biological activity
- Improving soil structure
- Reduction of erosion
- Increasing the supply of nutrients available to plants (particularly by adding nitrogen to the system by fixation)
- Reducing leaching losses
- Suppressing weeds
- Reducing pest and disease problems
- Providing supplementary animal forage
- Drying and warming the soil

A number of disadvantages can also be identified:

- Direct costs of seed and extra cultivations
- Lost opportunities for cash cropping
- Extra work at busy times of the year
- Exacerbated pest and disease problems (due to the 'green bridge' effect)
- Potential for the green manures to become weeds in their own right

A wide range of plant species can be used as green manures. Different ones bring different benefits and the final choice is influenced by many considerations which will be examined later on in this review. If the most is to be made from green manure crops it is important that they are carefully integrated into the crop rotation and proper attention paid to their husbandry.

Green manuring was identified as a key area for investigation when the Research Department at HDRA was established in the 1980s. Initially, work focussed on screening suitable varieties for use as either spring or autumn sown crops. Later, external funding enabled researchers to examine the effects of the green manures on the soil and following cash crops (DEFRA projects OC9016 and OF0118T). This necessarily had to be focussed on a smaller number of species and grazing rye and winter vetch were chosen as contrasting 'model' crops for much of this work. A lot of data was collected on the effects of green manures on nitrate leaching and subsequent nitrogen mineralisation patterns. More recently HDRA has conducted some long term work to evaluate the effects of contrasting fertility building strategies in organic field vegetable systems (DEFRA projects OF0126T, OF0191 and OF0332). It has also been involved with an international project to develop a computer model which will help with planning rotations that include green manures (EU project QLK5-2002-01110).

A lot of the work done by other scientists during the 1990s focussed on the use of winter green manures (often called cover crops in this context) to reduce nitrate leaching (eg DEFRA project NT2302). More recently DEFRA project OF0316 included a large review of leguminous fertility building crops, focussing particularly on nitrogen fixation and utilisation.

2. Types of green manures

Not all green manures will bring all the benefits listed in Section 1. Different green manuring strategies must be selected depending upon the main purpose for which they are being grown. A general description of green manure types is given here followed by more detail on each species. Unless otherwise stated, information was gathered from Suhr *et al*. (2005), NIAB (2005), Hally (1983) and unpublished work by HDRA. Varieties are given as examples only, and more detailed information on selecting varieties can be obtained from the NIAB Pocket Guide to Livestock Crops (2005). A practical guide to using these crops can also be obtained from the website of the DEFRA funded project, 'The development of improved guidance on the use of fertility building crops in organic farming (OF 0316)' (http://www.organicsoilfertility.co.uk/reports/docs/leaflet.pdf)

Long term green manures. Leys, usually established for two or three years, are a basic part of many organic arable rotations. Where animals are present on the farm the leys would usually be grazed or cut for silage but in stockless systems they are normally cut monthly during the summer period and the mowings allowed to remain on the surface as a mulch. Such leys may be pure clover (when nitrogen fixation is a priority) or a grass/clover mixture (when organic matter build up is also important).

Winter green manures are usually sown in the autumn and incorporated in the following spring. They can be a good way of fitting a fertility building crop into a rotation if they can utilise land that would otherwise be bare. However, it can be difficult to establish them early enough to do any good if harvest of the preceding summer crop is delayed. They can be legumes (eg vetch) but a major use for this class of crops (even in conventional agriculture) is to minimise nitrogen leaching; when used for this purpose they are often called winter cover crops.

Summer green manures are usually legumes grown to provide a boost of nitrogen in mid rotation. They may be grown for a whole season (say April to September) or for a shorter period between two cash crops. These shorter-term green manures can include non-legumes such as mustard and phacelia. They are sometimes referred to as catch crops but this term is rather misleading.

Green manures may also be used in ***intercropping systems***. On arable farms leys are usually established by ***undersowing*** them in the preceding cereal crop – this gives the green manure a longer growth period and can help in weed control. A similar thing can be done with horticultural crops but care is needed to avoid too much competition. The practice may be particularly valuable as a pest control measure.

Protected cropping systems offer particular challenges and opportunities for green manuring. Because of the warmer temperatures it may be possible to sow 'summer' green manures at any time of year but trial and error would be needed to fit them in to the particular cropping plan of an individual grower.

Fertility building in orchards is particularly difficult because nitrogen must be provided at the right time to ensure good fruit set and quality. Green manures grown as an understory can also play an important role in attracting beneficial insects and management decisions to achieve these twin goals must be carefully integrated. Similar issues also apply in other long term cropping situations (eg asparagus production).

A wide variety of plants can be used as green manures in different situations and the list below is not exhaustive. General characteristics for suitability might include cheapness of seed, rapid germination and growth, competitiveness with weeds, ability to grow in nutrient-poor soil, ease of incorporation and unlikeliness to return as a weed in the next crop. The basic division is into legumes and non-legumes. Some species (especially red and white clover) have been highly bred to provide particular characteristics as forage crops and for these there is a wide choice of cultivars. In other cases there may be no choice of variety at all. It may be difficult to get hold of the seed of some crops but they are listed below as they may be beneficial in particular situations. Many of the crops are known by a range of common names and this can result in considerable confusion.

Suitability for various green manure situations is indicated by the symbols:

Ley	Winter green manure	Summer green manure	For intercropping
L	**WG**	**SG**	**I**

2.1. Legumes

These are generally considered to be nitrogen fixing but this will only happen in the presence of correct strains of *Rhizobium* bacteria. For more common legume species these will certainly be present naturally in the soil but some more unusual species may benefit from inoculating the seed before sowing. *It must be remembered that some of these plants, if grazed without being diluted with other feed, may cause bloat or reproductive problems in the animals.*

CLOVERS (*Trifolium* spp.) are the most widely grown crops for fertility building purposes. There are many species with different characteristics.

White clover (Trifolium pratense)

Suitability:	L or I
pH range preferred:	5.6-7.0
Height:	15-30cm
Frost tolerance:	Good

This is the most common component in grass/clover leys since it is very persistent, producing a branching network of creeping stems and buds very close to the ground. It is the most common legume used for grazing leys. White clover is shallow rooted and makes little growth in dry conditions. Continued defoliation stimulates root growth and N fixation.

Varieties are classified into small leaved and large leaved. Small leaved varieties such as Aberystwyth S.184 and Grasslands Demand maintain good ground cover under hard grazing. Large leaved varieties such as Alice and Barblanca are more suited to light grazing and are less persistent. Medium leaved varieties (AberConcord, and AberDai) have intermediate characteristics relative to large and small leaved varieties. Most varieties are susceptible to clover rot (*Sclerotinia trifoliorum*).

Red clover (Trifolium repens)

Photo shows red clover and ryegrass mix

Suitability:	L or I
pH range preferred:	6.0-7.5
Height:	15 – 30 cm
Frost tolerance:	Good

This is higher yielding and taller than white clover yet it does not spread and is less persistent. It can suffer severely from clover rot and stem eelworm. Its deep taproot makes it more drought resistant than white clover. Varieties traditionally fall into early and late flowering groups. Early types (AberRuby and Merviot) produce more early spring growth with most of the yield coming from the first cut. Late varieties (Britta) are more persistent and can be used in medium term leys. Typical annual yields of dry matter are 10 – 15 t/ha.

Crimson clover or ***Italian clover*** *(Trifolium incarnatum)*

	Suitability: L pH range preferred: 5.5-7.0 Height: 30-60 cm Frost tolerance: Good

This is characterised by brilliantly coloured flowers. It is an annual and does not recover after grazing or cutting and gives lower yields than red clover although it may be established later in the autumn since its seeds are relatively large.

Subterranean clover *(Trifolium subterraneum)*

	Suitability: I pH range preferred: 5.5-7.0 Height: 20 cm Frost tolerance: Good

This is a prostrate plant with long branched creeping stems. It may be particularly suitable for intercropping. The flowers (self pollinated) are pushed into the soil; the plant then dies off but regenerates the following year (possibly causing a weed problem).

OTHER CLOVERS:

Alsike clover *(Trifolium hybridum).* Despite its name this is not a hybrid. It is of Scandinavian origin and is better adapted than white or red clover to wet acid soils and cool conditions although under more favourable circumstances it will not yield as well. Its growth habit it is similar to red clover.

Strawberry clover (*Trifolium fragiferum)* is similar to white clover but has better autumn and winter growth and is tolerant of wet and salty soils.

Yellow suckling clover (*Trifolium dubium)* is a common contaminant of white clover seed but is much less productive and persistent.

Rose clover *(Trifolium hirtum).* Like subterranean clover this produces most of its growth in the spring following autumn germination and slow growth overwinter. It may be useful in conditions of low fertility and rainfall.

Caucasian clover *(Trifolium ambigium)* is a persistent pasture plant of cool climates although it remains dormant over the winter and is slow to grow in spring. It tolerates waterlogged conditions and is superior to white clover at low pH and phosphate levels.

Berseem or Egyptian clover *(Trifolium alexandrinium)* and ***Persian clover*** *(Trifolium resupinatum*) are annuals really requiring warmer temperatures than those of the UK although they may give reasonable yields during the summer months.

