

# **A review of the management of selected perennial weeds**

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## Introduction

Perennial weeds have developed a variety of strategies that enable them to persist, multiply and spread. The different species rely to a greater or lesser extent on both seed and vegetative means to enable them to succeed in both relatively stable and disturbed habitats. Some perennial weeds are a problem in both situations while other cannot cope with disturbance or cannot compete with an established stand of vegetation. Bracken is a problem in grassland but not in cultivated fields. Rushes are also unlikely to be of concern on land that is regularly ploughed. Creeping thistle, common couch, field horsetail and the docks though are serious weeds in both situations. However, even within the docks, the broad-leaved dock will survive longer in permanent grass while the curled dock can be at more of an advantage in disturbed soils.

The vegetative organs of perennial weeds may be located at a considerable depth or may be within the plough layer. This is an important consideration in the application mechanical weed management. The regenerative ability of the weed is also a factor. Couch will only regenerate from pre-formed buds at nodes on rhizome fragments not from the internodes. Docks will regenerate from adventitious buds that develop on root pieces. Creeping thistle will also produce adventitious buds on underground organs. Field horsetail regenerates from the rhizomes and also from tubers.

Plant morphology will determine how competitive the weeds are with the crop. Docks and thistles produce tall leafy, therefore photosynthetically active, flower stems. Bracken forms a dense leaf canopy. Common couch and the rushes appear less competitive but in some situations can form dense patches that exclude other plants. Field horsetail lacks true leaves and does not form a canopy so is less able to compete with a dense crop. Seedlings of all the weeds are more sensitive to competition and cannot succeed in established vegetation. However, seedling docks that emerge in cereals and other arable crops may not mature and set seed but can form a taproot that will survive post-harvest cultivations. The docks can regrow and emerge in a following crop with an advantage over the crop seedlings.

Perennial weeds are thought to increase in organic systems over time. Whether this is the expansion of an existing infestation or the onset of a new weed problem as a result of the changes in weed management that follow the conversion to organic growing methods is not clear. The principal methods of non-chemical control for perennial weeds are cultivation, cutting or grazing and competition. The aim is to prevent seeding and to starve out the perennial organs. Seed production is more important in some species than others but its significance should not be discounted. It is generally thought that reduced cultivations favour perennial weeds. Historically, fallow season tillage has been used to control severe infestations of perennial weeds. Like repeated mowing, it starves the underground organs and prevents seed production. No single method of control and still less a single weeding operation will give adequate control, a sustained approach is needed. Biological control has obvious appeal and has received much attention but it

unlikely to provide reliable control. Natural control such as seed predation that goes on in the background is important in supporting other control measures.

Håkansson (1995) groups perennial weeds into:

#### Stationary perennials

tufted grasses	<i>(Agrostis capillaris)</i>
broad-leaved with short subterranean stems	<i>(Artemisia vulgaris)</i>
Broad-leaved with taproot	<i>(Rumex obtusifolius)</i>
	<i>(Rumex crispus)</i>

#### Creeping perennials

above-ground prostrate shoots or stolons	
subterranean creeping shoots, rhizomes	
sensitive to cultivation	<i>(Juncus spp.)</i>
	<i>(Pteridium aquilinum)</i>
tolerant to cultivation	
shallow	<i>(Elytrigia repens)</i>
deep	<i>(Equisetum arvense)</i>
plagiotropic, thickened roots	
shallow	<i>(Sonchus arvensis)</i>
deep	<i>(Cirsium arvense)</i>

The biology, persistence and management of docks (*Rumex obtusifolius*, *Rumex crispus*), rushes (*Juncus* spp.), bracken (*Pteridium aquilinum*), common couch (*Elytrigia repens*) and creeping thistle (*Cirsium arvense*) are reviewed in the following sections.

### Control of perennial weeds

#### *Tap-rooted* (Docks etc)

Fallowing – Shallow cultivations at regular intervals for a month or so (Bastard) or for the whole summer. But this takes land out of production and is bad for the soil structure. Undercutting the roots by deep rotovation is better than burying the whole plant by ploughing under.

#### *Shallow creeping* (Couch etc)

Cultivations should not be too deep otherwise the vegetative organs are dispersed further and protected from desiccation. Spring tines will bring the weed to the surface to desiccate, or the weed should be chopped up into small pieces. Cultivations need to be repeated when regrowth appears. Stock such as sheep can be put on the land soon after cultivations to feed on the exposed weed.

#### *Deep creeping* (Creeping thistle)

A full fallow is required. Undercutter bars can be useful. Ploughing has a limited effect. Cultivations will force the plants to regrow and reduce their reserves. It is only effective if the regrowth is dealt with by further cultivations or mowing.

There is considerable interest in the enhancement and restoration of floral diversity in grasslands but many of the potentially important management factors used for the control of perennial weeds also influence species diversity. The use of cutting, grazing, fertility balance and pesticide application to reduce weed infestations will also minimise the likelihood of desirable species becoming established. Conversely, the reduced fertility, periodic local soil disturbance and reduced sward density needed to encourage greater species diversity is also likely to encourage invasion by weeds.

### **Chemical weed control**

Controlling perennial weeds usually requires an integrated management approach, combining both cultural and chemical methods to achieve effective long-term results in all farming systems. In general terms the majority of the perennial weeds are not problematic in arable crops due to the rotations and availability of herbicides. Many of these weeds can be a problem in some long term horticultural crops, but these are often controlled by spot treatments. Problems with perennial weeds in grassland tend to be a result of poor stocking management and so the use of chemical control may be a temporary requirement for short-term weed control that then must be integrated with cultural control as a long term approach. The introduction of set-aside schemes in 1988 resulted in an increase in perennial weed species such as docks and creeping thistles and trial results from a number of sites in England and Wales highlighted, along with a competitive ground cover, the need for spray treatments in addition to cutting as a form of weed control (Aquilina and Clarke, 1994).

Selective herbicides are generally the preferred choice for perennial weeds, particularly when control is required in grassland. Product choice and usage in grassland will also be determined by whether it is a new sown ley or established ley with or without clover (Connabeer, 2005).

Herbicide application methods include knapsack sprayers and the more recent weed wick applicators that apply spot treatments. These have the benefits of being targeted to specific species and reducing the environmental impact of spraying by applying more targeted chemical. However, wick applicators can be problematic on uneven ground such as upland grassland areas and when the canopy has varied height differences or there is insufficient height difference between the target weed and remaining vegetation. Tractor mounted sprayers are used on some occasions but are least favoured, as they generally provide a blanket spray and not as selective, however patch spraying techniques are beginning to be used in certain situations. Multiple herbicide applications may be required for total weed control depending on the species and the infestation levels.

The most appropriate herbicide application timing for perennial weeds like couch and thistles is when the plants are actively growing in the spring and summer, so maximum translocation of the herbicides can occur (Kudsk, 2002). There have been a number of issues with herbicides being detected in water, including 2,4-D, MCPA, mecoprop and asulam. Product choice, dose and application timing must all be optimised to prevent any environmental pollution.

## **The biology and control of Bracken (*Pteridium aquilinum* (L.) Kuhn**

### **Occurrence**

Bracken is considered to be the most widespread vascular plant in the world (Hudson, 1987). In the UK it is found on damp soils, meadows and pastures up to 1,920 ft (Salisbury, 1961). In Wales, western and northern England and western Scotland it dominates large areas of land. Unusually for a fern, bracken is a very successful coloniser and is widespread on neutral to acid soils (ADAS, 1980). It is tolerant of a wide range of climatic conditions, is highly disease resistant and releases allelopathic compounds that inhibit the growth of other plants (Hudson, 1987). The vigorous growth and dense foliage shade out other vegetation (Pakeman & Marrs, 1993). In the Countryside Survey 1990, the total area of bracken in Britain was estimated to be 17,000 km<sup>2</sup> (Barr *et al.*, 1994). Of this, 28% was dense bracken on open land, 25% was scattered bracken on open land and 47% was bracken in woodland. The data indicated there had been a decrease of about 10% in the dense area of bracken between 1984 and 1990.

Originally a lowland and woodland plant bracken now infests many upland areas and has done so for over 150 years (Watt, 1954). In the 1800's sheep replaced cattle on much of the rough grazing, scattered rural populations were dispossessed and bracken fronds were no longer made use of (Fenton, 1937). Bracken is often present in oakwoods on light non-calcareous soils (Tansley, 1949a). It was probably never more than a minor component of the woodland flora (Daniels, 1986). In woodland and in controlled conditions of shade, bracken plants have fewer fronds that are thinner and with a greater surface than those in the open. Deep shade restricts the vegetative spread but even under moderate shade it can become dominant. Bracken is less invasive when growing in woodland but following tree clearance the increased light level stimulates luxurious growth. The thick litter of fronds built up under bracken in then prevents woodland regeneration.

Bracken is normally found on acid soils and is uncommon on calcareous land. It prefers well-drained sites as the young rhizomes cannot stand waterlogging and stops abruptly at the edge of marshy ground. Improved drainage on hill land has allowed bracken to colonize formerly wet sites. A dense litter builds up under bracken that prevents most other vegetation becoming established and may even affect the bracken itself if the litter layer is too deep (Grime *et al.*, 1988). Bracken does not normally spread rapidly into heathland perhaps due to the compacted peat soil (Tansley, 1949b). However, where the soil is loose or disturbed the bracken will advance and out-compete the heathers. Bracken has spread into bent-fescue grassland severely reducing the grazing value (Tansley, 1949b).

Bracken is better protected from fire than most other species on moorland but it will not survive where late spring frosts regularly kill off the emerging fronds. The litter of dead fronds provides some protection against frost but the upper limit for bracken growth on hills is determined by the effect of frost and wind on the fronds. It does not succeed on exposed slopes due to wind damage. In coastal areas bracken fronds suffer salt damage during gales and this may lead to rotting of the rhizomes (Gillham, 1955).

Bracken is a very variable plant and is often divided into separate species, subspecies and varieties (Stace, 1997). There are reported to be 12 geographic varieties, ssp. *aquilinum* has eight of these and ssp. *caudatum* has four (Mitich, 1999). Plants within patches usually consist of several genetically distinct individuals (Pakeman & Marrs, 1993).

Bracken is poisonous to stock, the fronds being most toxic at the newly emerged 'crozier' stage (ADAS, 1983). The fronds become less toxic with age but fronds cut for animal bedding should have died back entirely. Bracken remains poisonous if cut green, dried and stacked (Forsyth, 1968). Fronds cut and cured with hay have caused poisoning in horses in winter when hay was the sole feed (Huffman & Couch, 1943). The rhizomes are also poisonous and are a potential hazard to pigs that may uproot them and to cattle when ploughing exposes the rhizomes. Bracken causes ulceration and blood loss in cattle, bright-blindness in sheep and a vitamin deficiency that in horses leads to 'staggers' (ADAS, 1980). Bracken is implicated as a human health hazard due to its suspected carcinogenic spores. It also provides a habitat favoured by sheep ticks that transmit Lyme disease. It has been considered of little conservation value in terms of wildlife because fewer birds breed in bracken and the abundance of invertebrates is lower (Hudson, 1987). However, there are associations between bracken growing with violets and some fritillary butterflies (Pakeman *et al.*, 2005). It is also the preferred habitat of the whinchat and nightjar. Glands at the base of the pinnae exude a substance attractive to ants (Mitich, 1999).

In the past, bracken was used for animal bedding and as a source of potash for glassmaking (Pakeman & Marrs, 1993). It has even been used to make a rather unpalatable silage and as a covering for potato clamps (Willis, 1954). Bracken that has been utilized for animal bedding can be used to produce FYM. The fronds themselves make a good compost of low pH that improves soil texture (MAFF, 1949). A mixture of bracken fronds, sheep's wool and manure has been composted to produce potting compost. Fronds are also a potential biofuel and the plant ash has a high pH and is rich in potash and other beneficial minerals (Donnelly *et al.*, 2002; Donnelly *et al.*, 2006; Davies, 2006). There have been suggestions that bracken could be harvested as a renewable energy source (Callaghan *et al.*, 1984; Hudson, 1987). A mulch of bracken fronds may have an allelopathic effect on the germination and growth of weeds. Extracts of bracken are thought to have anti-fungal and insect repellent properties and to kill aphids (Donnelly *et al.*, 2002). Bracken contains flavanoids that have antibiotic properties, and ecdysones that may have potential for insect deterrence.

### **Biology**

Bracken is a perennial with an extensively branched rhizome system that constitutes a formidable reserve of growth potential (Pakeman & Marrs, 1993). There are two types of rhizome, long thick storage organs that branch and run deep underground but produce no fronds and short thinner, shallower rhizomes on each of which a single frond is borne each growing season. A dormant bud at the base of each frond gives the plant a potential replacement set of fronds (Mitich, 1999). On deep soils the rhizomes may extend to a depth of more than a metre. Elsewhere, a high proportion may be found in the top 23 cm

of soil. Extension rhizomes that advance ahead of the main patch may grow one or more metres in a year (ADAS, 1980). Rhizomes grow particularly strongly in the autumn when large numbers of frond buds are initiated (Cody & Crompton, 1975).

Fronde generally emerge in May and arise singly from short lateral branches of the rhizome (ADAS, 1980). Fronds that develop early in the main flush of emergence become the fertile fronds. Those that expand later seldom develop mature sporangia. Spores ripen from July to August and are shed from August to October (Clapham *et al.*, 1987; Grime *et al.*, 1988). Bracken has relatively small spores for a fern (Conway, 1957). In optimum conditions spore output can be extremely high. It has been estimated that a single frond can produce 30 million spores. However, fertile frond numbers and hence spore production can vary from habitat to habitat, area to area and year to year. Fertility is reduced by shade in woodland habitats for example. Plants need to reach 3 to 4 years of age before fertile fronds are produced. Prior to this, most of the resources go into rhizome development. Periodic defoliation can limit spore production. Early defoliation in May has a limited effect but if this is repeated in June, fertile fronds are reduced by 85%. A further defoliation in July will eliminate them completely. Late frosts can destroy emerging fronds while wet conditions in August and September prevent spore dispersal. Any delay in dispersal may not allow spores time to germinate and establish young sporophytes before the winter.

Under controlled conditions, bracken spores readily develop but the sexual phase of reproduction is delicate and requires the right amount of moisture (Salisbury, 1962). Sporeling plants have been found in cracks and crevices in rocks and brickwork (Conway, 1953). A large number of prothalli and young sporelings were found in the rubble heaps of bomb damaged towns 1943-45. The prothalli often suffer fungal damage and the bomb-sites may have provided disease-free sites. The prothalli and sporelings are susceptible to prolonged periods of frost.