MEDICS (*Medicago* spp.) are another important genus of legumes. They have trifoliate leaves and so appear superficially similar to clovers but can be distinguished because the midrib projects beyond the leaf margin.

Lucerne or alfalfa *(Medicago satvia)*

Suitability:	L
pH range preferred:	Over 6.5
Height:	40 – 90 cm
Frost tolerance:	Good

This is a long-lived perennial plant with a deep taproot ideally suited to light and chalky soils (pH 6.2-7.8) and dry climates. Where it can grow well it is the most high yielding of the herbage legumes, producing 15 t/ha of dry matter annually. A very different management to grass/clover leys is required if the lucerne is not to die out; excessive competition must be avoided particularly when young. Lucerne is particularly susceptible to verticillium wilt and can suffer from clover rot and crown wart disease. Varieties include Europe, Mercedes and Vela.

Trefoil, yellow trefoil, black medick or hop clover *(Medicago lupulina)*

Suitability:	SG, I
pH range preferred:	No specific requirements
Height:	10 – 15 cm
Frost tolerance:	Good

This is an annual or biennial legume that can give good yields even on thin calcareous soils. It may be grazed by sheep but its main use is as a green manure undersown in cereals. Because it is relatively low growing it may also have potential in vegetable intercropping systems

OTHER MEDICKS:

Snail medick *(Medicago scutellata)* produces characteristically snail shell shaped seed pods which may persist in the soil and cause a weed problem. The seeds are large and the plants become established rapidly from either spring or autumn sowings.

M. littoralis, M. tornata, M. rugosa, M. denticulata, M. minima, M. laciniata and *M. polymorpha*. These originated in a Mediterranean climate and do best in mild winters. They may be suitable for sowing as summer catch crops, possibly being the most favourable species under some soil conditions although little side by side evaluation of the possibilities has been done.

TREFOILS (Lotus spp.) are mainly adapted to cool climates and fairly acid, damp soils. There are indications that trefoils can assist in controlling internal parasites in sheep.

Birdsfoot trefoil (*L. corniculatus)* has a distinct crown with several stems but no stolons: it is used for forage in a similar manner to lucerne but it must not be cut too close as regrowth comes from lateral buds well above the soil. It is suitable for soils too poor for red clover or lucerne.

Greater birdsfoot trefoil, marsh birdsfoot trefoil or lotus (*L. pedunculatus/ L. uliginosus/ L. major)* are similar to the above but produce spreading shoots. They are more suited to wet soils but establishment is slow.

Slender or narrow leaf trefoil (*L. tenuis)* can stand greater soil salinity than almost any other legume.

THE SWEET CLOVERS (*Melilotus* spp.) are vigorously growing plants capable of rapid establishment. They may be grown for one season or overwintererd for a second year. The plants are tall and the rather woody stems contain a substance which may decompose to form toxic compounds in hay or silage. They are drought resistant and tolerant of poor conditions.

White sweet clover, honey clover or white melilot *(M. alba)*. This is a fast growing legume but too competitive to be undersown in cereals. It is very productive.

Yellow sweet clover or yellow melilot *(M. officinalis)*. This is hardy and better than white sweet clover at establishing in dry conditions although it may be less persistent.

OTHER LEGUMES

Sanfoin, St Foin, cockshead or Holy Grass *(Onobrychis viciifolia).*

Suitability:	SG, L
pH range preferred:	Above 6.0
Height:	30-60cm
Frost tolerance:	Reasonable

This was once grown extensively on chalk and limestone soils. It needs good drainage and prefers a warm climate; it is perennial with a deep taproot and is drought resistant. It is a valuable animal feed nutritionally although yields are much lower than lucerne. There are two types. Common sanfoin is truly perennial but can only be cut once a year. Giant (or double cut) sainfoin is more productive but only persists for a couple of years. Common available varieties include Cotswold Common and Perly.

Lupins: White lupin *(Lupinus albus)*, ***bitter blue lupin*** *(Lupinus angustifoilus)* and ***yellow lupin*** *(Lupinus luteus)*

Suitability:	SG
pH range preferred:	Can tolerate acid conditions
Height:	60-70 cm
Frost tolerance:	Poor

These were the traditional green manures of temperate climates. They are well adapted to sandy soils. Wild lupins contain toxic alkaloids in their foliage and seeds but modern breeding has developed varieties which may be grazed. Flower colour is not necessarily related to the name of the species. The plants have deep penetrating taproots and the stems are erect yet easily crushed and readily decomposed.

Fenugreek *(Trigonella foenum-graecum)*. This has a long growing season and thus considerable bulk production may be achieved.

Field beans *(Vicia faba)*. Although used as a green manure in a garden situation, particularly on 'heavy land' the cost of seed can be prohibitive on a field scale. In addition beans are not completely frost hardy and may be particularly susceptible to the disease 'chocolate spot'.

Peas (*Pisum satvium)* are a highly bred vegetable with many varieties for particular purposes. They may be used as a green manure but frost tolerance is generally very low. Winter varieties are, however, available. They may suffer from drought.

***Common vetch** or **tares** (Vicia satvia*) and ***hairy vetch** (Vicia villosa*) are annual plants with trailing stems and tendrils. The latter appears to be more commonly grown in North America.

Suitability: WG	
pH range preferred: 7.0	
Height: 50cm but can also climb	
Frost tolerance: Good	

Both winter and spring varieties of vetch are available and they may be sown mixed with cereals for grazing or silage making. Winter vetch is very valuable as an autumn sown cover crop because its large seeds enable it to become established later than most other legumes and thus be fitted in after the harvest of many summer- grown crops. Pest damage (insects and birds) may be devastating in some places but where it grows well vetch can release large amounts of available N to a following crop. A common variety available is English Early.

***Cow pea, crowder pea or black eyed pea** (Vigna unguiculata* or *Vigna sinensis)* have been cultivated for their seeds, green pods and leaves. They are not frost tolerant but have been used as summer green manures in vegetable and cereal systems.

***Serradella** (Ornithopus sativus*) is adapted to moist sandy soils and is grown for forage or as a green manure in southern and central Europe.

***Kidney vetch** (Anthyllis vulneraria*) is a perennial legume adapted to sandy and calcareous soils and used mainly for grazing sheep.

Lespedeza spp. are grown for hay in the USA since they do well on soils of low fertility.

2.2. Non Legumes

These will not fix nitrogen but can be very effective at preventing nitrate leaching, adding organic matter to the soil and smothering weeds.

CEREALS

Rye (*Secale cereale*)

Suitability: WG	
pH range preferred: 5.0-7.0	
Height: 60-80 cm (in mid April)	
Frost tolerance: Good	

This has frequently been found to be the most vigorously growing overwinter green manure. Varieties bred specifically for winter grazing (sometimes called Hungarian grazing rye) are generally considered to be better cover crops than grain varieties since they produce more leafy growth. It is best incorporated in mid-April – any earlier and it may regrow and if left later it will produce vast amounts of dry matter that may lock up available nitrogen.

***Oats** (Avena sativa)* or ***barley** (Hordeum vulgare)* may be grown as alternatives to rye (seed is often available on farms without buying it in specially) although these crops are unlikely to be as effective at preventing leaching. Oats appear to be particularly suitable when sown thinly as a nurse crop for establishing legumes.

GRASSES

***Perennial** ryegrass (Lolium perenne)*

Suitability: L (WG)
pH range preferred: 6.0-7.0
Height: 30-60 cm (if uncut)
Frost tolerance: Good

Perennial ryegrass establishes rapidly and will survive for 3-4 years. It will thrive on fertile soil, establishing deep and dense fibrous root systems but on poor or drought prone soil other grasses, such as cocksfoot may be more suitable. Typical annual dry matter production is 15 t/ha. Ryegrass is most commonly used in a mixture with various clover species – it may be established by being undersown in a cereal crop. Its high sugar content and digestibility make it particularly suitable for silage production.

There are many varieties of ryegrasses which are divided into early, intermediate and late groups. Early varieties such as AberTorch, Donard and Moy will provide good early growth and head in mid May. Intermediate varieties include AberDart and AberGold and later varieties such as AberCraigs will head in mid June.

***Annual** ryegrass (Lolium multiflorum)*

Annual ryegrass (often known as Westerwolds ryegrass) is useful where rapid production is needed within 3 –6 months of sowing. When sown in the summer or spring they will flower in the same season and not persist over winter. In mild climates they can be sown in autumn to provide early spring growth.

***Italian ryegrass** (Lolium multiflorum)*

Suitability: L (WG)
pH range preferred: 6.0-8.0
Height: 25-70 cm (if uncut)
Frost tolerance: Moderate
Annual dry matter: 16 t/ha

Unlike annual ryegrass, Italian ryegrass is a biennual not flowering until the second season. It can be used for short term leys of up to three years. They produce more early season growth than perennial ryegrass but midseason growth tends to be stemmy. Frost tolerance is not as good as perennial ryegrass and they are also susceptible to drought. Diploid varieties such as Adin and Alamo are more suited to wet environments and under these conditions will outyield tetraploid varieties in the second year. Tetraploid varieties such as Danergo and Fabio will produce higher yields in the first year than diploid varieties. Their drought tolerance and cold tolerance is better than diploid varieties.