Spores are likely to fall on agricultural soil with a high level of mineral nutrients. Nitrogen, potassium, phosphorous and calcium have been shown to be important in the establishment of young bracken plants (Conway & Stevens, 1957). In studies on agar and a sand/peat compost increased levels of the different nutrients tended to slow spore germination but at later growth stages nitrogen and potassium stimulated development. When sporelings with 4-5 fronds unfurling were transferred to garden beds the addition of lime, potash, phosphate and nitrogen fertilizer all increased the growth of the young bracken plants. Nitrogen in the form of ammonium salts had a greater effect than nitrates. Higher mineral nutrition markedly increased frond initiation, secondary shoot numbers and the production of a network of branched rhizomes. There was a greater incidence of dormant stem apices at the end of the growing season that could potentially increase the ability of plants to survive extreme cold. The plant can control this itself to some extent by the disruption of the soil caused by rhizome growth.

A large number of rhizome buds occur per unit area on a favourable soil (Watt, 1950). Frond differentiation takes place mainly in summer but only a proportion of the buds become new fronds. The same shoots do not differentiate new fronds every year and

some may remain dormant for several years. Not all the differentiated fronds emerge and the developed fronds are just a fraction of the potential fronds. New fronds can differentiate while a current frond is intact but if the current frond is killed or injured by frost or mechanical damage the new frond grows faster. The older rhizomes at the centre of an infestation are nearer the soil surface because of the litter layer that builds up under the fronds than the newer rhizomes around the edge (Watt, 1954). However, the apices of the advancing rhizomes around the margins are more susceptible to frost because the litter layer is thinner and there is less frost protection. Also the soil warms up sooner without the insulating layer of litter and the fronds emerge earlier in the year. These fronds of deeper origin are longer than those of shallower origin and in March the apices are nearer the soil surface and more susceptible to frost (Watt, 1950). Depending on the severity of the winter, apices at depths of 1.9 to 7.1 cm may be killed. A severe winter frost can kill a high proportion of fronds and rhizome apices near the soil surface unless a blanket of snow is present to protect the bracken. Severe winter frosts kill the apices of the rhizomes whereas hard spring frosts damage the emergent fronds. Dormant buds soon replace the damaged fronds (Salisbury, 1962).

Young plants produce a relatively higher number of foliar organs than older plants whose whole rate of growth slows down as the plant matures (Conway & Stephens, 1957). Three phases of bracken growth are recognised; a pioneer phase, a mature stage and a degenerate phase (Anderson, 1961). The length of the frond bearing rhizomes decreases as plants behind the leading edge of the patch reach maturity.

### **Persistence and Spread**

Spores are probably only important in colonizing new sites. Spores may persist in the soil and can remain viable for up to 10 years (Grime *et al.*, 1988). However, culture studies on agar and in soil, and short-term burial studies suggest that there is considerable predation of the spores by insects (Conway, 1953). The development of new plants from spores requires constant moisture and freedom from frost, conditions that less likely to be met outside of woodland. Spores are not therefore a major source of spread in grassland (ADAS, 1980). However, in a rich soil a young plant could develop very rapidly (Conway & Stephens, 1957).

Woodland clearance begun in prehistoric times and continued to the present day has contributed to the spread of bracken (Hudson, 1987). The increased incidence of burning and higher grazing pressure has prevented tree regeneration allowing bracken to invade the disturbed areas. In competition with gorse (*Ulex europaeus*) and other scrub vegetation, bracken is favoured by burning (Salisbury, 1929). Heavy grazing reduces the competitive ability of palatable grasses allowing bracken to spread further and putting greater grazing pressure on the remaining grassed areas. A fall in the management of uplands and reduced use of bracken foliage for stock bedding has allowed expansion to continue unchecked.

At all localities in Britain where the rate of encroachment has been monitored, bracken is spreading not receding (Hudson, 1987). The overall rate of encroachment has been estimated as 2.8% per annum. However there is not a constant advance and sometimes

the margins may retreat (Watt, 1954). After severe winter frosts that kill the main rhizome apices, there may be a substantial check to the rate of advance. Biochemical tests used to determine the extent of individual plants of bracken have indicated a maximum dimension of 390 m (Sheffield *et al.*, 1989). This may signify plants of considerable antiquity. Individual rhizomes have a limited lifespan of just a few years but the rhizome system is persistent (Pakeman & Marrs, 1993). Individual clones of bracken in Finland have been dated back to the middle of the Iron Age (Sarukhán, 1974).

Separate plants may arise where there is fragmentation of rhizomes due to rotting or mechanical damage (Cody & Crompton, 1975). In pot culture, the capacity for regeneration appears to be unaffected by the type of rhizome planted and the presence or absence of apical buds (Daniels, 1985).

### **Management**

Bruising the unfurling bracken fronds with a 'bracken bruiser' is one control technique (Soil Association 2002). The damage causes the stems to bleed and this weakens them. It is best carried out after late May, preferably in late June/early July but before August. Crushing with a roller twice a year for 3 years is also said to be successful. The 'Bracken o'Bliterator' fits onto an ATV and is a simple heavy roller fitted with 10 crushing bars. The standard machine has a working width of 1.5 m but larger versions are available. A bracken roller can be towed by tractor, quad bike or horse. In the past it was thought that the sap trickling from the damaged fronds killed the roots (Smith & Secoy, 1975). Care should be taken to avoid harm to late-nesting birds in July.

Pulling of bracken is effective but is little used. The 'Eco-puller' has been developed to mechanically remove perennial weeds such as common ragwort (*Senecio jacobaea*) and creeping thistle (*Cirsium arvense*) from grassland (Soil Association, 2002). It has a working width of 1.5m and a ground speed of 5 kph at 540 rpm. The weed gripping height is adjustable but weeds should be at least 30 cm tall. It can be used in bracken once the croziers lose brittleness and before the fronds open fully.

Cutting is less effective than crushing because the cut surfaces heal more rapidly. A range of different cutting dates and frequencies has been suggested. According to early publications of good husbandry it was thought best to cut bracken at all times of the year (Mitich, 1999). For best results cutting should commence in early June/mid-July with a second cut in late July/August after fronds regrow and a final cut in September before the frosts (Crofts & Jefferson, 1999). The timings should aim to cut the bracken at 4 to 6-week intervals through the growing season. Nevertheless, cutting the fronds before August is the most common form of control in organic systems (Donnelly, 2004). Cutting should be done twice each year in late May and early August. Up to the time when the bracken reaches full height but before the fronds fully unfurl, the plant is nourished by food reserves in the rhizomes. Cutting at this time exhausts the reserves and repeated cutting in successive years weakens the plant progressively (MAFF, 1949). Bracken reaches the most vulnerable stage around the beginning of June. A second cut should be made in mid-July or as soon as the fronds are sufficiently high to make cutting practicable (Willis, 1954). Cutting twice each year should be repeated for at least three

years but complete clearance may take seven years. A third cut each year reduces the time taken to clear an area but may not be feasible to carry out. Morse & Palmer (1925) suggest cutting at monthly intervals from June to September. A dressing of lime is said to be beneficial after cutting. Cutting and slashing machines are equally effective initially but bruising machines are less so on the smaller fronds. All the machines have some difficulty reaching the fronds as the bracken regrowth becomes shorter.

In an experiment to study the effect of frond removal, bracken plants were cut in late-May or late-May and late-June, or late-May and late-June and late-July but after the first year there was no difference in bracken growth compared with uncut plants (Stephens, 1953). After 3 years of treatment, frond number and height were reduced and the effect increased with cutting frequency. However, there was little extra advantage in making 3 cuts compared with 2. The number of rhizome tips remaining alive was lower after cutting and a higher proportion were non-dormant. Dormant rhizomes are more likely to survive cutting treatments because their reserves remain intact.

In a 3-year study of bracken management across a range of climatic zones in Great Britain, while some treatments gave a consistent effect at all sites others did not (Paterson *et al.*, 1997b). Treatments included cutting once a year, cutting twice a year, and applying asulam once at 4.4 kg a.i./ha alone, preceded by a single cut or followed by a single cut of the bracken. The bracken was cut with a brushcutter and the fronds left where they fell. Cutting once yearly was the least effective management regime and the one that exhibited the greatest variation between sites. A single application of asulam had the greatest effect on frond biomass and density but cutting twice a year reduced rhizome biomass more. It was concluded that the choice of treatment should depend on the management objective and the option for treatment continuity.

FronD treatments will affect bracken cover in the current season but it is the effect on frond development in future years that is important (Conway, 1960). In a study of the effectiveness of cutting over a ten-year period, cutting once annually reduced bracken fronds by 70%, cutting twice reduced them by over 90% but did not eradicate them completely (Lowday & Marrs, 1992a). The fronds were cut in mid June and late July when cut twice, and in July if cut just once. Establishing a good vegetation cover helped to suppress any regrowth but a sown cover was better than relying on natural regeneration. Extrapolation of the results suggested that cutting for a further 8-10 years would be needed to eradicate bracken completely (Marrs *et al.*, 1993). If cutting ceased before eradication, the bracken gradually recovered. The above ground frond biomass was closely related to the rhizome biomass. Cutting back the bracken fronds twice a year for 10 years reduced the frond bearing rhizomes to 2-4% and storage rhizomes to 8-11% of the untreated (Marrs *et al.*, 1992). The treatment also reduced the litter layer. Cutting once a year was less effective. Where the cutting treatments ceased after 6 years the rhizomes exhibited considerable recovery.

With an annual cutting treatment, the biomass of bracken fronds has been found to increase relative to an untreated area in the year following the initial cutting treatment (Marrs *et al.*, 1998a). However, in subsequent years there was a gradual reduction.

Cutting bracken once a year for 18 years reduced frond biomass to 6% of untreated levels. Seeding with heather (*Calluna vulgaris*) had no consistent effect on the level of bracken control but there was a clear negative relationship between the biomass of bracken fronds and that of understorey heath vegetation. Where annual cutting ceased after 6 years frond biomass recovered rapidly to untreated levels after 4 years. The effect of cutting twice a year for 6 years persisted after treatment ceased and frond biomass remained depressed for at least 12 years. Although cutting twice a year was superior to a single annual cut when both treatments were applied continuously for 10-12 years, after 18 years the single cut was superior (Marrs *et al.* 1998b). Neither cutting treatment eradicated bracken completely after 18 years of application. After a continuous period of treatment the bracken seems to reach a new equilibrium at a lower level of biomass production. Cutting frequently, each time the fronds regrow, may diminish the plant more but is very labour intensive (Tansley, 1949b).

Ploughing in May, June or early July gives good control of bracken especially if crops such as potato, rape, turnip or oats are then grown (MAFF, 1949; ADAS, 1980). Cultivation in two successive years will eradicate bracken. If sown down immediately to grass there may be regrowth especially after winter ploughing when the rhizomes are dormant. Ploughing exposes the rhizomes to frost action that may give additional kill (The Southern Uplands Partnership, 2001). Cutting the fronds before ploughing stresses the rhizomes (Crofts & Jefferson, 1999). Ploughing in very hot weather increases the damage to the exposed shoots and rhizomes. Deep tine cultivations in 2 directions can give a measure of control without ploughing (Pakeman *et al.*, 2005). Regular cutting or further tillage will be required to prevent re-establishment.

The rhizomes may suffer greater frost damage if the protective litter layer is removed (Donnelly, 2004). However, burning off the litter puts valuable nutrients back into the soil and promotes subsequent bracken growth. The application of NPK fertilizers has been shown to give a general increase in frond numbers and rhizome extension (Daniels, 1986). On steep slopes where there is little underlying vegetation, burning off the bracken may result in soil erosion (The Southern Uplands Partnership, 2001). Deep tine cultivations will cause mechanical damage to the rhizomes and increase their exposure to frost or desiccation.

In the dormant season and during early frond growth restricted areas of bracken have been cleared through trampling by sheep or cattle (ADAS, 1983). This destroys the young shoots as they unfurl which together with the destruction of the litter layer tends to reduce subsequent bracken growth. Cattle have a greater effect than sheep (Popay & Field, 1996). Winter feed can be used to attract stock onto the bracken area (Pakeman *et al.*, 2005). Poultry in moveable runs can be effective too. In Scotland studies are underway using wild boar to clear bracken and allow tree plantations to be established. Pigs can also be turned out onto land that has been ploughed to expose the rhizomes (Salisbury, 1961). In grassed areas with a deep soil, rooting out by pigs works well on small patches but stirs up the soil. An alternative food source needs to be available to avoid the animals eating only bracken (Willis, 1954). Grazing by sheep favours bracken and is thought by some to be responsible for the widespread increase in the weed

(Tansley, 1949a). Although bracken is rarely grazed there may sometimes be damage (Fenton, 1940). Rabbit activity was greater where cutting treatments had been applied (Marrs *et al.*, 1998c).

It has been said that when bracken takes over grassland it may be best to just re-establish forest (Tansley, 1949b). The large-scale clearance of bracken on hill pasture is unrealistic without measures to improve the husbandry techniques that have allowed the problem to exist (Nicholson, 1960). In cleared areas, species that can cover the ground quickly and prevent the bracken returning need to be present already or sown soon after clearance. Cock's-foot (*Dactylis glomerata*) and creeping softgrass (*Holcus mollis*) are two of the best grasses for this (Williams, 1976). The choice of species for reinstatement of the vegetation during and after bracken clearance depends on the situation (The Southern Uplands Partnership, 2001). The land may be seeded down to heather, to grass or woodland may be established from tree seedlings or saplings. Grazing will need to be restricted for several years to allow the vegetation to establish successfully. In uplands, mixed cattle and sheep grazing is said to encourage heather growth. Where heather and bracken patches occur adjacent to each other, either may advance into and replace the other (Watt, 1955). The balance of dominance depends on the growth phase of the heather and whether it has suffered damage from cutting, burning or rabbits. Bracken tends to advance on a continuous front while the heather infiltrates and develops behind the leading edge of the bracken where frond growth is less vigorous.

The litter layer limits the restoration of a heathland even when the bracken fronds are cut back or killed. Where bracken had been killed by applications of the herbicide asulam a number of different methods of litter reduction were compared on land that was seeded with locally collected seeds or left unsown (Lowday & Marrs, 1992b). The treatments included rotovating the litter into the mineral layer, burning the litter in situ or raking off the litter and removing it. All the treatments allowed faster restoration by sown species. Complete removal of the litter layer was best where the site was recolonized with heather (*Calluna*). Increased rain penetration and higher nutrient levels after bracken clearance can encourage colonization by unwelcome species. On a sown *Calluna* heath in Breckland over a 10 year period two clonal species, sand sedge (*Carex arenaria*) and wood small-sedge (*Calamagrostis epigejos*), invaded in large patches where vegetation cover was poor (Marrs & Lowday, 1992). In a grass heath, the sown sheep's-fescue (*Festuca ovina*) became co-dominant with wavy hair-grass (*Deschampsia flexuosa*) which colonized naturally.

In long term studies on unmanaged heathland, there is a cycle where bracken invades grass heath, increases in density and then degrades to leave grass heath again (Marrs & Hicks, 1986). The bracken does not die out completely and may increase again at a later date. The bracken degeneration could be the result of a build up of frond litter. Bracken management may stimulate regeneration as cutting will reduce the litter layer and also stimulates the production of new frond buds on the rhizomes.