Hybrids of Perennial and Italian ryegrasses

Hybrid ryegrasses possess some of the characteristics of both types, having the early season growth of Italian ryegrass and the sward density of perennial ryegrass. Varieties such as AberExcel are closer to the characteristics of Italian ryegrass whereas AberStorm and Citeliac are closer to perennial ryegrass in type.

OTHER GRASSES

***Cocksfoot** (Dactylis glomerata)*

Photo shows cocksfoot and red clover mix

Suitability:	L (WG)
pH range preferred:	6 - 8
Height:	60 – 100 cm
Frost tolerance:	Good

Cocksfoot is slower growing in the first year of sowing than perennial ryegrass but is more tolerant of heat and drought and is suitable for growing in drier areas with free draining soils. Cocksfoot has a reputation for producing a large amount of root mass which is beneficial for soil organic matter content and soil structure. Cocksfoot may use water more efficiently than perennial ryegrass (Garwood & Sinclair, 1978; Thomas, 1985). Cocksfoot is much less commonly grown than perennial ryegrass, especially in systems that are grazed, due to its poor palatability. A high lignin content, low sugar content and sharp leaf structure are thought to contribute to this (Van Dijk, 1958). It often forms clumps within the field especially if establishment is poor. Common varieties of cocksfoot include Prairial and AberTop. Typical annual dry matter is 14 t/ha.

***Timothy** (Phleum pratense)*

Suitability:	L (WG)
pH range preferred:	6.0-7.0
Height:	30-50 cm
Frost tolerance:	Good
Annual dry matter :	12.5 t/ha

Timothy is well adapted to cooler wetter areas and has good winter hardiness. It is slow to establish but can produce yields similar to perennial ryegrass in the second year. When sown on its own, it has a tendency to become thin and for this reason it is normally sown with other grasses such as perennial ryegrass. Varieties used include Motim, Erecta, Pomesse and Comer.

***Fescues** (Festuca spp.)*

Meadow fescue (*Festuca pratensis*) is more tolerant to lower soil fertility than perennial ryegrass. It forms a fairly open sward which can be prone to weed invasion so is often sown as a companion grass with timothy or cocksfoot. Its popularity has declined over the last 20 years as fertiliser use has risen and use of perennial ryegrass has increased. Other species of fescue such as tall fescue (*Festuca arundinacea*) are not commonly used except where grass is dried.

BRASSICAS

These species may be best avoided by horticultural producers because they suffer from the same diseases as the brassica vegetable crops. However, their decomposition can release chemicals which inhibit soil borne pathogens, pests and weeds.

Mustard *(Sinapis alba)*

Suitability: SG, WG	This is one of the most widely grown green manures, largely as a result of the cheapness of the seed. It grows large very quickly but it is very shallow rooted. It is not completely frost hardy but survives in some winters. Frost kill need not be a disaster for a winter green manure, providing that it occurs late in the season and there has been time for significant nitrogen conservation to have occurred. Much interest has been shown in caliente type varieties recently. These have been bred for their high glucosinilate content that under the right conditions can have biocidal properties against pests, weeds and diseases. These properties are discussed in more detail under section 4.5.
pH range preferred: 5.3-6.8	
Height: 30-60 cm	
Frost tolerance: Poor	

Stubble turnips, Oil seed rape, Fodder radish. *(Brassica rapa, Brassica napus, Raphanus sativus)* The main role of these crops is as a source of winter grazing (usually for sheep) with green manuring effects after incorporation of secondary importance.

OTHER NON LEGUMES

A number of other species may be suitable (even sunflowers have been suggested) but three in particular, quite unrelated to other agricultural plants, are usually thought of as green manures.

Phacelia *(Phacelia tanacetifolia)*

Suitability: SG, WG	This grows rapidly from either winter or spring sowings. Although not completely frost hardy it will survive in mild winters. It produces striking blue flowers and is sometimes planted solely to attract beneficial insects but by this stage the plants will have become very stemmy and slow to decompose. It also has a strong tendency to become a weed in subsequent crops.
pH range preferred: No specific requirements	
Height: 30-60 cm	
Frost tolerance: Poor	

Buckwheat *(Fagopyrum esculentum)*

Suitability: SG	This is a broad leaved summer annual that requires only a short growing season (2-3 months). It may self seed to produce a second crop – this may cause a weed problem. It will tolerate infertile soils but performs badly on heavy soils. It is believed to be effective at scavenging the soil for phosphorus. The crop may be grown as an attractant for beneficial insects
pH range preferred: 5.0-7.0	
Height: 40-60 cm	
Frost tolerance: Poor	

Chicory *(Chichorum intybus)*

Suitability:	SG, WG, L (with grasses)
pH range preferred:	6.0-8.0
Height:	40-100 cm
Frost tolerance:	Good

Chicory has become more popular in the last 20 years with Puna varieties being the most widely grown. It can have beneficial effects on soil structure, producing a large taproot which can break through plough pans. It is good for grazing, containing high levels of calcium and potassium (Barry, 1998) and other micronutrients (Rumball, 1986). It has also been shown to reduce the effects of internal parasites in sheep (Scales *et al*., 1994). Chicory can be sown in autumn or spring (Li & Kemp, 2005) either as a pure stand or as part of a grass clover mixture. It is important that reproductive growth is cut to prevent an abundance of unpalatable woody material forming.

2.3. Mixtures

It is often desirable to sow a mixture of species so as to combine the benefits of each (see Table 1). There is also an element of 'hedging your bets' in case one of the components does not do well in a particular season. Although short duration green manures may be sown as mixtures the practice is much more common when establishing leys to last a year or more. Sometimes one of the species is not intended to be persistent in the longer term but to provide good ground cover in the early stages.

Table 1. Characteristics of commonly used green manure mixtures

Red clover/ryegrass	This is potentially the most productive mix in terms of both dry matter production and nitrogen fixation. The ryegrass is often either Italian or a vigorous perennial variety – such rapidly growing varieties contribute significantly to the dry matter production. Both this and the following mix can be undersown into a preceding crop.
White clover/ryegrass	This is typically a longer-term green manure than the other mixtures. It can be used for a period of 2-5 years depending on the persistence of the varieties in the mixture. The clover will fix nitrogen for the duration of the ley while the ryegrass provides a balance. The mixture is able to utilise nutrients and water more effectively and the ley can be grazed to give some income through the fertility-building period.
Oats/peas/vetch	This is another dual purpose mixture in that it can be taken as whole crop silage or incorporated into the soil as a green manure. It is a relatively expensive choice for a short term green manure. If it is cut for feed then there should be a payback in manure from the livestock operation.
Rye/vetch	As an overwintered green manure this can result in effective nitrogen conservation and fixation with large amounts being made available to the following crop. However, there is a danger of the rye swamping the vetch; careful tailoring of the seed rates may be necessary to achieve a good balance of each plant.

Commercially available green manure mixtures can be quite complex containing several different varieties of several species of grasses and clovers. This is particularly the case when the mixture is aimed at the organic farmer. The organic standards stipulate a maximum proportion of seeds that can be derived from conventional production. Because not all the varieties are available as organic seed (and because these seeds are more expensive) different varieties are combined to produce a mixture that complies with the regulations. However, it is no bad thing to have a range of varieties as different ones are likely to do well under different conditions.

3. Management of green manures

Management of green manures in the ground will depend on the planned duration of the crop, the type of green manure and the nature of the farming system in which they are used. The key management events for some common species is summarised in Table 2.

Table 2. A guide to sowing and management of green manures

Crop	Seed rate (kg/ha)	Sowing time	Can be mown or grazed?	Duration
White clover	**10-15**	**Mar-Aug**	**Yes**	**2-5 years**
Red clover	**15-20**	**Mar–Aug**	**Yes**	**1-2 years**
Crimson clover	**15-18**	**Mar-Jun, Aug**	**No**	**2-3 months**
Sub clover	**10-15**	**Mar-Jun, Aug**	**Yes**	**5-7 months**
Lucerne	**20–25**	**Mar-Jun, Aug**	**Yes**	**1-3 years**
Trefoil	**10-15**	**Mar-Aug**	**Yes**	**Up to 1 year**
Lupins	**200-250**	**Mar-May**	**No**	**3-5 months**
Field beans	**200-250**	**Mar or Oct**	**No**	**5-7 months**
Winter vetch	**75-125**	**Mar-Sep**	**Not generally**	**3-6 months**
Grazing rye	**150-180**	**Aug-Oct**	**Yes**	**7 months**
Mustard	**8-12**	**Mar-Sep**	**No**	**2-3 months ***
Stubble turnips	**8-10**	**Apr-Aug**	**Yes**	**8 months**
Phacelia	**10-15**	**Apr–Jul, Sep**	**No**	**2–3 months***
Buckwheat	**60-80**	**Apr-Aug**	**Yes (if done early)**	**2-3 months**
Westerwolds ryegrass	**32–38**	**Mar-Jun, Aug**	**Yes**	**9-12 months**
Chicory	**12-18**	**Apr-Aug**	**Yes**	**12-18 months**

* this depends on the time of sowing – longer if overwintered

3.1. Fertility management

No crop will grow well without adequate nutrition and it has to be remembered that maximum performance will depend on a good nutrient balance, adequate moisture levels and an appropriate pH. As a rule short term green manures should not need additional fertility inputs as long as nutrient balances are addressed as part of the general management of the rotation.