A bracken growth model (BRACON) has been developed to predict bracken stand dynamics in relation to cutting and other control regimes (Paterson *et al.*, 1997). The

model provides a reasonable description of rhizome dynamics for individual treatments but tends to underestimate bracken resilience. However, the effect of climate fluctuations on frond biomass can distort the accuracy of any predictions. There are also effects due to the slope and aspect of a site that can limit the accuracy of any long-term predictions without further improvement of the model (Pottier *et al.*, 2005).

A review of the literature in 1967 gave an indication of the number of insect species known to attack bracken in Europe (Simmonds, 1967). The prospects for biological control of bracken with insects and mycoherbicides were later discussed by Burge *et al.*, 1988. Biological control has been tried with the caterpillars of two South African moths (*Conservula cinisigma* and *Panotima* sp.) (Fowler *et al.*, 1989) but with little success (Pakeman & Marrs, 1993). The use of mycoherbicides has also been investigated (Munyaradzi *et al.*, 1990). The fungal pathogens *Ascochyta pteridis* and *Phoma aquiline* cause curl-tip disease of bracken. Trial results so far indicate a need for adjuvants to ensure adequate uptake of the inoculum.

Where the fronds are cut as a crop, September onwards is the time for cutting if reserves in the rhizomes are not to be depleted (Donnelly, 2004). The fronds can be baled for storage. Cutting for animal bedding does little to reduce plant vigour as the fronds are dry when harvested (Tansley, 1949b).

### **Chemical control**

The chemical control of bracken can be very effective (> 90%), but a long term management plan needs to be implemented to ensure any necessary follow-up treatments are carried out (Pakeman *et al.*, 2005).

The two herbicides recommended for bracken control are:-

- **Asulam** (various products including Asulox, Spitfire, Greencrop Frond)  
This is a selective herbicide which is therefore appropriate for use in areas of less dense bracken with other surrounding vegetation. Asulam is approved for aerial applications which may be required for very large or inaccessible areas. Application should occur after full frond expansion, but before tip die-back, allowing maximum absorption to the underground rhizomes.  
The re-growth of bracken post-spray has been found to be related to the number of fronds per m<sup>2</sup> prior to herbicide application and the survival of any live rhizome (Lee *et al.*, 1982).
- **Glyphosate** – commonly used in wick applicators (1:1 dilution with water) or knapsack sprayers as spot treatments. A cheaper alternative to asulam. Timing of application is the same as asulam. Glyphosate has the disadvantage of being non-selective, so is most suited to very dense bracken areas where there is very little surrounding vegetation.

## **Discussion**

There is such a vast body of literature on bracken and it is beyond the scope of this review to collate more than a proportion of this. In particular, the present review has concentrated on the extensive literature that deals with the biology and control of bracken and the factors that determine its success as an invasive plant. The RDS technical advice note (Pakeman *et al.*, 2005) summarised the findings of UK research, much of it funded by Defra. It provides guidance on the available mechanical and chemical methods of control and the options for restoring the vegetation during and after bracken clearance.

Much of the literature is concerned with the control of bracken and there is much less emphasis on the prevention of an infestation arising. There is anecdotal evidence that bracken increased due to changes in land use. Intensive sheep grazing is one of the factors credited with providing the conditions that bracken requires. There may be some merit in determining whether there are aspects of current land management that could be modified to make invasion less likely.

Bracken produces spores not seeds and sexual reproduction occurs only under a narrow range of conditions. Vegetative spread is therefore of greater importance in established stands. Nevertheless there have been examples of bracken plants developing in isolation and sexual reproduction may be a source of new infestations under some conditions. It is unlikely that this could be investigated over a 3 year study period.

Direct mechanical control of bracken is mainly by cutting or crushing the fronds. The frequency and the timing of defoliation or bruising to attain optimum control have been determined and the likely duration of treatment needed to achieve success. While pulling is considered as an alternative method of mechanical control and commercial equipment is available, there has been little evaluation of its efficacy compared with the other methods. With all the direct treatments, control is not complete and the persistence of effect is limited. Livestock, in particular cattle, can provide a measure of control from the damage caused by treading. Pigs have also been used to root out the rhizomes. Classical biological control has been investigated but attempts to achieve control in the field have not been successful.

Bracken is not a problem on land that is cultivated regularly. Faster control of bracken on pasture can be achieved where the area can be ploughed and cropped for a year or two before being put back to grass. Reseeding immediately after cultivation can result in regeneration and re-establishment of the bracken from surviving rhizome fragments. However, ploughing is not an option on many problem areas. Shallower cultivations may prove equally effective and not require the pulling power of a large tractor.

It is acknowledged that bracken control requires a long-term strategy and an ongoing management plan to avoid re-invasion. The importance of restoring the original or a desirable alternative vegetation cover is recognized. The removal of bracken litter has been shown to hasten this. Burning of the litter may aid reseedling but can have adverse

effects. The restoration of the vegetation cover can limit the use of herbicides to clear bracken.

There is renewed interest in the uses that can be made of bracken it may prove of benefit to determine the conditions under which bracken makes the optimum frond growth and how to maintain plant vigour. Such information could also assist with bracken control by identifying the conditions to avoid.

## **The biology and control of common couch** **(*Elytrigia repens* (L.) Nevski)**

### **Occurrence**

Common couch is a native perennial grass found throughout the British Isles on cultivated, waste and rough ground (Clapham *et al.*, 1987; Stace, 1997). It grows on most soil types except those with a low pH but prefers heavier soils. However, while common couch occurs on both heavy and light soils (Brenchley 1911; 1913), it is able to spread more readily on lighter land (Salisbury, 1962). Common couch has a preference for fine, stone-free soils low in organic matter of pH 6.5 to 7.8 (Dale *et al.*, 1965).

Common couch thrives in cooler climates and is one of the most serious weeds in the Northern temperate zone but it is absent from the tropics (Palmer & Sagar, 1963). As a C<sub>3</sub> plant, in terms of photosynthetic pathways, couch is not well adapted to hot dry climates (Håkansson, 2003). At higher temperatures biomass production is lowered and the allocation of photosynthates to the underground organs decreases. Rhizome production is reduced, limiting the plants invasiveness. In South America and other warm countries, it may be found growing in cooler mountain regions (Holm *et al.*, 1977). The aerial shoots do not appear to be harmed by freezing but a few days exposure to frost is said to kill rhizomes left on the soil surface (Håkansson, 2003). However, when the freezing resistance of overwintering rhizome buds of common couch was evaluated in the laboratory the temperature required to reduce survival by 50% was colder than -20°C. (Schimming & Messersmith, 1988).

When the distribution of common couch was mapped using botanical survey and soil survey data, the occurrence was closely correlated with the distribution of arable land (Firbank *et al.*, 1998). Common couch populations are often concentrated in the hedge bottoms and in field margins (Marshall, 1985). The weed then spreads out from the field margins into cultivated fields. In a 3-year set-aside, common couch frequency exhibited some decline with increasing distance from the field edge but distribution was patchy (Rew *et al.*, 1992). In a survey of UK cereal field margins recorded as part of Countryside 2000, common couch was the third most frequent species recorded (Firbank *et al.*, 2002). In a comparison of the ranking of arable weed species in unsprayed crop edges in the Netherlands in 1956 and in 1993, common couch remained in 6<sup>th</sup> place (Joenje & Kleijn, 1994).

In a survey of conventional cereal crops in central southern England in 1982 couch was the most frequent grass weed (Chancellor & Froud-Williams, 1984). It remained widespread between 1978 and 1990 despite increased herbicide use (Firbank, 1999). In the UK, common couch was considered to be more abundant in the 1990's than it had been in the 1960's (Marshall *et al.*, 2003). In Finland too there was an increase in the frequency of common couch in conventional spring cereals in the period 1980 to 1990 (Hyvönen *et al.*, 2003). This may reflect a change in the rate or type of herbicides used. However, in Denmark, a comparison of weed surveys made in spring barley in 1970 and 1989 showed that there had been a dramatic decrease in common couch frequency due to the extensive herbicide use (Streibig *et al.*, 1993). In a series of 4 national weed surveys

made in Hungary between 1950 and 1997, common couch moved from 27<sup>th</sup> to 12<sup>th</sup> place in the rankings (Tóth *et al.*, 1999; 1997). In a survey to identify the main weed species causing problems in organic farming in the new EU member states and the acceding countries, common couch was the main problem grass weed identified (Glemnitz *et al.*, 2007).

In a study of seedbanks in some arable soils in the English midlands sampled in 1972-3, common couch was recorded in 50% of fields sampled in Oxfordshire and 6% in Warwickshire but the seeds were never abundant (Roberts & Chancellor, 1986). Couch seed was found in less than 1% of arable soils in a seedbank survey in Scotland in 1972-1978 (Warwick, 1984). In a survey of seeds in pasture soils in the Netherlands in 1966, while common couch was frequent in the sward it was not represented in the soil seedbank (Van Altena & Minderhoud, 1972). In other studies comparing weed vegetation with the weed seedbank, while common couch was well represented in the vegetation it was absent from the soil seedbank (Hill *et al.*, 1989).

Common couch can form dense stands that exclude other vegetation (Weber, 2003). However, it is not resistant to treading and does not persist on well-used paths across grassed areas (Bates, 1935). Couch growth is especially vigorous on fallow land and in the first few years after tillage ceases (Werner & Rioux, 1977). It may make up to 90% of the biomass in an abandoned field for several years preventing colonization by dicotyledonous species. Couch is sensitive to shading, however, and when scrub take over the grass gradually dies out. In set-aside land in Scotland, perennial grasses in general and common couch in particular made up a significant proportion of the vegetation after the first 2 years (Fisher *et al.*, 1992). Old permanent pastures tend to have little couch present (Long, 1938). Nevertheless, Peel and Hopkins (1980) found that infestations were as common in swards over 20 years old as in recently sown swards. In a survey of 502 grassland farms, couch was found to affect 1% of all fields but was more common in eastern England where 10% of fields were infested. It was recorded more often on dairy farms than beef farms.

Common couch like other grasses is an alternative hosts for the frit and gout flies (Morse & Palmer, 1925). It is a carrier of take-all disease of cereals, *Ophiobolus graminis*, the disease being present in the rhizome internodes (Hughes, 1966; Moore & Thurston, 1970). It can also be infected with several other fungal diseases that affect cereals including ergot (*Claviceps purpurea*), barley leaf blotch (*Rhynchosporium secalis*) and cereal wilt (*Cephalosporium gramineum*) (Thurston, 1970; Moore & Thurston, 1970). Common couch growing in barley may harbour a species of root lesion nematode (*Pratylenchus* spp.) that also attacks the crop (Franklin, 1970).

Reviews of common couch have been made previously by Palmer & Sagar (1963), Holm *et al.* (1977), Werner & Rioux (1977) and Boyall *et al.* (1981).

### **Biology**

Common couch requires a minimum temperature of 23°C for flowering. Aerial shoots initiate flowers during April or early May that open in May, June or July. The flowering

period extends from June to September (MAFF, 1974; Clapham *et al.*, 1987). Couch is self-sterile which could be problematic where a patch consists of a single clone but as the flowers are wind pollinated, fertilisation is not necessarily impeded (Werner & Rioux, 1977). A high level of seed production has been recorded (Sagar, 1960).

The seed heads mature during August and September at the time of cereal harvest. Many seeds are viable when green and immature (Williams, 1971a). Twenty percent of the final number of mature seeds may be viable 10-18 days after flowering depending on prevailing conditions. Viable seeds were found in 95% of flower spikes of couch collected shortly before cereal harvest (Williams & Attwood, 1971). Plants may produce up to 400 seeds per flower stem but 25-40 seeds is more usual of which on average 13 are viable. Seed collected within 3 weeks of the flowering date showed much less germination than those collected later. The percentage germination increased the later the date of sampling. There was a 1% increase for each additional day after 15<sup>th</sup> July.

Common couch seed does not require an after-ripening period and can germinate anytime after shedding if conditions are right. Laboratory studies suggest that diurnal fluctuations in temperature with an amplitude of 4°C promote germination in the light (Thompson *et al.*, 1977). Light is of less importance but for germination to occur, fresh seed requires the temperature to alternate between 15 and 25°C. Seed will not germinate under constant temperatures (Palmer & Sagar, 1963). Although seeds appear indifferent to light, when seeds were put to germinate under a leaf canopy or in diffuse white light there was just 4% germination under the canopy and 90% in the light (Górski *et al.*, 1977). Couch seeds germinate mainly during autumn in the UK but germination can be delayed by cold temperatures, inadequate moisture or deep burial (Williams, 1971a). Seeds buried 5 cm deep in soil germinated and emerged completely but only 4% of seed buried at 10 cm deep emerged and none from depths of 12.5 or 15 cm. In greenhouse studies germination of seeds on the soil surface was significantly less than from 1-2 cm deep (Boyd & Van Acker, 2003).

In Sweden, studies of common couch seeds mixed with soil in the autumn, put in frames in the field, exhumed at intervals and put to germinate at alternating temperatures showed the seeds to have the lowest dormancy and greatest tendency to germinate from April to May (Håkansson, 1979). The seeds exhibited little dormancy under any conditions. Many seedlings emerged in the autumn after sowing, and most of the remaining seeds germinated in the following spring.

According to Werner & Rioux (1977), germination normally occurs in early spring which is true in many countries including Sweden and Russia. The seedlings begin to tiller at the 4-6 leaf stage and produce rhizomes at the 6-8 leaf stage. Håkansson (1970a), however, found that seedlings began to develop rhizomes at the 4-5 leaf stage in mid- to late-June. Subsequent development of plants from seed was similar to that of plants growing from rhizome pieces (Håkansson, 1967). The young seedlings are unable to regenerate vegetatively until rhizomes several centimetres long have developed. Large variations occur in the growth and morphology of seedlings from seeds collected in different areas even when grown under relatively uniform conditions (Williams, 1973a).

Variation between seedlings and clones in the number of shoots per plant was very great. It was noted that plants with the least shoot weight had the most rhizomes.

Vegetative reproduction in common couch is far more important than from seed but like the seeds, rhizome pieces from different clones demonstrate differences in growth physiology under similar conditions (Pooswang *et al.*, 1972). The depth at which the majority of rhizome buds develop in the soil can also differ between clones (Mortimer & McMahon, 1982). In some, the majority of buds occur in the top 10 cm of the soil profile while in others most buds are in the 10 to 20 cm layer. Some buds are found below 20 cm deep but not below 40 cm. In compacted soil, the rhizomes grow more or less horizontally. The rhizomes are very shallow where infested land has been down to grass for many years (Frankton & Mulligan, 1970). In undisturbed arable land a mat of young rhizomes is found in the top 10 cm of soil at the end of the growing season. In uncultivated land with a layer of deep litter the rhizomes may grow above the soil surface under the litter. In pasture, couch has short rhizomes and apical dominance maintains buds in a dormant state. In loose soils the rhizomes grow down at an angle of 5-10° to the horizontal and may reach depths of 40 cm (Palmer & Sagar, 1963).

Rhizome growth is renewed annually from axillary buds that develop in the crown tissue at the base of the aerial shoots, and in the transition zone between shoot and rhizome (Håkansson, 1982). Rhizomes grow horizontally beneath the soil in late spring and summer before turning erect in autumn ready to form a primary aerial shoots that survive the winter. At this time, the aerial shoots of the parent plant die. The new shoots develop tillers and rhizomes in spring (Sagar, 1960). The same transformation occurs anytime that the parent plant or rhizome is disturbed by cultivation (Palmer & Sagar, 1963). Aerial shoots that develop in spring die in autumn or early winter (Werner & Rioux, 1977). Shoots that develop later in the season may survive the winter to a greater or lesser extent (Håkansson, 1982).

At first the rudimentary aerial shoot has only a few transitional leaves and one small shoot leaf (Palmer, 1958). The primary shoot emerges during the autumn, grows slowly over-winter and by spring has 2-3 mature aerial leaves. Once the soil temperature consistently exceeds 0°C new roots and primary aerial shoots begin to grow (Håkansson, 1982). In late March or early April active growth begins, new leaves are produced in rapid succession and the stem quickly elongates. The dormant buds at the base of each shoot grow out to form either upright tillers that resemble the aerial shoot or horizontal rhizomes. In a closed community each primary shoot typically produces three tillers and 3-4 rhizomes. In an open or disturbed community the primary shoots produce a tuft of tillers and develop abundant rhizomes. The rhizomes themselves form numerous lateral rhizomes in July. A plant may produce 150 rhizomes in the first growing season. The rhizomes generally reach lengths of 50 cm before the tips turn erect. In one growing season a rhizome may attain a length of 2 m but in a closed community maximums of 5-15 cm are more common (Palmer, 1958). Most shoots emerge from the apices of secondary rhizomes (Mortimer & McMahon, 1982). Infestations of common couch show a regular spatial arrangement of shoots.

At high soil nitrogen levels tiller production increased leading to an increase in the development of secondary rhizomes (McIntyre, 1965). An increase in the nitrogen supply also reduces apical dominance in the rhizomes leading to the development of more lateral buds. The loss of apical dominance probably results from a reduction in the competition for nutrients within the rhizome. In rhizomes that were detached from the parent plant, even at high nitrogen levels, apical dominance was restored as the competition for the more limited supply of nutrients increased (McIntyre, 1969).

Common couch plants growing alone on recently disturbed soil produce considerably greater rhizome growth than those growing in established patches (Sagar, 1960). In undisturbed soil, where no fragmentation occurs, the majority of buds remain inactive due to apical dominance from the actively growing shoots. The parent rhizome may survive for two or more seasons depending on soil conditions and the frequency of cultivations. In well-established stands the soil beneath the surface may become crowded with a mat of rhizomes of mixed ages. Rhizomes normally die in the 3<sup>rd</sup> year after production. Only the most recently formed rhizomes are growing actively but all the living rhizomes are capable of regenerating if disturbed or fragmented. The old parent shoots die back in autumn, occasionally buds grow out from the old stock and produce rhizomes and tillers.

Temperature and light levels can affect couch development, all buds have the potential to develop either as shoots or rhizomes and environmental conditions can influence the result. Low constant temperatures favour the growth of underground organs in the winter (Palmer & Sagar, 1963; McIntyre, 1967). Higher temperatures encourage top growth at the expense of the rhizomes. Temperatures above 35°C depress all growth. Bud development at the base of new shoots is dependant on light intensity. At lower light levels, more buds develop into shoots and rhizome production is inhibited. In longer photoperiods and higher light levels rhizomes are thicker and more numerous (Werner & Rioux, 1977). The strongest couch growth is achieved at low temperatures in long photoperiods. At high temperatures and short photoperiods growth is depressed. In the USA, Majek *et al.* (1984) found that the rhizome tips curved upwards when grown at 32 or 10°C or given less than 10 hours light. Shading reduces plant growth, rhizome development being more affected than top growth (Håkansson, 1969b; Williams, 1970a; Skuterud, 1984). Plant height is increased at a light intensity of 50 or 25% of full daylight but shoot number is reduced. Shading later in the season, when the production of new rhizomes takes place, reduces rhizome production more than early shading. Rhizome growth is not affected by flower formation but growth ceases during mid-August to mid-October when the aerial shoots become senescent or growing conditions become unfavourable (Palmer & Sagar, 1963). The effect of nitrogen levels on bud development varied with the axillary position of the bud (McIntyre, 1967). At high nitrogen levels the bud in the axil of leaf one develops into tillers, at low nitrogen levels the buds form rhizomes.

Couch rhizomes exhibit the minimum regenerative capacity after deep burial in May (Håkansson, 2003). Low bud activity in spring is thought to be due to low food reserves causing low regenerative capacity (Leakey *et al.*, 1977a). Rhizome buds decrease in

activity from mid-April to June and then increase again from July onwards. New rhizomes develop below ground in the greatest numbers during July-August. Tillers and new rhizomes start to develop when the dry matter in the underground organs has exceeded a minimum level after the decrease due to early root and shoot development. This generally occurs when primary shoots have 3-4 visible leaves. Subsequent undisturbed growth allows a gradual dry matter increase that proceeds until autumn.

When a rhizome is separated from the parent plant, the axillary buds develop into aerial shoots that grow vertically upward (Palmer & Sagar, 1963). Cultivation may therefore displace the seasonal growing cycle. Renewed tillering and rhizome production will follow soil disturbance at any time except mid-winter. The stem bases of the aerial shoots also possess a regenerative capacity and can develop into new plants after fragmentation (Håkansson, 1969a). Shoots had a lower capacity for recovery from burial when they had 3-4 leaves than at any other stage (Håkansson, 1969c). Repeated burial at intervals of 1-4 weeks killed couch shoots when this began early in the year. Later in the year, shoots had a greater capacity for survival possibly due to the larger stem system. The shoots died but basal parts survived and new shoots developed from lower buds. Couch has a great capacity for regeneration after tillage even during the weakest stages of growth (Håkansson, 1995).

Shoots from single bud rhizome fragments begin to form new rhizomes at the 3 to 4-leaf stage. With single node fragments the greatest regenerative capacity was between November and April and the least was in June. The poor regeneration in June and July can be improved by applying nitrogen (Leakey *et al.*, 1977b). In rhizome fragments collected in May-July, and having late spring dormancy, the percentage of active buds increased with increasing potassium nitrate concentration. Chilling slightly increased active bud numbers. Shoot growth was generally greater from fragments of the current year's rhizome than the previous year's but chilling for 2 weeks at  $-2^{\circ}\text{C}$  stimulated the growth of older rhizome pieces. Even under cool soil temperatures, cultivation and fragmentation will stimulate rhizome buds to sprout (Cussans, 1972a). Bud production on rhizome segments continues well into the winter (Lemieux *et al.*, 1993).

In the USA, rhizomes were sampled at intervals and the growth of single bud segments was assessed in the laboratory (Johnson & Buchholtz, 1962). Buds were fully active in late-March and early-April but decreased in activity from mid-April to early-June when the buds became dormant. The activity resumed in July and continued through the summer. This period of bud inactivity that occurs despite favourable growing conditions is referred to as late-spring dormancy. It differs from summer dormancy which may occur in hot dry conditions.

It appears that at certain times of year but not always, the original node position of a rhizome fragment influences its regenerative capacity (Leakey *et al.*, 1977b). In rhizome pieces collected in autumn, regenerative capacity was greater in fragments from near the apices of the rhizomes and least from basal fragments. This may be related to differences in the nitrogen gradient found in spring and autumn. It suggests that unlike seed dormancy, rhizome dormancy may be related to nitrogen levels.

In experiments with rhizome pieces 4 to 32 cm long planted 0-30 cm deep in soil, most shoots emerged from rhizomes in the top 7.5 cm of soil, with a peak at 2.5 cm depth. The 32 cm fragments were able to emerge from up to 30 cm deep but most emergence was from 2.5-10 cm deep (Håkansson, 1968a). It was noted that death rates for planted rhizomes increased with depth and decreased with rhizome length except on the soil surface where conditions were not conducive to rhizome survival (Håkansson, 1969a). The optimum depth for survival was 5 to 10 cm. Regardless of planting depth, most new rhizomes that develop from buried fragments were found in the surface 10 cm of soil. The number of rhizome pieces that survived and sent out aerial shoots was much lower for 4-8 cm pieces than longer ones (Håkansson, 1968b). Greater survival of longer pieces is partly because of greater food reserves and partly because rotting from the ends kills shorter fragments quicker. Weak shoots developed from short rhizome pieces, the longer the rhizome segment the stronger the shoot (Vengris, 1962). In greenhouse tests, small rhizome fragments with one or two nodes buried in sandy loam soil at depths of 30, 60 or 90 cm produced shoots but only those from the 2-node fragments were able to emerge above ground and then only from 30 cm deep (Chancellor, 1966). The maximum shoot length on 2-node fragments was 53 cm. Shoots on the 1-node fragments grew to a maximum of 16 cm.

In a given area, more shoots are produced when cultivations cut rhizomes into smaller pieces but the shoots are less vigorous than those on longer fragments (Proctor, 1972). Rhizome mortality is also greater with smaller rhizome pieces. There is competition between the regenerating rhizomes and elongation of individual rhizomes is much greater when the couch population is low.

It is considered by many that common couch never develops a real innate dormancy and soil cultivation resulting in decapitation of the rhizome in any season when conditions are favourable causes immediate regrowth. The nearest bud to the apical end develops into a shoot, buds a little further from the apex produce rhizomes (McIntyre, 1970). The renewed growth follows a pattern of morphological and dry matter changes similar to that in spring. After extensive rhizome fragmentation at least one bud per fragment develops a new shoot except in winter when low temperatures retard growth. Leakey *et al.*, (1972a), however, have reported the occurrence of innate dormancy in 1-node rhizome fragments. This late spring dormancy, as it is termed, was greatest in June and July and lowest between October and May. There was little difference between young and old rhizomes. The dormancy is broken by nitrogen and it is suggested that nitrogen in the soil prevents dormancy occurring in the field.

Light inhibited bud growth in multi-node fragments incubated at 23°C but this could be reversed by transfer to darkness (Leakey *et al.*, 1978b). There was no inhibition if fragments were sprouted for 3 days in darkness before exposure to the light. In darkness, shoot growth occurred within 4 days but in the light it was delayed for at least 28 days or prevented completely. The position of the fragment on the intact rhizome may have an effect on this. In the dark, the percentage of active growth was at a maximum within 5-6 days and dominance by a single developing shoot was imposed within about 4 weeks. In

the light, where activity was delayed but not prevented, the period of bud activity was extended and in some instances dominance did not develop. In the absence of dominance all the shoots grew. The spectral quality of the light, especially wavelengths around 700 nm, appears to be important for the effect on dominance.

Where fragments have several buds some will remain dormant due to correlative dominance. However, it has been noted that buds are not completely inhibited for a 10-20 day period after fragmentation. Around 70-80% of buds on 7- and 15-node fragments were found to have made detectable growth in that period, only buds at the basal end of longer rhizome pieces remained dormant (Chancellor, 1968). On short fragments all the buds made significant amounts of growth until the leading bud re-imposed dominance. The longer these shoots develop before growth ceases, the more vulnerable they become to subsequent cultivations. If the lead shoot dies for any reason, the inhibited shoots recommence growth to replace it. When 7-node rhizome fragments were incubated in the dark at 23°C, after an initial flood of activity, buds were inhibited in a highly ordered sequence leaving only 1 dominant bud growing (Leakey *et al.*, 1978a). At 13 to 23°C dominance was established in 30 days, at 3°C dominance took 170 days to fully establish, at 33°C only 6% had established dominance after 65 days. Applications of nitrate delayed the onset of dominance and increased shoot growth.

The angle that decapitated rhizomes are left at in the soil following cultivation can influence which of the new shoots that develop will exert dominance (Leakey *et al.*, 1972b). In rhizomes with the apical end pointing down the bud at the first node became dominant. In rhizomes with the apical end pointing up or horizontal, it was the bud at the second node that exerted dominance. The rate of bud growth and the time for dominance to develop were hastened at higher temperatures.

Growth is slowed under dry conditions (Cussans, 1972a). However, pieces of couch rhizome have demonstrated considerable resistance to drought (Håkansson, 1970b). Couch appears able to tolerate drought because plant metabolism falls under dry conditions. In this state, the rhizomes are much less susceptible to desiccation. Plant growth is restricted, preventing the depletion of food reserves and limiting the success of control by soil tillage.

In petri-dish tests, water extracts from plant residues of common couch inhibited the germination of lettuce and radish but had less effect on clover and wheat seed (Carley & Watson, 1968). The root and hypocotyl length of seedlings of all the test species except wheat was considerably reduced. In culture solutions, the growth of winter wheat roots was severely reduced by the roots of common couch (Sagar & Fernandez, 1976).

### **Persistence and spread**

Common couch seeds are not innately dormant and most germinate during the first autumn (Williams, 1978). Seeds germinate most readily when shallowly incorporated in soil and persist longer when left on the soil surface. Seed may exhibit dormancy in excess of 3 years but seed sown in the field emerged mainly in the first year and few seedlings emerged in year 3 (Chepil, 1946a). Seed can remain viable in undisturbed soil

for more than 5 years (Salisbury, 1961). In cultivated soil only 7% of seed remained viable for longer than 1 year (Chancellor, 1982). In Duvel's seed burial experiment, 19% of seeds buried at 107 cm remained viable after 4 years but only 1% at 56 and none at 20 cm deep (Toole & Browne, 1946; Goss, 1924). After 10 years, 2% of seeds were still viable at 107 cm deep but none at the shallower depths, and none remained alive at any depth after 16 years. Seed buried in soil in subarctic conditions had <1% viability after 2.7 years (Conn & Deck, 1995).

In a 3-year old grassland in the USA only 33% of the rhizome mat was viable (Johnson & Buchholtz, 1962). New rhizomes develop as older ones decay, keeping the proportion of viable rhizomes constant. A single node rhizome fragment has produced over 80 m of growth in a 12-month period (McRostie *et al.*, 1932). Field margins infested with common couch act as a source for repeated spread into arable fields. The rhizomes extend readily into cultivated soil. Once there, tillage fragments the rhizomes and scatters the pieces further into the field. Common couch allowed to flower in the field margins could set seed that would be readily dispersed within the field or beyond.

Common couch is usually introduced into new areas as seeds (McRostie *et al.*, 1932). Weed seed contamination of crop seed was a common source of couch infestations. In a survey of cereal seed drilled in 1970 on UK farms couch seed was found in 39% of samples from home saved seed and 5% of merchants seed samples (Tonkin & Phillipson, 1973). Sowing couch seed with the crop seed may not only contaminate clean land but may also introduce new clones to areas previously occupied by a single clone, thereby facilitating further seed production (Mackay, 1964). Combine harvesting a cereal with seed heads of common couch present will spread the seeds as efficiently as a seed drill (Sagar, 1960).