It can be a different story for the longer-term leys that can be in the ground for as long as two to five years. One of the main functions of such leys is the re-building of fertility after a period of cropping. It is also often the case that conservation cuts are taken in a mixed farming situation. Both of these situations require the replacement of nutrients other than nitrogen.

The organic standards recommend the application of composts and manures to the fertility building phase. Some care is required as all bulky organic inputs contain some nitrogen and if these levels are high, fixation by the legumes in the ley can be inhibited. This is less likely where mature composts are used as the nitrogen should have been more or less stabilised.

3.2. Seed bed preparation

It is important to pay as much attention to seed bed preparation for green manures as for harvestable crops. One of the aims of green manure use is to achieve 100% ground cover so maximum germination is a priority. Another factor is that some green manures seeds are relatively expensive so wastage due to poor germination needs to be minimised .

A seedbed should be prepared using standard techniques aiming at loosening the soil to a reasonable depth. The early development of effective root systems is vital to the overall performance of the green manure crop. This is particularly important for the shorter term green manures. Compaction on the surface or at depth should be broken up and the soil worked down to an appropriate tilth. This will depend on the size of seed and it is particularly important that small seeds such as clover is sown into a fine, well-firmed seedbed. Although it may seem obvious there should be adequate moisture in the seedbed prior to sowing.

3.3. Sowing techniques

The essential choice is between broadcasting and drilling and in theory all the green manures described in Section 2 can be established using both techniques. In practice the choice is often determined by what machinery is available. Even distribution of seed and uniform sowing depth are the prime requirements for successful establishment in conjunction with a fine firm seedbed.

This will require accurate adjustment and calibration of the available equipment. If a good corn drill is available then this would be the first choice for some of the crops on the list. The same applies to precision drills though it may not be possible to achieve close spaced rows. A significant advantage of drilling is that the sowing depth can be set before starting and this should remain constant over the field, providing a level seedbed has been achieved.

It is generally quicker and easier to broadcast seed though it can be difficult for small quantities in a tractor mounted implement. Even distribution of seed is easily achieved providing the operator is competent in calibrating the machine. Small-scale vegetable units may find it more effective to use a pedestrian broadcaster. Those sold for professional use are robust and can be calibrated quite accurately providing a constant walking speed can be maintained.

The seed is left on the surface by the process and one or two passes with a harrow will be required to cover the seed. The seed must be covered though care must be taken not to bury fine seed too deeply. It is usually useful to take a light roll over after harrowing to consolidate the seedbed and ensure good soil/seed contact. Using a ring roller before broadcasting can be useful to create channels for the seed to fall into, thus making burying easier.

Legumes require infection with an appropriate strain of Rhizobia bacteria before they are able to fix nitrogen. Most UK soils already contain sufficient Rhizobium populations that can result in nodulation of common legumes such as clovers, peas and beans. Crops such as lucerne require different strains and may benefit form inoculation of the seeds. Rhizobia are available commercially and easily applied.

3.4. Where to buy seed

There is a small group of companies that have been specialising in this area for a number of years though it has been possible to buy seed of the more common types from most seedsmen. As the organic seed regulations have tightened all growers have had to seek organic seed when available. The same requirement applies to green manure seed and it is relatively easy to research availability by using the Organicxseeds website (www.organicxseeds.com). The site includes an index of suppliers with contact details and websites where appropriate. They can be contacted directly to check availability or a search can be carried out for the particular green manure. This should return information on available varieties and the companies stocking that variety.

The establishment of some green manure crops can be expensive, given the high seed rates that are required. It is therefore crucially important to accurately calculate seed requirements and then to apply the seed accurately. The timing of establishment can sometimes affect the seed rate, especially for autumn sowings of over-winter green manures.

An alternative is to save seed from current crop though in practice it is the exception rather than the rule. Much will depend on having the correct equipment on the farm and this will include cleaning and drying equipment as well as harvesting machinery. The other problem is that the crop will often need to be left in place for longer than normal to allow seed to set and mature.

3.5. Mowing

Most short-term green manures are grown to generate bulk and this is turned in at the end of the growing period, ideally before the crop has set seed. Longer-term green manures need active management if they are to generate the required benefits. In stockless systems this is achieved by periodic mowing in the so-called 'cut and mulch' approach. The frequency of mowing will depend on the performance of the crop but as a general rule the crop is mown when it reaches about 45cm; any higher than this and the volume of cut material is likely to cause problems with smothering.

Unless there is a severe weed problem the cut should take the crop height down to no lower than ankle height (10-15cm). This is to ensure that re-growth is rapid and is particularly important for non-grass crops where new growth often arises from aerial buds. To avoid swathes of plant material that can smother new growth a rotary or flail topper should be used to mince up the cut material and distribute it evenly across the sward.

Some farmers may wish to remove the cut material to use as forage or graze their fertility building leys. This will obviously provide some cash return. There is evidence (Goodlass *et al*, 2006) that removal of the herbage will stimulate nitrogen fixation (because less nitrogen is available though fixation) and it may be possible to apply the mowings to a cash crop elsewhere, or to compost them for use later. However, with this approach there is a danger of depleting nutrients such as potassium to such an extent that regrowth may be inhibited.

3.6. Incorporation techniques

Effective incorporation of the green manure crop is as important a job as the growing of the crop. Breakdown of the green material should happen quickly and this will depend on good mixing and adequate aeration of the soil. It is also important that the green manure has not become too mature and woody.

The top growth should ideally be wilted before incorporation. If there is a lot of bulk a topper should be used to chop the growth, which is then wilted for up to 7 days before incorporation. An alternative approach uses disc harrows or a shallow rotavator to chop the green material into the soil surface. This material is then wilted in situ for 4-5 days before a further pass is made to finish the job.

The relative merits of different incorporation machinery are listed in Table 3. The final choice may depend on the following crop eg the material must be well chopped up if there is to be a subsequent destoning operation before a root crop like potatoes are grown. Ploughing can be very effective – it should bury all the material and leave clean furrows for working down to a seedbed. Care should be taken with heavy soils not to bury the material too deeply as further decomposition could be slowed down or prevented. The use of powered implements can be more effective in mixing but they are more expensive in terms of their power requirements

Table 3. The relative merits of machinery for incorporation of green manures

Plough	Good for turning under crops but does not chop or mix crops; inverts the soil and crop layers
Disc harrow	Good for reducing stubble and crops; heavier models mix crop and soil well; does not work at depth
Rotavator (rototiller)	Good for reducing crop and excellent at mixing; requires high power input; high expenditure on parts
Power harrow	Suited for reducing crops and good at mixing; preserves soil profile but does not bury residues
Cultivators	Good for loosening soil surface but does not achieve much mixing or burying
Chisel plough	This will tear up green manure crops and also loosens the subsoil; ineffective for mixing and burying
Combinations of implements	Various combinations of the above will give benefits such as thorough mixing with soil loosening but power requirements are very high especially in heavy soils

4. The effects of green manures

This section describes the conclusions from experiments that have been conducted to examine some of the specific benefits of green manures. Unfortunately some of the effects are very difficult to quantify scientifically and have been little studied. It is important to remember that these crops can bring several benefits at once.

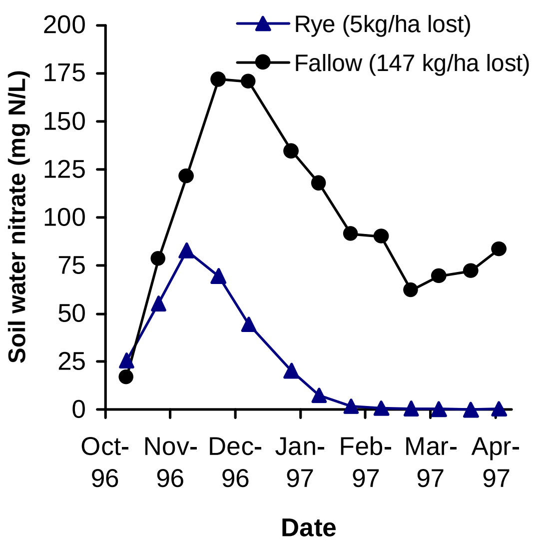
4.1. Minimising nitrate leaching

Large quantities of nitrate can be lost from soil which is left bare overwinter. This is because, unlike other nutrient ions, nitrate is not strongly attracted to soil particles. Any that is in solution in the autumn will be washed away as water moves down through the soil with the onset of heavy winter rains. This is bad for the environment (nitrate can contribute to the formation of algal blooms in watercourses) and for human health (when contaminated water is drunk). As a result EU regulations have been introduced to control farming practices likely to result in large nitrate losses. This has resulted in the establishment of Nitrate Sensitive Areas (Tunney, 1992). For farmers, leaching also represents the loss of a valuable resource – this is particularly serious for organic farmers because it is much harder for them to replace the lost nitrogen. It is widely recognised that one of the best ways of preventing nitrate leaching is to maintain a vigorously growing crop over the winter period (MAFF, 1998).

Winter green manures can be very effective crops for 'mopping up' excess nitrate in the soil in the autumn and this effect was studied at HDRA. One example is shown in Figure 1; nitrate concentrations were measured at 60cm depth and the wave of nitrate passing down the profile can be clearly seen.

Green manures vary in their ability to reduce leaching. Grazing rye is particularly effective – in trials conducted at HDRA leaching was reduced by an average of 95%. Vetch reduced losses by 45% and field beans had scarcely any impact at all. What is essential is rapid early growth and the development of an effective root system. Once leaching has begun the plants have very little time to take up the nitrogen before it is all washed away. If the crop cannot be established in good time it may be worse than useless because the cultivations used to establish the seedbed may stimulate the mineralisation of nitrogen that then cannot be captured by a green manure struggling to germinate and grow under ever colder conditions. Grazing rye is suitable because it is adapted to produce large amounts of leafy growth in relatively cold weather.

***Figure 1**. An example of overwinter nitrate concentrations below bare soil plots and plots on which grazing rye was growing. This trial was set up directly after the incorporation of a grass/clover ley.*



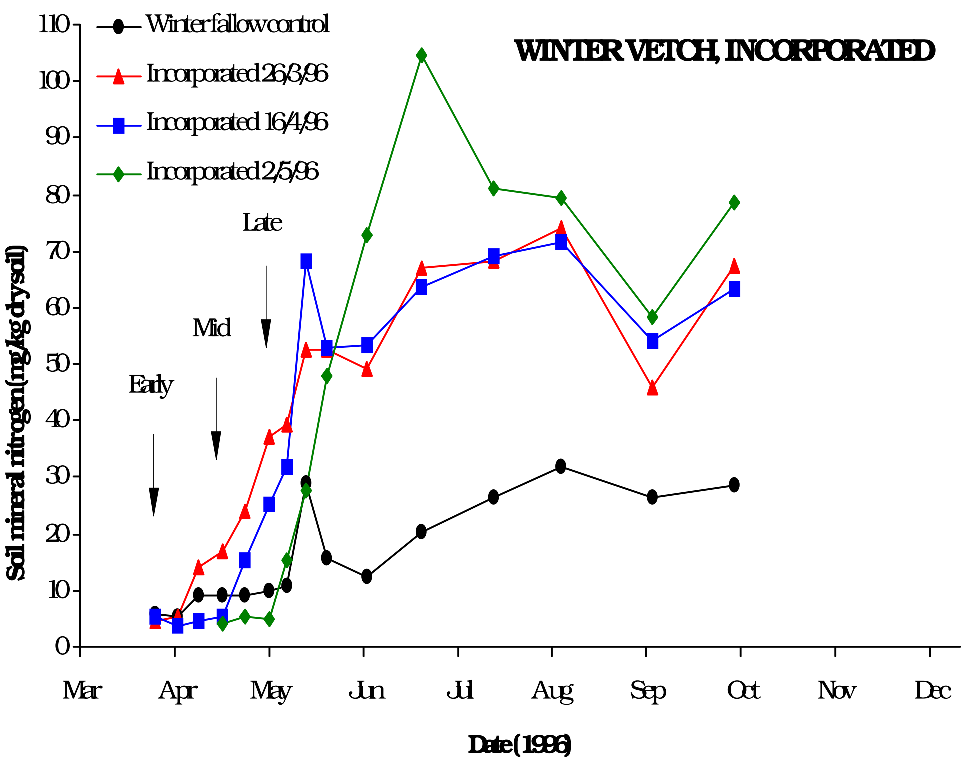
4.2. Provision of nitrogen to the following crops

Of all the nutrient elements, nitrogen is the most labile in soil and the one most likely to be affected by green manures. This is because it exists in so many different forms that are inter-converted by a range of biological processes – some of these forms are prone to losses (by leaching or gaseous emissions of ammonia, nitrogen or nitrous oxides). For some crops (eg cauliflowers) it is particularly important that sufficient nitrogen is available at certain growth stages to ensure that the plants produce yields of a marketable quality and correct management of green manures can be used to manipulate its availability. Large amounts of nitrogen are added to the soil by a successful green manure (eg an overwintered crop of vetch may accumulate up to 200kg N/ha by early May). How soon this becomes available to plants (a process of conversion of complex molecules to ammonium and nitrate ions known as mineralisation) will depend on many factors (Jarvis *et al* , 1996).

Mineralisation proceeds fastest when the soil is warm and moist. The quantity of nitrogen released is also dependant on the total amount actually added to the soil and the chemical composition of the incorporated material. It is not just the C;N ratio which is important. The carbon can be in different forms (eg lignin is more resistant to decomposition than cellulose) and some plants contain chemicals (eg polyphenols) which can inhibit microbial action. Rahn *et al* (1999) compared the chemical characteristics of various agricultural residues with their patterns of decomposition.

Figure 2 shows example results from an experiment where overwintered vetch was incorporated at three different dates in the spring. Vetch is a plant which has a high nitrogen content throughout its life (3-4% of its dry weight). And is consequently readily mineralisable. It puts on a lot of growth in late April and this is reflected in Figure 2 – the highest levels of mineral nitrogen resulted from the latest incorporation date in May. In some cases a 'priming effect' may be seen ie the addition of green manures can stimulate the mineralisation of organic matter already in the soil. See Rayns and Lennartsson (1995) for more information.

Figure 2. *An example of patterns of soil mineral nitrogen (0-30cm) after incorporation of an overwintered vetch crop at three different dates in the spring*



Non legumes (eg grazing rye or mustard) may add as much nitrogen to the soil as legumes but less of this is made available in the short term. This is because they have a lower nitrogen content (1-2%) and so more carbon is added as well (ie these plants have a higher C:N ratio). This means that nitrogen is released more slowly as they are decomposed by microorganisms. Furthermore, the nitrogen concentration in these crops usually decreases as the plants age and prepare to set seed so the date of incorporation is crucial eg rye incorporated at the end of April will release nitrogen (although not as much as vetch) but if left until May the decomposing organisms will actually have to compete with plants for soil nitrate in order to tackle the residues. This is sometimes called 'nitrogen robbery'.

In the longer term, the nitrogen conserved by cover crops, especially the slower mineralising non legumes, is prone to leaching in the first winter after incorporation if the land remains uncropped; rotation design should take account of this (see section 5). Green manures have their biggest effect on soil mineral nitrogen within the first year after incorporation and so this is the crucial period when the cropping regimes need to be planned to make effective use of it.

The potential risks of mismanaging green manure nitrogen are greater with the longer term ley crops. Classical ley/arable rotations, as practiced by many organic farmers have a potential leaky point just after the ley is incorporated and indeed this is a common criticism of the system. This was the subject of a study by Elm Farm Research Centre (Philipps and Stopes, 1995).

4.3. Effects on the availability of other nutrients

Section 4.1 clearly showed the effectiveness of green manures in preventing nitrogen losses from organic rotations. However inputs of other nutrients, such as P and K, are often limited in organic systems, so it is important that these nutrients are made available to crops and their losses minimised.

Potassium can be lost through leaching out of the soil and measurements of annual losses range in the literature from 6 kg/ha (Alfaro *et al*., 2004) to 42 kg/ha (Askegaard *et al*., 2003). Losses of phosphorus are traditionally thought to be more through surface run off and erosion but some studies (Turner & Haggarth, 1999, Nelson *et al*., 2005) have shown that losses by leaching can make a significant contribution, especially if the soil is saturated with P when large amounts are added through animal manures. Phosphorus availability is also frequently restricted by binding to calcium carbonate on calcareous soils or iron oxide on more acidic soils (Wandruszka, 2006).

In comparison to the work done on using catch crops to minimise N looses much less attention has been paid to P and K. The most extensive study was carried out by Jensen *et al.* (2005) where the effectiveness of five types of catch crop (Italian ryegrass, lupin, chicory, rumex and kidney vetch) were compared on a soil deficient in P and K. In this study, nutrient uptakes of catch crops were all low with 2-4 kg P / ha and 15-30kg K /ha taken up annually. This low uptake was attributed to low biomass production (1-2 t/ha) of the catch crops on the infertile soils. Moreover, after incorporation, the catch crops had no effect on the P uptake in the subsequent barley crop. The conclusions that could be drawn from this study were that under these conditions of poor soil fertility, catch crops made very little contribution to making P and K more available to subsequent crops. However, this work does not answer the question as to whether they have a role to prevent losses on more fertile soils. Askegaard (2006) concluded from trials of grass and clover grown on sand that although catch crops reduced annual N leaching they did little to prevent K leaching over the winter because K uptake in the catch crop was very low during this period. However, there is work to suggest that, over a longer period of 1 –3 years, green manures can take up substantial amounts of P and K. Chicory, in particular, is deep rooting and in a three year trial was found to take up an average of 95 kg/ha of K annually; this was 50% more than the shallower rooting ryegrass (Hogh-Jensen *et al*., 2006). In grass clover leys, Mengel and Steffens (1985) found that the grass component took up more K than the clover which could be related to the more extensive rooting system of the grass. Differences in ability to take up K exist between genotypes (Liu *et al*., 1995) and there is the potential to exploit these differences.