Seed was found in 2-4% of cereal seed samples tested by the Official Seed Testing Station in 1960/61, an increase since 1951/52 (Gooch, 1963). In purity tests made on wheat, barley and oats between 1961 and 1968 common couch seed was found around 3% of samples from 1961-67 but in 1967/8 the frequency in all the cereals had increased to over 5% (Tonkin, 1968a). In most seasons common couch was the most frequent injurious weed in samples of wheat, oats and rye (Tonkin, 1968b). In the period 1978-1981, common couch seed was found in 10-25% of wheat and 11-19% of barley seed samples tested (Tonkin, 1982). At the Official Seed Testing Station for Scotland the incidence of common couch and other weed seeds in certified and pre-certified barley seed 1996/97 showed that seed of couch was present in 31.5% of pre-certified samples and 6.3% of certified samples (Don, 1997). While the incidence of most weed seeds in certified barley seed samples has decreased, there was a regular increase in couch seed from its occurrence in 0.76% of 1986/7 samples, to 3.58% in 1991/2 to 6.26% in 1996/7. A similar increase was reported in certified oat and wheat seed samples. The results are thought to be due to an increase in couch infestations following its introduction in contaminated cereal seed!

In seed samples tested by the Official Seed Testing Station in 1960-61, common couch seeds were found in up to 13.8% of perennial ryegrass seed samples of UK origin and in

up to 7.5% of samples of other grass seeds (Gooch, 1963). Up to 63.7% of grass seeds of Scandinavian origin were found to contain couch seed. The seed was not an important contaminant in clover, forage, root and vegetable seed samples tested at this time. In clover and grass seed samples tested in Denmark for the period 1927/8, 1939, 1955/57 and 1966/1969, common couch was a frequent contaminant being found in 4.2, 9.6, 18.6 and 26.4% of samples tested respectively (Olesen & Jensen, 1969). It was most frequent in seed of perennial ryegrass and red fescue.

Common couch seed retains viability after passage through the digestive systems of horses, cows and sheep but not pigs (Mitich, 1987). Apparently-viable seed has been found in samples of cow manure (Pleasant & Schlather, 1994). Seed has been recovered from irrigation water in the USA (Kelley & Bruns, 1975). Seed stored in freshwater for 27 months did not germinate (Zimdahl, 1993).

### **Management**

Although vegetative propagation is considered to be the main source of spread it is important to ensure that new infestations are not introduced as seeds in contaminated grass or cereal seed (MAFF, 1949). Once couch is established repeated ploughing, grubbing and harrowing must be practiced to reduce it (Long, 1938). The land should be ploughed shallowly and as much weed as possible collected by grubbing and harrowing when the soil is dry. The weed should be burnt and the ashes spread on the land. Isolated patches may be forked out and burnt (Weber, 2003). Machinery has been developed with two banks of rigid soil-loosening tines fitted with 30 cm wide wing- or duck-foot shares that tear up the stubble ahead of a pto-driven horizontal rotating shaft fitted with long curved tines (Anon, 2005). These flick the rhizomes out onto the soil surface where they can be left to desiccate or can be collected up for burning (Van der Schans & Bleeker, 2006).

In western Canada the one-way disc has been used to cut through the common couch rhizomes and destroy top growth rather than dragging the couch out and spreading it around (Hardy, 1949). It may require one operation per week during the 6-week period when the couch rhizomes are being depleted of resources. The discs are operated at 2.5-3.5 cm deep to minimise damage to the soil structure.

Couch was controlled traditionally by cultivation, harrowing, raking and burning during fallow periods (Morse & Palmer, 1925). It can be almost completely killed in one season by repeated cultivations that begin in spring (Håkansson, 1982). The optimum time for repetition of tillage is when regrowth has reached the 3-4 leaf stage (Håkansson, 2003). In a fallow period, progressively deeper spring-tine cultivations aim to bring rhizomes to the soil surface to be desiccated. Actively growing rhizomes are readily killed by desiccation when exposed to dry air for a few days at moderate temperatures (Low & Buchholtz, 1952). However, if covered even with a shallow layer of dry soil the rhizomes may survive. Moisture loss from the rhizomes must be greater than 80% to be effective (Cussans, 1972a). The best time to work the land is when the soil falls readily from the rhizomes. Rolling greatly assists the harrows in shaking off the soil (MAFF,

1949). Repeated cultivations are not good for a poorly structured soil but a full fallow should not be needed on light land.

In the north of England, the later and more protracted ripening of cereals favours couch and other rhizomatous grasses (Attwood, 1981). There is a long period after the cereal leaves dieback and before harvest when the canopy opens and couch can make good growth and build up reserves. After the later harvest there is usually only a short period for cultivations before the land becomes too wet to work. A rotation of continuous cereals leads to a steady increase in common couch (Pallutt, 1993).

In Norway, ridge fallowing was regarded as the most effective system of fallowing (Bylterud, 1965). After ploughing and harrowing the soil is laid up in large ridges 75 cm apart. When the couch grass shoots are 5 cm long the ridges are split with a plough. In this way some rhizomes dry out on the surface others are cut up and buried. The splitting is repeated 5-6 times at intervals of 10-20 days. Unfortunately ridge-fallowing is best performed with a one share broad plough. Some ploughs with multiple shares may not invert the soil fully leaving strips of couch grass visible between slices. Autumn fallowing has been used in Denmark when there is low precipitation and the cultivations after cereal harvest are used to bring couch rhizomes to the surface for drying out. However, if conditions are too dry couch growth ceases and soil tillage has no effect on the dormant rhizomes.

A bastard or half fallow can precede fodder or vegetable crops in spring or ploughing can be delayed following a forage crop or early cereal harvest (MAFF, 1974). Vetches or a mixture of oats and vetches may be sown in autumn (or oats and peas in spring) for making into hay or silage. As soon as this crop is removed the land is ploughed and fallowed until autumn (MAFF, 1949). A short rotation including extra root or hoed crops is of value in combating couch. The use of a smother crop such as lucerne or clover has sometimes proved effective (Salisbury, 1961).

In Denmark, a midsummer fallow followed by a catch crop gave a consistent reduction in couch and limited nutrient losses (Melander *et al.*, 2004; 2005). The fallow was started on 1<sup>st</sup> July by shallow ploughing to 10 cm followed by weekly tine cultivations until early August. At the end of the fallow the soil was ploughed to 20 cm and sown with a catch crop of red clover, fodder radish and winter rye. This gave over 90% control of the couch population. There was more variable control of couch when mechanical cultivation was carried out within 2 days of cereal harvest and a cover crop sown within a week of this. The reduction of couch emergence in the barley crop sown in spring was variable due to cold wet conditions overwinter and poor establishment of the cover crop. In general, the strategy gives around 40% control of the couch population.

In cropping systems without fallow periods, apart from repeated inter-row cultivation in row crops, the main period for couch control is after harvest. In cereals it is critical that rhizome fragmentation takes place as soon after harvest as possible (Barnes & Elliott, 1970). The aim is to stimulate dormant buds to grow and then destroy the resulting shoots (Sagar, 1960). A tractor mounted L-blade rotavator working to a depth of 15-cm

is needed to cut the rhizome into short lengths (Fail, 1956). The first cultivation should cut rhizomes into 2.5-15 cm lengths many of which will perish or partially die back. Survivors will develop a new root and shoot at one node; a further rotavation 2-3 weeks later will kill many of these. Rotavation needs to be repeated when survivors have developed shoots 5-10 cm long (2-leaf stage). Allowing regrowth to remain beyond 15 cm tall (3-4 leaf stage) before reburial will replenish the food reserves and make control less effective. The number of cultivations needed to eradicate the weed varies between 2 on light friable soil to 6 on heavy clay. Cultivations may be repeated at 3-week intervals until winter sets in (Barnes & Elliott, 1970). A rotary cultivator has proved more effective than disks or rigid tine cultivators for breaking up the rhizomes. In Denmark, intensive stubble cultivations resulted in a decrease in couch populations in the year after treatment but the effect is lost after a further year unless the treatment is repeated (Rasmussen & Askegaard, 2004). Perennial weeds are traditionally controlled by stubble cultivations in the autumn after a cereal or pulse crop followed by ploughing in late autumn on a heavy soil or early spring on a light soil but this can result in nutrient losses (Rasmussen *et al.*, 2005a; 2005b). A catch crop can prevent nutrient loss but will limit stubble cultivations. Couch populations tend to increase in the presence of cover crops and absence of stubble cultivations.

In barley stubble, a single rotary cultivation in late-August/September reduced spring shoot emergence by 80% (Cussans & Wilson, 1970). A second cultivation, 3 weeks later when regrowth had 1-2 leaves, reduced spring emergence by 90%. In addition to the rotary cultivations, the land was ploughed, cultivated and drilled with spring barley. Common couch weakened by autumn cultivations is more susceptible to burial than an undisturbed stand (Cussans, 1972a). The treatment works best when conditions at the time of rotavation are good for stimulating bud growth on the rhizome fragments (Elliott *et al.*, 1966). A comparison between rotary cultivations in spring barley stubble aimed at fragmenting rhizomes and tined cultivations that shake rhizomes free of soil and allow them to desiccate on the soil surface suggested both were equally effective in reducing rhizome mass (Hughes & Roebuck, 1970). In Canada, repeated tillage from the beginning of August has given excellent couch control (Werner & Rioux, 1977). Rotary cultivations after cutting hay in July/August gave better control than disking and ploughing (Lowe & Buchholtz, 1952). In New Zealand, undersowing cereals with clover had no apparent effect on couch shoots. A summer fallow during which the soil was rotary hoed three times eliminated couch while a single rotary hoeing followed by a green feed crop did not (Popay & Stiefel, 1994).

Proctor (1960) found that the level of control of rhizomatous grass weeds with a rotary cultivator was limited by the machinery used. With a 'Howard Rotavator' towed by an underpowered tractor PTO speed was inadequate at a reasonable penetration depth. Even on a light silty soil the final depth was 10 cm while rhizomes had been ploughed down to 27.5 cm. A 'Selectatilt Rotovator' with a wider range of motor speeds and powered by a more powerful tractor gave deeper penetration although dry soil conditions made this difficult to achieve. Control was reasonable but more rhizomes were brought to the surface by deep ploughing to break up any soil pan that the rotovations may have produced. Rhizomes ploughed down to 35 cm are killed.

After a period of undisturbed growth the first deep tillage should invert the soil so that the upper layers where the majority of new rhizomes have developed will be buried (Håkansson, 1969a). Preceding this with shallow cultivations to break up the rhizomes will give the best results. Ploughing to 30 cm will bury foliage and rhizomes under 15-20 cm of soil (MAFF, 1974). The aim of deep burial is to cause activated buds to perish without establishing aerial shoots or to exhaust the rhizomes food reserves as it regrows to the soil surface. Vengris (1962) recommends cutting rhizomes into short lengths by cultivation, allowing shoots to grow to 5-7.5 cm then ploughing under to at least 15 cm. Repeated rhizome fragmentation without deep burial leads to an increase in the number of aerial shoots rather than greater rhizome production (Håkansson, 1968b). In a Norwegian study, infestations of the perennial common couch greater following shallow and less intensive tillage (Børresen & Njøs, 1994). The minimum capacity for recovery from burial was generally when rhizome pieces had aerial shoots 12-15 cm long with 3-4 leaves and with new rhizomes and tillers about to develop (Håkansson, 1967; 2003). The food reserves in regenerating rhizomes are said to be lowest when developing shoots are at the 2-leaf stage (Cussans, 1972a). It was noted that couch infestations declined over a 3-year period in a field cropped with spring barley when a change of plough increased the depth of burial of the rhizomes (Scragg, 1981). Rhizome buds can remain viable for up to 30 months and 2-3 years of total control is needed to eradicate common couch (Lemieux *et al.*, 1993).

The rhizomes of couch infestations that develop in minimum tillage systems remain in predominantly in the upper 10 cm of soil (Lemieux *et al.*, 1993). Where autumn ploughing is practiced 68% of rhizomes are below the 10 cm soil layer and 19% are below 20 cm. Shoot emergence is more protracted where rhizomes are distributed through a greater depth of soil.

In an organic rotation improved nutrient supply increased cereal crop competitiveness against common couch but not sufficiently to control the weed (Olesen *et al.*, 2005). In long-term crop rotation experiments in Denmark, stubble cultivations in autumn decreased couch infestations but increased nitrate loss through leaching. Cover crops helped to retain the nutrients and improved yield in the cereals that followed but couch infestations increased.

Stubble cultivation before ploughing was the most effective way to reduce the amount of common couch when bringing a long-term ley to an end (Kakriainen-Rouhiainen *et al.*, 2003). It made little difference whether the land was ploughed in September, October or in Spring (Kakriainen-Rouhiainen *et al.*, 2004). A midsummer bare fallow treatment prior to ploughing reduced shoot numbers significantly in the following barley crop.

Cutting the aerial shoots from regenerating rhizome pieces at weekly intervals inhibited further rhizome production and may kill plants eventually but less frequent cutting was not successful. Cutting at soil level was more effective than at 2 cm above the soil surface. Defoliation of the shoots from regenerating rhizome fragments prevented new rhizome growth and exhausted the reserves in 7.5 cm fragments within 35 days (Turner,

1966). Rhizome fragments 11.3 and 22.5 cm long, lost their reserves too but more slowly. Defoliation at 28-day intervals was not effective in preventing new rhizome growth. The addition of nitrogen fertilizer increased root and shoot growth and helped to reduce food reserves under frequent defoliation. The time of year has not been shown to be of importance in measures to deplete food reserves. In Sweden, defoliation repeated when regrowth reached a height of 2.5 cm prevented new rhizome formation (Håkansson, 1969c). Rhizome growth became less suppressed as cutting height was increased. In roadside verges, increased cutting frequency reduced the incidence of common couch (Parr & Way, 1984; 1988).

A strategy of post-harvest fragmentation and uprooting of common couch rhizomes followed by a suppressive cover-crop with a dense leaf canopy has given variable results depending on the successful establishment of the catch crop (Melander, 2006). Competition from the crop can enhance the control of couch weakened by burial or fragmentation but, in general, smother crops alone have less effect on couch growth than cultivations (Lowe & Buchholtz, 1952). Seedling development from common couch seed sown in both spring and winter cereals was slow and few rhizomes were formed (Williams, 1972). Seedling growth was more vigorous in spring field beans and rhizome production was much greater. The lower light level in a spring oat crop is more likely to reduce couch growth than a spring wheat crop (Skuterud, 1984). Under-sowing with ryegrass or red clover reduced couch seedling growth in both spring barley and field beans. Common couch that regrew from rhizomes was suppressed more by spring barley and wheat than by spring field beans (Cussans, 1970). At low weed populations (45 shoots/yard<sup>2</sup>) the cereal yield was not affected but higher weed numbers (180 shoots/yard<sup>2</sup>) reduced yield by around 20%. Field bean yield was reduced by 43% and 79% by low and high couch populations respectively. Seedlings of couch were much more susceptible to competition from wheat than plants derived from single node rhizome pieces. The faster emergence and initial growth of the wheat seedlings reduced the biomass of even the rhizome derived plants by 77% (Williams, 1973b). When the couch and wheat seedlings were grown alone, the later growth of the weed was much faster than that of the cereal mainly due to a greater leaf area (Williams, 1970b). Undersowing cereals and grain legumes with Italian ryegrass, red clover or a mixture of the two can retard the spread of couch grass (Lampkin, 1998; Williams, 1972, Cussans, 1972b). Establishment and early development of barley was consistently more rapid than couch (Cussans, 1968a). The early growth of regenerating couch was markedly suppressed by barley and by oilseed rape (Cussans, 1968b). The number of flower heads was also reduced. Field beans were much less competitive and wheat was intermediate in its ability to suppress couch. The main effect was to reduce light levels under the crop canopy. In the past in the UK, a field infested with couch would be put down to potatoes so that the scuffling, ridging and other operations both before and after crop emergence would reduce the weed.