There is work that has focussed on the ability of some plants, particularly lupins and buckwheat to increase phosphate mobility in the soil. Lupins grown in P deficient soil were found to extrude protons and organic acids such as citric acid, increasing the mobility and uptake of P (Shen *et al.*, 2005; Sas *et al.*, 2001; Neuman *et al.*, 2000). P deficiency also stimulated the formation of cluster roots which are more active in P uptake (Sas *et al.*, 2001; Neuman *et al.*, 2000). Buckwheat has also been shown to extrude organic acids (Zhu *et al.,* 2002; Annan & Amberger, 1989) and under conditions of low P availability on a calcareous soil, P uptake was ten fold higher than in wheat (Zhu *et al.,* 2002).

There is also work to suggest that micronutrients such as sulphur may be leached out of sandy soils and eventually become deficient in low input systems (Eriksen & Askegaard, 2000). One study (Eriksen & Thorup-Kristensen, 2002) found that cruciferous crops such as winter rape or fodder radish were particularly effective at preventing sulphur being leached into lower soil profiles. Moreover this increased availability was realised as an increase in sulphur content in the subsequent barley crop. Other green manures such as chicory have also been reported to accumulate large amounts of micronutrients including sulphur, boron, manganese, molybdenum, and zinc (Rumball, 1986).

4.4. Soil structural improvement

Green manures can improve soil structure in a number of ways. The extensive fine roots of some, such as rye, enmesh the soil, helping to stabilise aggregates and increasing pore size thus improving seedbed structure (Breland, 1995). Some species also produce deep tap roots which help break up compacted soil. A series of pot experiments (Lofkvist *et al*., 2005) identified lucerne roots as being particularly effective at penetrating hard layers, with chicory, lupin, red clover as having intermediate ability and barley the poorest. A key function of green manures is the addition of organic matter to the soil. They do this whilst still growing, producing root exudates which provide food for micro organisms, which in turn produce polysaccharide gums, which “glue” soil aggregates together (Reid & Goss, 1981). They may also provide a bridge between mycorrhizal crops in order to maintain a high population of soil mycorrhiza, which help maintain soil structure, again by enmeshing soil aggregates. Brassicas and lupins, however, are non mycorrhizal and will break that bridge.

Once incorporated, the green manure provides a pool of fresh organic matter and there are numerous examples where using green manures increases soil organic matter in comparison to treatments where inorganic fertilisers alone are applied (e.g. Shepherd *et al*., 2002; Campbell *et al*., 1991). This organic matter provides food to soil micro organisms, encouraging an increase in numbers and activity (Campbell *et al*., 1991; N’Dayegamuye & Tran, 2001). Functions of the soil organisms are diverse and are summarised by Hendrix *et al*. (1990) - see Table 4.

The more succulent a green manure is the more rapidly it will decay once incorporated and the less effect it will have on long term soil organic matter. Older woody green manures with a higher C:N ratio break down more slowly and breakdown is reported to decrease to a very slow rate at C:N ratios above 16:1 (Enwezor, 1975). Legumes which have a low C:N ratio, break down rapidly so have little effect on long term soil organic matter but give a larger short term boost to soil structure as they have a large short term effect on soil micro organisms.
Green manures can also play a part in reducing soil erosion both by wind and rain (Cransberg & McFarlane, 1994). Wind erosion is reduced as the green manure increases surface roughness reducing the wind speed close to the soil. The root system also has a binding effect on the soil. The green manure also reduces run off substantially, at ground covers of greater than 75%, reducing erosion by rain.

Table 4. Influences of soil biota on soil processes in ecosystems (based on Hendrix et al., 1990)

Organism group	Effects on nutrient cycling	Effects on soil structure
Microflora (fungi, bacteria, actinomycetes)	Catabolize organic matter; mineralize and immobilize nutrients	Produce organic compounds that bind aggregates; hyphae entangle particles onto aggregates
Microfauna (Acarina, Collembola)	Regulate bacterial and fungal populations; alter nutrient turnover	May affect aggregate structure through interactions with microflora
Mesofauna (Acarina, Collembola, enchytraeids)	Regulate fungal and microfaunal populations; alter nutrient turnover; fragment plant residues	Produce fecal pellets; create biopores; promote humification
Macrofauna (isopods, centipedes, millipedes, earthworms, etc.)	Fragment plant residues; stimulate microbial activity	Mix organic and mineral particles; redistribute organic matter and micro-organisms; create biopores; promote humification; produce fecal pellets

4.5. Pest, disease and weed control effects

The effects of green manures on pests, weeds and diseases can be beneficial or detrimental and depend on the type of green manure used and the subsequent crops grown. With pests, they may act as a habitat for predatory insects to reduce pest numbers but they can also result in a build up of pests such as wireworms or slugs in subsequent crops, so careful attention should be paid to cropping sequences. With diseases there are plenty of instances of green manures having a suppressive effect but some green manures could act as a bridge for diseases especially brassica green manures in horticultural rotations. Weed suppression can be one of the key benefits of green manures, but again there can be a negative effect if weed control in the green manure has been poor, or the green manure itself becomes a weed in subsequent crops. The various roles of green manures in pests, disease and weed control, both positive and negative are considered here.

4.5.1. Overwintering habitats for generalist predators

Green manure can influence pest levels in a number of ways. One of the positive effects can be a boost in the number of predators that control pest levels. There are plenty of reports of grasses acting as habitats for the overwintering of generalist predators, especially carabid and staphalinid beetles (Andersen, 1997; Collins *et al.*, 2003; Kajak & Lukasiewicz, 1994). Tussocky grasses such as cocksfoot or tall oat grass (Collins *et al.*, 2003) are reported to be the most effective species acting as overwintering habitats. There may also be some benefit from predators moving from grass clover leys into nearby crops (Kajak & Lukasiewicz, 1994) but transfer depends on species. In some instances, the grass crop was found to have little effect on insect predator populations in the subsequent crop and the field margins were considered more important (Thomas *et al*., 2004; Andersen, 1997). Field margins are widely acknowledged to be a highly effective refuge for predatory insects (e.g. Northing, 2003) but the relative importance of grass clover leys in this role almost certainly depends on a whole magnitude of factors including site, season and species.

4.5.2. Pollen and nectar source for predators

Flowering green manures can also act as pollen and nectar sources for predatory insects such as ladybirds, hoverflies, lacewings and parasitic wasps. Commonly used green manures such as crimson clover (Tillman *et al*., 1999), phacelia (Hickman & Wratten, 1992; Denys & Tscharntke, 2002) and buckwheat (Bowie *et al.*, 1995) have all been reported to act as attractants to predatory insects when grown in conjunction with other crops. However little work was found that investigated whether these species are effective at boosting predator numbers in the subsequent crop after they have been incorporated.

4.5.3. Slugs

There are instances of increased slug populations in subsequent crops as the result of a grass clover ley being sown (Frank, 1998). As slugs are considered one of the major pests in organic vegetable crops (Peacock & Norton, 1990), it is essential that the green manure does not increase their numbers. A trial investigating the effect of different fertility building crops on slug populations (IACR- Long Ashton, 2002) came up with the following recommendations:

- For short term cover crops grown to prevent nutrient leaching, ryegrass resulted in less severe slug problems in the following crops compared to legumes such as clover or vetch.
- Where a leguminous fertility building crop is required, Lucerne resulted in slower growth of the slug population than other popular legumes such as clovers or vetch.

It is important to note that this work was only carried out at one site and further work needs to be done as slug numbers vary with soil type, crop and season.

4.5.4. Wireworms

Wireworms (*Agriotes* spp) are another pest that can be harboured by green manures or grass clover leys. They are the larvae of the click beetle and even relatively low populations can cause large reductions in marketable yields of potato crops. In the UK, high numbers of wireworms have traditionally been associated with long grass clover leys (Miles, 1942, Anon 1948) especially those longer than one year (Schepl & Paffrath, 2005). The only way to ensure that wireworm damage does not occur in potato crops is to test the soil and to grow the crop somewhere else if it is present. Levels can be monitored in the field but seemed to be an unreliable indication as to the level of damage that will be inflicted on the subsequent potato crop (Parker, 1996). Therefore tests can only be used as a simple indicator as to the presence or absence of the pest. Some measures can also be taken to ameliorate the effects of fertility building crops on wireworm populations. Schepl & Paffrath (2005) suggested that peas or lupins may be a better precrop to potatoes than field beans or red clover. Good weed control was also deemed important as perennial weeds such as creeping thistle and docks were found to increase numbers of the pest. Autumn ploughing followed by disking when wireworms are most active in the upper layers of the soil is more likely to have an effect on reducing wireworms than ploughing in the spring (Gratwick, 1989). The possibility of using brassica green manures such as mustard which contain glucosinilates as a biofumigant against wireworms was tested by Frost (2002). In this trial, effects on wireworm populations were negligible but it may be that other varieties with higher levels of glucosinilates may be more effective.