Common couch may have so little effect on the yield of spring barley that control is not merited (Scragg & McKelvie, 1976). In field trials in Denmark, the competitiveness of 5 crops against common couch could be ranked: winter rye > winter wheat, spring barley > spring oilseed rape, peas, with rye the most competitive (Melander, 1993). Yield losses ranged from 8% for rye to around 35% in peas and rape at a density of 100 primary

shoots of common couch per m<sup>2</sup>. In cereals there was a linear relationship between crop yield and primary shoot density of common couch. In peas and oilseed rape the relationship was curvilinear.

In some grass fields uniformly infested with couch, there was a gradual decline in the occurrence of couch from three years after establishment until recording stopped in year ten. It has been said that if land is laid down to grass, couch will be eradicated in 2-3 years (Morse & Palmer, 1925). In perennial ryegrass swards, as the interval between cutting increased to more than 4 weeks, common couch rhizomes increased in dry weight (Courtney, 1980). The rhizomes grew better at higher nitrogen levels despite greater competition from the ryegrass at higher fertility levels. Cutting at intervals of 2 to 4 weeks was more likely to reduce couch levels than allowing 8 weeks between cuts. Rhizome growth also depended on the composition of the sward (Courtney, 1972a). Tetraploid Italian ryegrass (*Lolium multiflorum*) and rough meadow-grass (*Poa trivialis*) were less competitive than perennial ryegrass (*L. perenne*) or cocksfoot (*Dactylis glomerata*).

Competition suppressed the growth of common couch in headlands sown with grass or wildflower/grass mixes in comparison with unsown headlands (West et al., 1997). The ingress of the weed from the field margins was reduced but not prevented. In a five-year study of weed spread, a boundary strip 2 m wide was sown with perennial ryegrass, mown twice a year, or was kept bare and rotovated twice a year (Milson et al., 1994). In comparison with a winter wheat cropped strip the boundary strips delayed the spread of common couch from the hedge into the field but did not prevent it. There was little difference between the boundary strip treatments.

Common couch is relatively palatable and is absent from heavily grazed pasture (Grime et al., 1988). It will not persist under a system of close grazing. If a suitable mixture of grasses and white clover is sown and efficiently managed for a few years the weed will be gradually suppressed (MAFF, 1949). Pigs in a moveable pen will root out and consume the rhizomes (Mitich, 1987). The rhizomes are also said to be relished by horses and cattle (Morse & Palmer, 1925). Geese will eat common couch and may be selective in certain crops (Quarles, 1999).

Common couch was not controlled by flame weeding and regenerated rapidly after treatment (Ivens, 1966; Bertram, 1997). An old method of controlling common couch was to light a series of small fires over an infested field. On heavy land this also had the effect of improving the soil texture.

In greenhouse tests, corn gluten meal (CGM) applied as a surface and incorporated treatment to soil has been shown to reduce plant development (Bingaman & Christians, 1995). The lowest rate of 324 g/m<sup>2</sup> had no effect on seedling survival but at 649 and 973 g/m<sup>2</sup> survival was reduced by 20 and 71% respectively. Root and shoot development of the survivors was reduced more by the incorporated treatment. Corn gluten hydrolysate (CGH), a water soluble material derived from CGM, was found to be more active than CGM when applied to the surface of pots of soil sown with common couch seed (Liu &

Christians, 1997). Wheat gluten meal (WGM) at 1 or 3 g.dm<sup>-2</sup> dusted over seeds put to germinate on moist paper reduced germination by 37 and 50% respectively (Gough & Carlstrom, 1999).

Like many weeds, common couch often occurs in patches that may require different treatment from the rest of a field. Techniques have been developed for mapping the spatial distribution of couch to facilitate patch spraying of the weed with herbicide (Rew *et al.*, 1996). It may be possible to use similar techniques to monitor weed spread and for treating weed patches using non-chemical methods. Mathematical models for the calculation of the rates of change in the size of weed infestations may be used to simulate weed management scenarios for common couch (Mortimer & Putwain, 1981).

### **Chemical control**

The most commonly used herbicides for controlling common couch are:-

- **Glyphosate** (*numerous products available*) has been applied pre-harvest to control perennial weeds such as common couch since the 1980's (Orson and Davies, 2007). The weed is in an active growth phase at this time resulting in good herbicide movement within the plant, as long as sufficient water is available. The timing of application also benefits the farmer as it does not delay the start of the next season's cultivations as no fallow area is required. Spot applications of glyphosate can be applied to couch patches in grassland.
- **Sulfosulfuron** (Monitor) – this is a spring applied foliar acting herbicide for winter wheat, best applied when the soil is moist and the plant is actively growing. This herbicide can be effective on couch up to growth stage 39. Growth is stopped rapidly, but the plants may die slowly (symptoms visible after about 5 days and plant kill between 14-25 days post application). *There is a following crop restriction for both oilseed rape and sugar beet.*
- **Attribut** (Propoxycarbazone-sodium) – used to control common couch in winter wheat. For most effective control of couch in the current and following season apply when the weed is at a growth stage of between 2 true leaves and the first node. A split dose programme may be most effective. This herbicide is an ALS-inhibitor and to avoid the build up of herbicide resistance only one application of an ALS-inhibitor should be used on any one crop. *There is a following crop restriction for following autumn, allowing only winter wheat, winter barley or field beans to be sown.*

### **Discussion**

In the cultivated soils of northern Europe, common couch continues to be the main perennial grass weed but other rhizomatous grasses including black bent are often mis-identified as couch. In the past, one of the main sources of introduction was as a seed contaminant in crop seeds, especially cultivated grasses and cereals. The importance of seed in the spread of common couch is probably underestimated but it is vital to prevent

the production and dispersal of fresh seed. In cereal crops, the combine harvester is likely to exacerbate the spread of couch seed. While there have been some studies of seedling establishment as a source of new infestations it would merit further investigation in arable crops of different competitive ability.

There is a vast amount of literature on the regeneration of common couch from rhizome fragments and how different factors affect this. However, laboratory and greenhouse studies have not always been linked with field practice. Two opposing direct management strategies have been used to deal with couch. One is to chop up the rhizomes and bury them, the other is to keep the rhizomes intact and drag them onto the soil surface for desiccation and disposal. A fallow period is known to help in reducing couch but is seldom practical and often the only opportunity for cultivation is after crop harvest in autumn. Intensive cultivation at this time will increase the risk of nitrate leaching. Cover crops and green manures reduce nutrient loss and improve subsequent crop yield but limit cultivation.

Common couch is not a particular problem in grassland but it becomes one when a ley is broken up and the land cultivated prior to arable cropping. There have been some recent investigations of the best way to avoid couch infestations developing after a ley.

There has been little interest in the biological control of common couch perhaps because biocontrol agents that attack the weed are also likely damage cultivated grasses and cereals.

## **The biology and control of Creeping Buttercup (*Ranunculus repens* L.)**

### **Occurrence**

Creeping buttercup is a native perennial weed common in damp meadows, pastures, gardens, lawns and waste places on a wide range of soils but mainly on wet, heavy land, moderately rich in nutrients (Clapham *et al.*, 1987; Long, 1938; Copson & Roberts, 1991). It is found throughout the UK and is recorded up to 3,400 ft (Stace, 1997; Salisbury, 1961). It has been found in prehistoric deposits. In early surveys of Bedfordshire and Norfolk it was distributed on most soils but seldom found on chalk (Brenchley, 1913). On arable land it is commoner on neutral and clay soils, less so on acid soils (Harper, 1957). Creeping buttercup is found on the peat of upland grassland but not on dry lowland peat. It is rarely found on chalk grassland except where the ground has been disturbed. It can be particularly abundant on heavy garden soil. Creeping buttercup can tolerate both waterlogging and a moderate drought (Lovett-Doust *et al.*, 1990; Harper, 1957). It can withstand compaction, trampling and disturbance, and is found in gateways and on paths even in woodland.

Buttercups are serious weeds of old pastures and hay meadows (Harper & Sagar, 1953). In a survey of seeds in pasture soils in the Netherlands in 1966, creeping buttercup was common both in the sward and in the soil seedbank (Van Altena & Minderhoud, 1972). In damp meadows creeping buttercup forms large colonies on heavy soil (Harper, 1957). It increases with poor drainage, and in ridge and furrow pasture it often forms bands along the bottom of the furrows. It is an efficient pioneer species capable of rapid colonisation of areas disturbed by man such as gardens, building sites, dredged riverbanks, cleared ditches etc. Creeping buttercup is also an efficient colonist of disturbed arable habitats such as cornfields where it can establish and spread rapidly even in dry conditions. It was relatively common in a survey of weeds in spring cereals in NE Scotland in 1985 (Simpson & Carnegie, 1989). In unsown set-aside land in Scotland, creeping buttercup was the second most frequently recorded species and constituted the highest ground cover (Fisher *et al.*, 1992).

Creeping buttercup is the most widely distributed of the common buttercups. A number of varieties have been described that differ in habit and flower colour (Harper, 1957). The plant is very plastic and its morphology and growth reflect the habitat (Lovett-Doust *et al.*, 1990). Stolon formation is linked to soil fertility. In close turf stolons are few, in open ground long stolons are produced for rapid colonisation (Harper, 1957).

Creeping buttercup can cause diarrhoea if eaten by sheep and cattle but it is normally avoided. Nevertheless it is sometimes browsed by stock, possibly due to the lower content of ranunculin than in other buttercups making it less unpalatable (Sarukhán & Harper, 1973). It normally has a creeping habit under intense grazing but makes erect growth when left ungrazed and can then withstand competition from tall grasses in hay crops. Increased nitrogen promotes stolon branching and this affects the shoot:root ratio. It is also said to deplete the land of potassium and may have an allelopathic effect on neighbouring plants.

## **Biology**

Creeping buttercup flowers from May to August and sets seeds freely (Long, 1938). The flowers are insect pollinated, some selfing occurs but flowers are predominantly cross pollinated. Only a few plants flower and then they only have 1-5 flowers. Flower heads contain 25-30 seeds (achenes) (Salisbury, 1961). A flowering shoot yields 140 seeds (Hanf, 1970). Estimates of the average seed production per plant range from 227 to 687 seeds (Pawlowski *et al.*, 1970).

Ripe seeds are highly dormant and may need an after-ripening period to break dormancy (Harris *et al.*, 1998). In laboratory studies diurnal fluctuations in temperature with an amplitude of 1°C promoted germination in the light (Thompson *et al.*, 1977). Soil temperature and moisture level determine the level of emergence (Harris *et al.*, 1998). The time to the onset of emergence decreases with increasing temperature above a base of 0°C. Germination normally occurs in late spring (April-May) but a few seeds germinate in the autumn if conditions are mild and wet, and odd seedlings emerge sporadically throughout the year (Harper & Sagar, 1953). Differences have been noted between the pattern of emergence of seeds from arable populations of creeping buttercup and those from wasteland (Harris *et al.*, 1998). Field emergence in plots cultivated at monthly, 3 monthly and yearly intervals or not at all extended from March to November (Chancellor, 1964). The main peaks of emergence were March to June and August to September. The least number of seedlings emerged from the uncultivated plots. Seed sown in a 75 mm layer of soil in cylinders sunk in the field and stirred periodically, emerged mainly from February to June and August to October but there was some emergence throughout the year (Roberts & Boddrell, 1985). Seed germinates at 5-30 mm depth in soil (Hanf, 1970).

Seedlings establish readily in open ground and often occur in patches or clumps. There may be rapid colonization of bare soil but seedlings are rare in grassland or other established vegetation (Lovett-Doust *et al.*, 1990; Lovett Doust, 1981a). Soil moisture level is important and it is the influence of the water table on germination and early seedling growth that determines the distribution of creeping buttercup along the furrow bottoms in ridge and furrow grassland (Harper & Sagar, 1953). Seedlings are frost tolerant (Salisbury, 1962b).

Creeping buttercup has a short swollen stem base, long stout adventitious roots and strong, leafy, epigeal stolons that root at the nodes. Daughter plants (ramets) form in the axils of the stolon leaves. Creeping buttercup overwinters as a small leafy rosette. In spring new leaves develop and later the buds low down in the rosette grow out into strong, above ground runners that root at the nodes. These stolons begin to develop at or just before flowering in May to June. Stolon production goes on into late summer (Lovett-Doust *et al.*, 1990). The production of daughter rosettes continues through July and August as the stolons extend (Lovett Doust, 1981a). The stolon internodes wither and rot in the autumn leaving the daughter rosettes as independent units. The process is accelerated if trampling by stock breaks up the plants (Sarukhán & Harper, 1973). The plants overwinter as rosettes with a few leaves (Hill, 1977; Zimdahl, 1993).

Sometimes the plants do not flower in the first year or flowering is delayed until later in the year, up to October. The parent plant dies after flowering, the overwintering unit being the stolon-borne daughter plants that have developed roots and leaf rosettes but have not flowered (Clapham *et al.*, 1987). Over the winter, growth slows due to the cold but in a mild period growth may continue for a while (Harper, 1957). The main flush of growth is in June and July (Grime *et al.*, 1988). The density of rosettes reaches a peak in July and August that is twice the density in winter (Lovett Doust, 1981a). The annual mortality of rosettes ranges from 30 to 70% and the calculated time for a complete turnover of the rosette population is 3 to 16 years in open woodland and 2 to 10 years in grassland.

The number of leaves borne by a rosette varies throughout the season, reaching a maximum in June-July and falling to its lowest value in October-November (Lovett Doust, 1981b). But this may depend on the habitat. In a study of the plasticity of creeping buttercup, clones from different habitats in Ireland; marsh, ruderal and turlough (submerged from October to May), were grown under identical conditions (Lynn & Waldren, 2001). Leaf number peaked at end of May then declined from mid-June to mid July. Clones varied in leaf number. The number of primary stolons depended on leaf number. The peak of primary stolon formation was in mid-July, few were produced after this because of leaf die-back. The decline in the leaves of the mother rosette may be due to reserves going to the daughter plants on the stolons. The number of potential daughters depends on the branching of the stolons. Branching to produce secondary and tertiary stolons declined in low nitrogen conditions. Some plants spread widely others remained relatively compact, but there was considerable plasticity. Peak flowering occurred at end of May but some clones carried on into June. Only 20% of plants flowered and most of these had only 1 to 5 flowers. Those from ruderal habitats tended to flower most, possibly because seed production has greater benefits in disturbed habitats.

### **Persistence and Spread**

Seed dormancy is enforced by burial leading to high populations of buried seeds. Creeping buttercup forms large seedbanks in soil and seeds can remain viable for several years (Weber, 2003). Seeds have been recorded in enormous numbers in the soil beneath pastures even though the plant may be poorly represented in the vegetation (Chippindale & Milton, 1934; Champness & Morris, 1948). Creeping buttercup seed constituted 36% of the seedbank in a pasture ploughed after 22 years (Chancellor, 1978). Up to 12,000 seeds per m<sup>2</sup> to 15 cm depth have been recorded (Lovett-Doust *et al.*, 1990). The annual decay rate of seed in soil has been measured at 38% (Sarukhán, 1970). There is usually considerable persistence of creeping buttercup seed after cultivation of grassland (Harper, 1957). In Belgium, it was one of the main species that remained in the seedbank of a reclaimed heath that was under arable cropping since 1924 and under grassland from the 1960s (Stieperaere & Timmerman, 1983).

Thompson *et al.* (1993) suggest that based on seed characters, creeping buttercup seed should persist for longer than 5 years in soil. Seed longevity in soil is 5 to 7 years (Guyot

*et al.*, 1962). Seed buried in mineral soil at 13, 26 or 39 cm depth and left undisturbed retained 51, 55 and 48% viability respectively after 20 years (Lewis, 1973). Seed buried in a peat soil at 26 cm for 20 years retained 17% viability. Seed recovered from excavations and dated at 80 years old was found to germinate (Ødum, 1974). Seeds survive 3 years of dry storage (Harper, 1957). Seed stored under granary conditions had 18% viability after 1 year but was not viable after 20 years storage.

In dry conditions creeping buttercup flowers and sets seeds, in wet conditions it tends to increase by stolons (Salisbury, 1962a). Creeping buttercup relies predominantly on vegetative reproduction to maintain established populations. Studies in grassland have shown seedling mortality to be greater than 60% while more than 80% of vegetative propagules survived (Sarukhán, 1970). Plants produce extensive stolons that root at the nodes (Long, 1938). In an open fertile habitat the stolons may grow up to 1.5 m in length (Grime *et al.*, 1988). The roots are long and stout. The stolons spread rapidly where the vegetation is opened up by poaching or puddling, mole activity and where grass has been killed (Harper, 1957). A large proportion of adult plants are replaced each year in late summer by new vegetative units (Sarukhán & Harper, 1973). While populations of creeping buttercup in grassland have a high turnover of individual rosettes population density remains remarkably stable (Soane & Watkinson, 1979). Recruitment is mainly through establishment of new rosettes from rooted stolon nodes, rarely from seedling establishment. The life expectancy of a rosette is 1.2 to 2.1 years. Local dominance of a few clones is likely unless seedling establishment occurs occasionally to maintain some genetic diversity.

In a survey of weed seed contamination in cereal seed in drills ready for sowing on farm in spring 1970, creeping buttercup seed was found in 2% of samples (Tonkin & Phillipson, 1973). Most of this was home saved seed. In a survey of seed contamination of grass and clover seed in 1960-61, creeping buttercup was found in 4.3, 12.8 and 1.8% of perennial ryegrass seed samples tested of English, Irish and Danish origin and 2.2 and 15.3% of samples of Italian ryegrass of English and Irish origin respectively (Gooch, 1963). It was found in 2.3% of meadow fescue, 1.6% of red fescue and 4% of white clover seed samples of English origin tested. In clover and grass seed samples tested in Denmark for the period 1966-69, 1955-57, 1939 and 1927-28, creeping buttercup seed was a contaminant in 1.4, 4.2, 8.2 and 7.4% of samples respectively (Olesen & Jensen, 1969).

Most of the seeds fall around the parent but some are eaten by birds (Harper, 1957). Seeds are dispersed by the wind and in the droppings of birds and farm animals (Lovett-Doust *et al.*, 1990). Seed has been found in cattle and horse droppings (Salisbury, 1961). Seeds eaten by earthworms have been recovered from worm cast soil (McRill, 1974). Seeds are also carried in mud on tyres and boots. Seedlings have been raised from the excreta of various birds. Viable seeds have been found in the droppings of house sparrows (Harper, 1957). Seed is eaten by partridge, pheasant and pigeon but is less likely to survive digestion in these birds. The seeds are also predated by voles and mice (Sarukhán, 1974). Some rodents carry off and store the seeds.

## Management

Creeping buttercup is controlled by frequent and vigorous cultivations in hot weather (Long, 1938). Deep ploughing may kill plants if burial is deeper than 6 inches. The plants are able to survive and emerge from shallower depths. Destruction of a grass sward by ploughing provides conditions for rapid spread especially if a spring crop is sown that takes time to establish (Harper, 1957). Two fallow crops may be taken in succession to clean the land, and mustard can be sown as a smother crop (Morse & Palmer, 1925). It appeared to be discouraged by root crops (Brenchley, 1920).

In grassland, small patches can be removed manually and repeated cutting may reduce plant vigour (Weber, 2003). Intense grazing prevents seed set (Lovett-Doust *et al.*, 1990). Rosette density increases with grazing but not with mowing. Plants may be weakened by cultivation but can regenerate after damage. Loosened plants and runners should be gathered up to prevent re-rooting. In pasture, creeping buttercup increases under tight spring grazing by sheep and decreases under lenient grazing (NERC, 2006). Meadows should be well harrowed in spring to drag out the creeping runners (Morse & Palmer, 1925). A dressing of lime may help on sour land. If the buttercup is very abundant it is best to plough and thoroughly clean up the field using one or more root crops before putting down to grass again using pure seed.

In roadside verges, creeping buttercup frequency increases with cutting frequency but is particularly favoured by cutting twice a year (Parr & Way, 1988).

The plant is attacked by a number of grazing animals and parasites including nematodes, thrips, aphids and other insects (Harper, 1957; Lovett-Doust *et al.*, 1990). Various fungi also occur on the plant. Seeds and leaves are eaten by partridges and pheasants. Seeds are also eaten by wood pigeons. Chickens and geese readily eat the leaves. Creeping buttercup tolerates rabbit grazing but growth may become more prostrate (Gillham, 1955).

## Chemical control

Creeping buttercups should be controlled chemically when they are actively growing at a growth stage between rosette and flowering. Repeat applications of herbicides may be required on more mature plants as they may recover from the first application, so monitoring re-growth is advisable.

- **MCPA** (Headland Spear *and added to various other products*) – a selective herbicide for use in permanent grassland, where this species is generally only a problem.
- **Metsulfuron** (Ally) – a selective herbicide that can be used in arable crops.
- **Glyphosate** (*various products*) – a non-selective option that can be used in wick applicators as a spot treatment, but needs to be very accurately applied to prevent kill of the surrounding vegetation.

## **Discussion**

The three main buttercups are the creeping buttercup, bulbous buttercup and the meadow buttercup. Each has a subtly different survival strategy and occupies a different niche in the habitat. Creeping buttercup like the others is a problem weed of grassland but it can also invade arable crops. Creeping buttercup can persist and spread as seed but it is the vigorous vegetative reproduction and spread by stolons that is the most important characteristic of the weed.

In grassland, harrowing in spring can drag out the runners but ploughing and reseedling may be the only option where there is a dense population of the weed. Mature plants develop strong adventitious roots that anchor them securely. A large rosette can survive burial and the main shoot will regrow and emerge above ground if not buried deeply enough. It is not clear if ploughing is completely successful in preventing the regrowth of well established creeping buttercup plants.

In arable soils, creeping buttercup is generally kept in check by regular cultivation. However, seedling emergence is more frequent in disturbed soil and seedlings missed by early cultivations can soon become rooted strongly and difficult to dislodge.

## The biology and control of Creeping Thistle (*Cirsium arvense* (L.) Scop).

### Occurrence

Creeping thistle is native in cultivated fields, waysides, waste places, hedgerows and grassland (Long, 1938; Clapham *et al.*, 1987; Stace 1997). It is an aggressive perennial weed found on most soils throughout the UK but it grows more extensively on lighter soils (Brenchley, 1911; 1913). Creeping thistle is often limited to hedge bottoms and field margins or within 5 m of them in the cultivated field (Marshall, 1985). It is most competitive on deep, well-aerated soils that do not become too warm (Holm *et al.*, 1977). Creeping thistle is a long day plant and this together with the high summer temperature limits its southerly distribution in America (Moore, 1975). In Canada, where creeping thistle can survive a winter temperature of  $-27^{\circ}\text{C}$ , land infested with the weed increased from 20,000 ha in 1975 to 200,000 ha in 1997 (Thomsen *et al.*, 2004). As a  $\text{C}_3$  plant it is less successful in hot, dry climates (Håkansson, 2003). It is recorded up to 2,300 ft in Britain (Salisbury, 1961).

While creeping thistle may be relatively indifferent to soil fertility it does grow better at higher nutrient levels (Sindel, 1991). High levels of nitrogen and of phosphorus stimulate creeping thistle growth (Edwards *et al.*, 2000). It can become the dominant plant on any land if allowed to grow unchecked. Creeping thistle has been found growing on soils with salinity levels of 2% (Wilson, 1979). The plants can survive flooding but subsequent growth is checked. Seedlings grow poorly in moist, badly aerated soils and do not tolerate drought. Moisture stress also limits shoot development. It is less common on light, dry soils (Frankton & Mulligan, 1970). Alkaline and high calcium soils can limit root development (Donald, 1994). The thistle foliage is relatively high in copper, iron and trace elements (Salisbury, 1961).

In Britain, creeping thistle is the most common perennial weed of grassland on beef and sheep farms (Haggar *et al.*, 1982). A survey of 502 grassland farms in England and Wales found that 50% of farmers thought creeping thistle was a problem (Peel & Hopkins, 1980). Creeping thistle was cited more frequently by beef farmers than dairy farmers and was more common in older swards, and on soils with low phosphate or high potassium levels. A survey of over 150 organic farmers in Germany showed that 30% of arable land was infested with creeping thistle (Böhm & Verschwele, 2004; Verschwele & Häusler, 2004). On average 33% of organic arable land was highly infested. In a survey to identify the main weed species causing problems in organic farming in the new EU member states and the acceding countries, creeping thistle was the main problem weed identified (Glemnitz *et al.*, 2007).

Creeping thistle is able to survive in all but the most intensively cultivated arable fields, interferes with harvesting and reduces crop yield (Long, 1938; MAFF, 1976). It is found as often among one type of arable crop as another (Brenchley, 1920). In a survey of weeds in conventional cereals in central southern England in 1982, creeping thistle was found in 4, 2 and 2% of winter wheat, winter barley and spring barley respectively (Chancellor & Froud-Williams, 1984). In a series of 4 national weed surveys made in

Hungary between 1950 and 1997, it moved from 2<sup>nd</sup> to 5<sup>th</sup> place in the rankings (Tóth *et al.*, 1999; 1997). In 1993 a survey of the most important weeds according to European weed scientists, ranked creeping thistle as an important weed in all arable crops except spring cereals (Schroeder *et al.*, 1993). It was also considered a problem in orchards and vineyards but not vegetables. In a survey of UK cereal field margins recorded as part of Countryside 2000, creeping thistle was the most frequent species recorded (Firbank *et al.*, 2002). Between 1978 and 1990 there was an increase in the mean cover of creeping thistle from 1% to 10% in fertile grasslands and the high infestations were maintained in 1998 (NERC, 2006).

Creeping thistle seed was found in 0.3% of arable soils in a seedbank survey in Scotland in 1972-1978 (Warwick, 1984). In studies of vegetation cover and the soil seedbank, creeping thistle was well represented in the vegetation but absent from the soil seedbank (Hill *et al.*, 1989). Creeping thistle seeds were present in very low numbers in the soil beneath pastures but were somewhat more frequent in arable soils (Champness & Morris, 1948). In a survey of seeds in pasture soils in the Netherlands in 1966, while creeping thistle was common in the sward it was not represented in the soil seedbank (Van Altena & Minderhoud, 1972).

Plants that form large patches were thought to belong to the same clone that developed from a single seedling. Some populations appear to have been established almost exclusively by vegetative reproduction (Jump *et al.*, 2003). However, while this may sometimes be true, DNA testing of the shoots within different clumps has demonstrated that several phenotypes may be present in a single clump (Heimann & Harding, 1996; Hettwer & Gerowitt, 2004). Creeping thistle exhibits the widest range of clonal diversity of any plant species (Jump *et al.*, 2003). Leaf shape is very variable between clones (Clapham *et al.*, 1987). In Canada, ecotypes of Canada thistle have been shown to vary in leaf shape, spininess, flower colour, seed size and time of emergence in spring (Hodgson, 1964). There was a 2 week difference in the time of emergence between the earliest and latest of the ecotypes. This was then reflected in the time of bud formation and flowering. Ecotypes may differ in the composition of foliar epicuticular waxes but this is primarily of importance for the effect on herbicide uptake during chemical control (Donald, 1994).

Creeping and other thistles are food plants for several insect pests including bean aphid, mangold fly, celery fly and larvae of swift moths (Morse & Palmer, 1925). Thistles are also hosts of the fungi that cause lettuce mildew and chrysanthemum rust. Both the roots and shoots of creeping thistle were formerly eaten by man (Grime *et al.*, 1988). The seeds are an important constituent in the diet of many farmland birds including linnets (*Carduelis cannabina*) (Moorcroft *et al.*, 1997).

### **Biology**

The biology of creeping thistle was reviewed previously by Donald (1994). Creeping thistle flowers from July to September, sometimes into October (Clapham *et al.*, 1987; Hanf, 1970). Small stems around the edge of a thistle patch produce no flowers (Bostock & Benton, 1979). The flowers are morphologically hermaphrodite but functionally male

or female (Lloyd & Myall, 1976). The functionally female flowers are purely female, the anthers abort development and are devoid of pollen. Male flowers have ovaries with poorly developed stigmas, however, the ovary of an occasional floret becomes fertilized and produces a viable seed (Clapham *et al.*, 1987, Hodgson, 1964). Normally it is considered that male and female flowers are borne on separate plants. The flask-shaped female or pistillate flowers are very fragrant and attractive to honeybees. The globular male or staminate flowers are less fragrant but produce abundant pollen (Derscheid & Schultz, 1960). The white, feathery pappus is produced by female flowers only, the male flowers fade to dark brown. Plants are sometimes found with hermaphrodite flowers that are able to set seeds freely (Heinmann & Cussans, 1996). The plants resemble those of the typical 'male' clones that have an average seed set of 0.1 per flower head (Kay, 1985). Hermaphrodite plants have 10 to 65 seeds per flower head and sub-hermaphrodite populations have an average of 2-10 seeds per flower head. The flowers are self-fertile but seed set is relatively low after self-pollination.