4.5.5. Leatherjackets

Leatherjackets are the larvae of craneflies (*Tipula* spp.) and have the potential to cause extensive damage in spring cereals, potatoes, leeks and lettuces following a ley (Soil Association, 2005). They will also result in loss of production of the ley itself. The most extensive damage occurs between September and mid June when the larvae feed on the roots of crops (White & French, 1968). Surveys of grassland (Blackshaw, 1984) showed populations ranging from 65 000 to 865 000 /ha and predicted losses 50 kg/ha of dry matter at populations of 125 000 / ha. Some measures are known to reduce the incidence of this pest (e.g. keeping ley tightly cut between July and September to reduce the chances of adults laying eggs) but more work is needed to investigate methods of control.

4.5.6. Bean seed fly

The bean seed fly (*Delia platura*), also known as the seed corn maggot, is another potential pest that may be influenced by the presence of green manures. It is a small dipterous insect that has a wide host range of up to 40 different crop types (Valenciano *et al.*, 2004). It attacks the cotelydons of germinating seeds as they emerge and can cause extensive stand loss. Ploughing in organic matter from green manures may provide a favourable environment for egg laying and timing of planting in relation to tillage can have a key effect on the amount of damage caused (Hammond & Cooper, 1993; Hammond, 1995). This can lead to an ongoing problem with further generations and will be addressed within Project FV 299. Hammond and Cooper (1993) suggested that eggs are laid at the time of tillage and that damage could be reduced by delaying planting until after the feeding maggots had pupated. Observations from this work suggested a period of 250 day degrees (above a base of 3.9°C) until pupation although it would be prudent to take this as a rough guide as it is highly likely that other factors will affect the life cycle of the pest.

4.5.7. Root knot nematode

Root knot nematode (*Meloidogyne* spp.) is a major pest of vegetable crops and potatoes. Fertility building legumes such as clover (Hallman, 2005) and common vetch (Guertal *et al*., 1998) can act as a host to the pest. However green manures may suppress numbers of nematodes as cereals and grasses have been found to be less favourable (McBride *et al*., 1999; Leroux *et al*., 1996). Some incorporated residues, such as rye have a nematicidal action, significantly reducing nematode populations (McBride *et al*., 1999). Brassica residues can also suppress nematode numbers, and particular attention has been paid to caliente varieties with high glucosinilate content, the precursor which breaks down to isothiocyanate when the green manure is incorporated. Much of this work has already been reviewed by Hockland (HDC project FV 273) who concluded that the biocidal effects were highly variable. This variation could be attributed to variety (not always specified in published work), soil type, climate conditions and, most importantly, the method of incorporation. It is in general agreement that rapid incorporation is essential for the biocidal properties of brassicas to be effective.

4.5.8. Cabbage root fly

Cabbage root fly (*Delia radicum*) is a serious pest with the potential to cause widespread economic damage to brassica crops (Coaker and Finch, 1971). It is now well accepted that growing a crop with another species, such as a green manure can decrease pest infestations significantly (O'Donnell & Coaker, 1975; Finch & Edmonds, 1993). Finch & Collier (2000) proposed that this is because the presence of a non-host plant species reduces pest colonisation. Consistent with this, they observed a 36-82% reduction in egg-laying by the cabbage root fly when cauliflowers were planted amongst 24 other non-host plant species (Finch, *et al*., 2003).

However, care must be taken that the green manure does not compete against the brassica crop as there are many instances where undersowing with clover have resulted in yield penalties of 30-40% (Finch & Edmonds, 1993). Less vigorous species such as yellow trefoil, subterranean clover and birdsfoot trefoil should be used to minimise this effect. An alternative approach of sowing companion plants in the modules of brassica plants is also being investigated (Rosenfeld *et al*., 2006, see also HDC project FV 251) as a means of targeting companion plants more effectively to reduce competitive effects.

4.5.9. Disease control

It is well established that green manures can suppress disease although these effects are variable and the mechanisms not fully understood. The way in which green manures suppress disease fall broadly into two categories: green manures can either provide organic matter to sustain microbial communities that suppress pathogens or the green manure may have a direct biocidal effect on the pathogen.

Green manures may support microbial communities of bacteria, non-pathogenic *Fusarium* species, streptomyces and other actinomycetes. These can suppress pathogens though competition, antiobiosis, parasitism or by inducing systemic resistance in plants (Hoitink & Boehm, 1999). There are numerous examples in the literature of green manures being effective against vegetable diseases eg lucerne hay against *Sclerotinia sclerotiorum* in lettuce (Asirifi *et al*., 1994), lucerne residues on common root rot of pea (*Aphanomyces eutieches*) (Williams-Woodward *et al*., 1997) and buckwheat against common scab (*Streptomyces scabies*) and verticillium wilt of potatoes (Wiggins & Kinkel, 2005).

Direct biocidal effects have most commonly been observed in brassica green manures containing high levels of glucosinilates. As with nematode control, fungicidal activity depends on glucosinilate content and method of incorporation. There are many such examples including control of *Rhizoctonia solani* in vegetable crops (Villeneuve *et al*., 2004) and sclerotinia wilt in lettuces (Pung *et al*., 2005). The latter found that disease incidence was negatively correlated to the glucosinilate content of the preceding brassica green manure.

Although green manures can act as a disease suppressive agent, care must be taken that they do not also act as a green bridge for diseases. The most obvious danger of this is growing a brassica green manure such as mustard in a rotation that already contains brassicas, as this will greatly increase the risk of introducing persistent soil-borne diseases such as clubroot (*Plasmodium brassicola*).

4.5.10. Weed control

One of the major benefits of green manures is the ability to suppress weeds. This can occur by a number of different mechanisms that were reviewed by Liebman & Davis (2000). The various mechanisms are considered here. Firstly green manures can reduce weed infestation by disrupting cycles. Weeds often become adapted to a particular niche cycle of planting and cultivations if similar types of crops are grown continuously (Blackshaw, 1994). Growing a green manure adds diversity to the rotation and reduces the opportunities for weeds to become adapted to a niche cropping cycle. Competition for light, water and nutrients is another important way in which green manures reduce weed infestation. Rapidly growing crops with large ground cover, such as mustard, are the most effective at doing this and McLenaghen *et al* (1996) found that weed suppression was directly correlated with the ground cover of the green manure. Management practices associated with growing a green manure can also suppress weeds. Both mowing (Norris & Ayres, 1991) and grazing (Dowling & Wang, 1993) will suppress weeds. The lack of soil disturbance during the long growing period of a ley can also reduce seed germination (Roberts & Feast, 1973).

Much work has been done on the allelopathic effects of green manures on weeds, where incorporated residues release chemicals that inhibit germination of weed seeds. This allelopathic effect can be used to advantage in organic systems although there is a danger of inhibition of the crop; transplants can be introduced directly into the system with a reduction in weed germination but drilling of direct sown crops should be delayed as the germination suppressive effect can last several weeks (Dabney *et al*., 1996). Putnam & DeFrank (1983) suggested that crops with large seeds are less sensitive to the allelopathic effects of green manure residues than small seeded weeds.

A wide range of legumes that are used as green manures have been found to have allelopathic effects including lucerne (Chung & Miller, 1995), crimson clover (Dyck & Liebman, 1994), vetch (Kamo *et al*., 2003), subterranean clover (Nagabhushana, 2001) and red clover (Fisk *et al*., 2001). Some cereals can have a similar effect, with rye being the most effective (Nagabhushana, 2001). High glucosilinate varieties of brassicas can also contribute to weed control (Vaughn & Boydston, 1997) but as with pest and disease control this depends on the varieties used and rapid incorporation is essential for there to be any effect.

Although green manures can have beneficial effects on weed control, care should be taken that they do not serve to increase weed infestation in a rotation by becoming weeds themselves. For example, phacelia in particular has the ability to self seed prolifically and may become a weed in subsequent crops.

5. Integration of green manures into the crop rotation

Green manures fall into two basic types when considering where to place them in the rotation. Examples of the first type include grass/clover leys, lucerne and other long-term fertility builders that are used to provide the fertility foundation for a period of cropping. The duration of the fertility crop and the subsequent cropping will both depend on a number of factors. A key factor is the inherent fertility of the soil – where this is good the cropping period can be maximised. Other factors include the type of cropping – if this is a combination of field vegetables and cereals then the fertility crop can be undersown into a cereal at the end of the cropping period. This should ensure a more reliable establishment of the ley and avoids the need for autumn cultivation. This can be a problem where the fertility crop is being established following a vegetable crop. This crop must be cleared early to allow time for establishment of the ley otherwise a spring sowing will be necessary. There is a growing interest in the idea of undersowing into vegetable crops (e.g. red clover into sweetcorn) though more work is needed before reliable recommendations can be made.

A different approach is needed for the short-term green manures as there are more factors to be considered. These include previous and following cropping, establishment time, frost hardiness, and soil type. The work described earlier on the release of nitrogen from incorporated green manures means that the requirements of the following crop should be taken into account. As an example lettuce could follow vetch and leeks could follow rye to make the best use of released nutrients. Rye has been shown to be the most effective overwinter nitrate scavenger and should be considered for use on lighter soils that could be more prone to leaching. Allowance should also be made for the timing of incorporation and breakdown; a minimum period of 2-4 weeks should be allowed to avoid the possibility of allelopathic materials released during breakdown inhibiting germination of the following crop. This can occur for all crops although vetch is said to have the strongest effect (Kamo *et al*, 2003).

These general principles are well established and a vast amount of research work has been done to investigate specific effects of green manures. However, more work is needed on the practical value of green manures in a wider range of situations.

5.1. Nitrogen budgeting and the use of computer modelling

Nutrient budgets are a commonly used tool for assessing the sustainability of rotations. All the gains and losses of a nutrient are considered to see if reserves are being built up or depleted. The first difficulty with this comes from deciding what numbers should be used. Many text books contain tables of offtakes for cash crops and additions by green manures (eg Lampkin 1990). Whilst the offtakes values are fairly reliable there is such a huge range of fertility building crop performance that it is difficult to tabulate a meaningful figure. Even for a particular crop it is difficult to measure the true biomass because such a large proportion of it exists below ground. Measurement at the time of incorporation does not show the full inputs because of the additions to the soil that have already occurred as a result of natural litter loss and mowings. Although fixation is closely related to plant growth not all the nitrogen in a legume will have been fixed – if mineral N is available in the soil then it will be utilised – so there may be a large element of recycling. Actually measuring nitrogen fixation is technically difficult and expensive. These problems are particularly difficult for the longer term green manures.

Factors determining the level of N fixation in legumes have been reviewed by Buttery et al (1992), Shubert (1995), Hartwig and Soussana (2001) and Ledgard and Steele (1992). Although different species will respond relatively differently to these factors (eg lupins are relatively tolerant of acid soils) they may be summarised as follows:

- Temperature (generally there is more fixation at higher temperatures)
- Rainfall (fixation is sensitive to moisture stress but is also limited by waterlogging)
- Soil nutrient status (of nitrogen and other nutrients)
- Soil pH (acidity can be a particular problem)
- Availability of suitable rhizobia bacteria

- Presence of a non legume companion (this can stimulate fixation by competing for mineral N in the soil but also limit it by reducing the amount of legumes in a given area)
- Growth stage of crop (fixation usually declines as flowering begins)
- Age of crop (fixation by perennial crops usually declines as the years go by, mainly because of the build up of readily decomposable leaf litter providing a source of mineral nitrogen)
- Management (frequency of cutting or grazing)

It will be apparent that these factors interact – as a result the scientific literature has reported a huge range of values for fixation by the main green manure species. A review by Cuttle et al (2003) tabulated measurements of fixation and Table 5 draws this information together. When constructing a nutrient budget careful judgement is required to decide if crop performance in a given situation is expected to be relatively good or relatively bad.

Table 5. Examples of nitrogen fixation by various green manures (based on information in Cuttle et al 2003)

Crop	Mean (kg/ha/yr)	Minimum (kg/ha/yr)	Maximum (kg/ha/yr)	Number of sources included
White clover/ grass	157	0	373	15 *
Red clover/grass	223	73	460	10 *
Subterranean clover	142	4	320	8 *
Lucerne	211	2	550	12
Winter vetch	121	40	208	2
Lupins	179	90	300	10

NB these measurements refer to above ground plant parts only *

A second disadvantage of nutrient budgeting is that it gives no indication of when the nitrogen will be available. As described in Section 4.2 it is vital that nitrogen is made available by mineralization at a time when it is needed by the plants – to much at other times is at risk of loss by leaching.

Many decision support systems have been developed to help farmers make informed management choices. (Watson *et al*, 2002) These are often computer based models of one type or another which predict nitrogen availability and crop growth by considering the weather and soil conditions. To this extent they may be regarded as a substitute for expert knowledge and they can be an effective way of generalising the findings from specific experimental trials. Models for predicting nitrogen release form plant residue have been reviewed by Paustian *et al* (1997). Some are very detailed and try to simulate all the processes occurring in soils (these are often more suitable for scientists as they may require many detailed parameters not generally available) whilst others take a more 'broad brush' approach and may be more appropriate for growers and advisors. Historically these models have been considered to be particularly suitable for optimising fertiliser applications in conventional agriculture (Rahn *et al*, 1996). Correctly simulating the growth of fertility building crops and their subsequent mineralization patterns on organic farms is a more difficult task. The EU-ROTATE_N model attempts to do this (Rayns *et al*, 2006); this model will be available in 2007 (www.hri.ac.uk/eurotate). Another model recently developed specifically for organic conditions is the FBC model (Cuttle, 2006).

5.2. Economic implications of green manure use

Growing green manures results in direct costs of seed and increased field work necessary for preparing the seedbed, incorporation and possibly for mowing. If the green manure replaces a cash crop, rather than being grown whilst the land would otherwise be bare, then there is also a direct loss of income.

It is possible to compare the value of the nutrients in the green manure with fertilisers. This is most usually done with nitrogen; even at present fertiliser prices this nitrogen will, for a conventional grower, appear to be expensive. However, in an organic cropping system there is no alternative. It is a requirement of organic standards that rotations are as self sufficient in nitrogen as possible although this may be relaxed somewhat for small scale intensive horticultural producers who may rely more on bought in manures and composts (Soil Association, 2005; Organic Farmers and Growers, 2005).

A direct financial return from the use of green manures can now come as a result of Single Farm Payments. Their use can contribute to meeting many of the environmental requirements for eligibility and this is the reason that many conventional farmers will consider their use.

Unfortunately, many of the other benefits of green manures are harder to quantify. It might be expected that rotations containing more green manures would give higher yielding or better quality crops. Long term work done by HDRA (see DEFRA project 0332) compared rotations with two year, one year or six month fertility building periods in a field vegetable/arable rotation. In the first cycle after conversion began there was no difference in the performance of the cash crops and the more intensive rotation was obviously most profitable. However in subsequent rotation cycles the crops in the rotations with longer fertility building periods did relatively better. This underlines the fact that whilst the direct effects of green manures on nitrogen availability are quite short term the changes in soil organic matter which lead to better soil structure happen only slowly.

The collection of information about the costs of green manures is one of the aims of Project FV 299 and the economic impact of green manures will be discussed in greater detail in the final report.

6. Other sources of information

Organisations

HDRA
Ryton Organic Gardens
Coventry
CV8 3LG
Tel: 024 76 303517
Email: research@hdra.org.uk
Web: http://www.hdra.org.uk or
http://www.organicveg.org.uk

Elm Farm Research Centre
Hamsted Marshall
Newbury
Berkshire
RH20 OHR
Tel: 01488 658298
Email: elmfarm@efrc.com
Web: http://www.efrc.com/

The Soil Association Producer Services
Soil Association
South Plaza
Marlborough Street
Bristol
BS1 3NX
Tel: 0117 914 2400
Email: ff@soilassociation.org
Web: http://www.soilassociation.org/foodandfarming

A series of technical guides is available

Cotswold Seeds Ltd
The Cotswold Business Village
Moreton in the Marsh
GL56 OBF
Tel: 0800 252211
Email: info@cotwoldseeds.com
Web: http://www.cotswoldseeds.com/

ABACUS
Rowan House
9 Pinfold close
South Luffenham
Rutland
LE15 8NE
Email: stephen.briggs@abacusorganic.co.uk
Web: http://www.abacusorganic.co.uk

VCS
Vegetable Consultancy Services Ltd
The Finches, Cake Street
Old Buckenham
Attleborough, Norfolk
NR17 1RU
Email: office @vcsagronomy.com
Web: http://www.vcsagronomy.com

Useful publications

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8. Glossary of terms

Legume is any plant in the leguminosae family. This includes lupins, clovers, vetches, peas, trefoils and many others. Under appropriate conditions, most of these will fix nitrogen in association with Rhizobium bacteria (see N fixation).

Green manure refers to any short term crop grown primarily to add nutrients and organic matter to the soil. It is usually grown for a fixed term before being incorporated.

Cover crop is grown primarily to protect and improve the soil during time when it would otherwise be vulnerable to erosion.

Alleochemicals are chemicals released by plants that suppress the growth of other species

Alleopathy is the suppression of one plant species by another through the release of inhibitory substances.

Leaching is the loss of water soluble nutrients from the soil through rain or irrigation.

Rhizobium is a genus of bacteria that forms an association with the roots of legumes in nodules and fixes nitrogen.

N fixation is the process of converting nitrogen (N_2) from the air into biologically useful compounds. It is carried out by Rhizobium bacteria in association with the roots of leguminous species

Mineralisation is the conversion of a mineral (e.g. nitrogen) from an organic form to a mineral form (e.g. nitrate). In this form it is more readily available to be taken up by plants but also more prone to being leached out of the soil.

Deposition is the conversion of gaseous elements from the atmosphere into biologically useful forms in the soil.

Denitrification is the conversion of nitrates in the soil into gaseous nitrogen in the atmosphere. It is carried out by denitrifying bacteria.

Mineral nitrogen is nitrogen in inorganic soluble forms (nitrate or ammonium). In this form it is more readily available to be taken up by plants but also more prone to being leached out of the soil.

Immobilisation is the conversion of a nutrient to an unavailable form through uptake of the microbial population

Glucosinolates are organic compounds found in brassica species. When plant tissue is macerated, glucosinolates are converted into isothiocyanates which are thought to have biocidal properties against pests, pathogens and weeds.