As plants within a clone cannot self-fertilise and since pollinating insects tend to keep within the same patch of plants there is little cross pollination and little seed is set unless a mixture of individuals is present in the thistle patch. The ratio of the sexes in any thistle patch is very variable (Lloyd & Myall, 1976). Estimates of the maximum distances between male and female clones that still ensure seed set vary from 50 to 390 m (Amor & Harris, 1974). Seed set is reduced in female flowers separated from males by more than 20 m especially when there are physical barriers such as roads and hedges (Kay, 1985). When pollen availability is low, flowers stay receptive for longer, 5 days instead of 2 (Lalonde & Roitberg, 1994). In greenhouse studies, the effect of pollination levels on seed development has been assessed by brushing all or only a third of stigmas in a flowerhead with fresh pollen (Lalonde & Roitberg, 1989). High pollination levels led to around 80% of ovules developing while low levels of pollination led to 20-40% of ovules developing. However, seeds were significantly lighter in the high pollination treatments. There is a tendency for progeny ratios to be female dominated to a high degree. Creeping thistle is said to produce mature seeds 2 weeks after flowering (Zimdahl, 1993). Seeds ripen from June to September (Bostock & Benton, 1979). Seed is shed from August onwards but may be retained in the seedhead until the winter (Grime *et al.*, 1988).

The importance of seeds and sexual reproduction in the population biology of creeping thistle was reviewed by Heinmann & Cussans (1996). It is a mistake to consider that creeping thistle produces no seeds and relies on vegetative propagation (Anon, 1937). Salisbury (1961), suggests there may be 20-200 seeds per flower head. The average is 80 according to Lloyd & Myall (1976). Seed numbers per plant range from 1,600 to 8,400 according to Sindel (1991) and 5,000 to 50,000 according to Guyot *et al.* (1962). The average seed number per plant in ruderal situations is given as 5,070 (Pawlowski *et al.*, 1967). In winter cereals the average seed number per plant ranged from 1,590 to 1,710, in spring cereals from 905 to 969 and in root crops from 650 to 742 (Pawlowski, 1966). Stevens (1932) gives an average of 680 seeds per stem for creeping thistle and a 1,000 seed weight of 0.90 to 1.575 g. The 1,000 seed weight is given as 1.82 g by Bostock

(1978). Hodgson (1964) found that the 1,000 seed weights varied between different years and between ecotypes, and ranged from 0.63 to 1.65 g.

The time from flowering to seeds becoming viable is around 8-10 days (Derscheid & Schultz, 1960). There is some variation within the flower head because the outer florets mature earlier. At 8 days after flowering around 13% of seeds are viable, at 9 days 80% and at 16 days 90%. A few creeping thistle seeds were viable when plants were cut at 7-9 days after flowering. More were viable if cutting took place after 10-11 days. Haggard *et al.* (1982) suggest that even plants cut down just 4 days after flowering can ripen some seeds. However, according to Gill (1938) plants cut down in flower produced very few seeds and, although they appeared normal, none were viable. But even ripe seed was found to have very low levels of germination in this study.

Research has shown that most seed can germinate on dispersal but this may vary with ecotype (Hodgson, 1964). Germination of freshly collected seed from different ecotypes ranged from 0 to 92% over a 4 week period. The seed coat may restrict germination in some instances and its removal promotes germination (Donald, 1994; Kay, 1985). Light stimulates the germination of creeping thistle seed. Seed has been found to germinate on the soil surface but the optimum depth for germination is 5-15 mm (Wilson, 1979; Donald, 1994), although, germination has been reported from up to 60 mm deep (Moore, 1975). Seeds produced in July-August may germinate that autumn (Salisbury, 1961). When ripe seed was sown, a flush of seedling emergence occurred in February-March but there was intermittent germination through the year (Salisbury, 1962). With freshly shed seed mixed into the top 75 mm of soil under field conditions and stirred periodically, the main emergence period was April to May (Roberts & Chancellor, 1979). On average, 60% of seeds germinated in the first year after sowing, but odd seedlings continued to emerge over the next 4 years. After 5 years less than 1% of seeds remained. In Australia, peak emergence was in late winter to early spring (Amor & Harris, 1975). The occasional seeds produced by functionally male flowers are smaller and germinate less well than those from female flowers but seedlings grow normally (Lloyd & Myall, 1976). Viability was high in seeds produced by hermaphrodite flowers (Kay, 1985).

Seeds germinated best at a relatively high constant temperature of 25-30°C (Kumar & Irvine, 1971; Heinmann & Cussans, 1996; Salisbury, 1961), and at alternating temperatures of 20 to 30°C and 30 to 40°C (Wilson, 1979). At lower temperatures germination was aided by high light intensity. Pre-chilling at 4-7°C also improved germination in the light and in the dark but was not essential in the light. An 8-16 hr photoperiod was more effective than continuous light (Kumar & Irvine, 1971). Seed is shed largely in autumn and chilling over winter results in germination occurring mainly in spring (April-May) but germination at other times is not precluded. Seed subjected to alternating temperatures of 10-20°C in the dark gave 20% germination. With alternating temperatures of 14-30 or 20-30°C in the dark germination levels were 80%. In one study, the optimum pH for germination was between 5.8 and 7. Above or below these levels germination was inhibited (Wilson, 1979). Light, nitrate, alternating temperatures and seed age can all have an effect on germination (Bostock, 1978). The first three were stimulatory, light and alternating temperatures have a synergistic effect. Fresh seed was

deeply dormant and germination was faster after soil storage. A chilling treatment also increased the germination of fresh seed. In Petri-dish tests, seed germination was relatively salt tolerant (Donald, 1994).

In Sweden, creeping thistle seeds mixed with soil in the autumn, put in frames in the field, exhumed at intervals and put to germinate at alternating temperatures showed the seeds to have the lowest dormancy and greatest tendency to germinate from March to November (Håkansson, 1979). Peaks of germination occurred in April/May and in November. Few seedlings emerged in the autumn after sowing.

It has been reported that seedlings emerging in the autumn may not survive the winter because they have not developed sufficient underground regenerative tissue before the above ground stem is killed by frost. Creeping thistle seedlings grow slowly at first and do not tolerate shade (Donald, 1994). The seedlings are sensitive to early competition for light and are unlikely to survive in dense stands of other plants (Holm *et al.*, 1977). In pasture, the development of creeping thistle seedlings is inhibited by grasses, particularly Yorkshire fog (*Holcus lanatus*) (Wardle *et al.*, 1992). Seedlings need soil disturbance to become established in standing vegetation (Weber, 2003). Seedlings emerge best from seeds near the soil surface (Mohler, 1993). Seed spread over an established pasture did not produce any seedlings, while 6-12% of seed spread on bare soil produced seedlings but only when mixed into the upper 5 to 10 mm of soil (Amor & Harris, 1975). Once established, spread is primarily vegetative. Seedlings, 19 days old with 2 true leaves, were able to resprout after removal of the top-growth (Wilson, 1979). At this stage the branched root system is up to 15 cm long (Holm *et al.*, 1977). Seedlings develop a taproot with spreading laterals within 8-10 weeks of emergence. At the base of these side roots adventitious buds develop. Once these are formed, the seedling is able to regenerate readily if hoed off. The buds grow upwards to form adventitious shoots. After six months a seedling can have penetrated over 60 cm deep. Creeping thistle seedlings undergo a juvenile vegetative period before they are able to flower but can flower in the year of emergence (Donald, 1994).

Shoots that emerge in spring form a rosette of leaves before growing vertically after a few weeks. Those that appear later in the year may elongate following emergence without forming a leaf rosette. Meanwhile the lateral roots continue to extend from the taproot. Mature plants on clay soil had roots that penetrated to 3.8 m but on sands and gravels the roots extended to just 1 m deep (Donald, 1990). In general, low temperatures and short photoperiods favour root growth more than shoot growth (Donald, 1994). Adventitious root bud formation is favoured by low temperatures in winter but growth is limited. Nitrogen fertilization stimulates root growth within the upper 10 cm layer of soil and this in turn increases adventitious shoot growth leading to greater shoot densities. Root length and the number of root buds per metre of root were increased by nitrogen fertilizer, particularly at shallower soil depths (Nadeau & Van Born, 1990). The adventitious root buds are susceptible to freezing injury. When the freezing resistance of overwintering root buds of creeping thistle was evaluated in the laboratory, the temperature required to reduce survival by 50% was  $-7^{\circ}\text{C}$ , (Schimming & Messersmith,

1988). However, freezing resistance is often greater in the field than under artificial conditions.

The underground system can be divided into 3 parts according to Chancellor (1970) and Hamdoun (1970a): thin roots, atypical thickened roots and subterranean shoots (). Four types of underground structure are recognised by Donald (1994): long thick vertical roots, long thick horizontal roots, adventitious shoots and vertical underground stems. The major method of vegetative propagation is the development of adventitious shoots. Although the depth of the subterranean system has been reported at 2-6m, regeneration normally occurs from roots within or just below the plough layer. Excavations of the root system have found 54% of roots in the 7-23 cm layer of soil, 30% in the 23-38 cm layer and 16% in the 38-53 cm layer.

The initial taproot is slender but it produces far creeping white lateral roots that bear numerous adventitious buds that develop into flowering and non-flowering shoots (Clapham *et al.*, 1987). The underground stems of creeping thistle arise as vertical developments of adventitious buds from vertical, horizontal or oblique roots (Hamdoun, 1970a). These shoot buds produce leaf primordia even before they emerge through the epidermis. The first leaves, which act as a protection for the apex when shoots penetrate the soil, remain as simple scale leaves. The lateral roots are very brittle (Salisbury, 1961). Lateral roots develop towards the root apex (Donald, 1994). Adventitious root buds and roots arise in association with lateral roots. Horizontal roots form more adventitious root buds than do vertical roots.

The deep-seated creeping root system is very brittle and easily breaks into pieces (Long, 1938). However, it is only thickened areas of root and the underground stems that are able to regenerate and form new plants. Regions of the lateral roots thicken due to the development of storage tissue and it is here that new shoots are initiated. The shoots that arise from these thickened regions produce aerial shoots and new roots. Adventitious buds are initiated on the roots of creeping thistle in the autumn and winter following aerial shoot death and at any time of year if the shoots are removed. Laboratory studies with root fragments suggest there is no seasonal pattern in bud development (McAllister & Haderlie, 1985).

A 20 cm long piece of thickened root developed shoots and roots within seven weeks of planting. Fragments below 2.5 cm long may not all regrow, units 5-6 cm long were the most successful at regenerating (Sagar & Rawson, 1964). Regeneration was least successful in November. Hamdoun (1972) found that root fragments less than 5 mm long did not form shoots. Shoots were produced by fragments 10 mm long and 1 mm diameter unless they came from immature apical regions. Regeneration was prevented by temperatures below 5°C, the optimum temperature for regeneration was 15°C. Shoots from fragments 2.5 cm long were able to emerge from depths of 50 cm. Under field conditions regeneration of creeping thistle roots was determined from depths of 0, 10, 20, 30 and 40 cm (Thomsen & Brandsaeter, 2007). Shoots emerged more rapidly from the shallower depths but after 2 months roots buried at 30 or 40 cm had produced a similar number of shoots to the other treatments. In pot studies, under controlled conditions, root

fragments were planted 5 cm deep in a loamy sand soil of pH 5.7 (Niederstrasser *et al.*, 2007). Fragments of 1 or 3 cm long rarely produced above ground shoots while 7 or 10 cm long fragments all produced shoots. A moderate level of soil compaction was found to increase sprouting by the 10 cm long fragments. Exposure of 10 to 20 cm root fragments to temperatures of  $-5$  to  $-7^{\circ}\text{C}$  reduced survival (Donald, 1994). Regeneration is poor in waterlogged conditions.

In sand culture, increased nitrogen levels significantly increased shoot and leaf production by leafy plantlets grown from 5 cm root fragments or from seed (Hamdoun, 1970b). The higher nutrient level had much less effect on root development. The higher nutrient level had much less effect on root development. In sand culture studies of different N levels on the development of creeping thistle seedlings, the greatest number of root buds was initiated at the lowest level of N tested (McIntyre & Hunter, 1975). However the greater number of buds initiated may not result in an increase in the number of emerged shoots. At low levels of N the buds have to compete with the parent shoot for a limited supply of the nutrient. Increasing the N levels can result in a marked increase in the number of shoots produced from root buds.

In pot tests, Gustavsson (1997) found that long root fragments (21 cm) produced a greater mass of primary shoots, new roots and shoots on these new roots than did short (5 cm) root fragments. Disturbing the shorter fragments after regeneration when the shoots had 4-7 expanded leaves stopped further regrowth. Disturbance at the 8-leaf stage following regeneration minimised further regrowth of the longer root fragments. In the field, roots buried at 20 cm deep took longer to regenerate than roots planted 5 cm deep. The regenerated plants exhibited minimum regrowth following disturbance at the 10-leaf and 7-leaf stages for shallow and deep planted root fragments respectively.

Lateral shoots that develop from axillary buds on the stem bases that remain after mowing or cutting has taken place are important in maintaining a thistle population in grassland. In cultivated land, creeping thistle shoots can also develop from the axillary buds on segments of stem that have become partially buried in soil (Donald, 1994). Although segments 2.5 to 5.0 cm long can form shoots they often fail to survive because of poor root development. While propagation from both aerial and subterranean stem sections has been successful in the greenhouse it is uncertain how much it contributes to the survival of creeping thistle after soil cultivation. The growth stage of the thistle, the type of stem and the extent of burial are important factors in regeneration in the field (Magnusson *et al.*, 1987). Cut down aerial stems regenerate when the basal 5-6 cm are buried in soil but not when the complete stem is buried. Survival is greatest from aerial stems cut in spring, least from stems cut at the flower bud or post bloom stages and moderate from new shoots that emerge in late summer. Subterranean stem sections cut at 10-13 cm below the soil surface and above the lateral root system did not regenerate in spring or at the flower bud stage whether partially or completely buried. There was some regeneration from new shoots in late summer but the greatest survival of subterranean stem sections was at the post-bloom stage of the thistle. The extent of burial made little difference. The surviving stem sections develop adventitious roots that form propagating roots able to overwinter and produce new shoots in spring.

Shoot emergence in Scotland recorded in field plots dug at monthly intervals began in April-May and continued through until September (Lawson *et al.*, 1974). After flowering in late-summer, assimilates pass down into the underground organs during July to October to build up carbohydrate reserves for the following year (Sagar & Rawson, 1964). The reserves are minimal between May and July. The plant dies down to just below soil level in the late autumn. Some of the underground organs may also rot away leading to fragmentation of the parent colony into units of swollen roots. In spring, shoots that developed on the storage roots the previous autumn grow to the soil surface and develop into aerial shoots. New adventitious roots develop on the shoots and parts of these swell to form the perennating organs for the following year. There is evidence that undisturbed pieces of swollen root can remain dormant in the soil for several years until disturbed by cultivation (Moore, 1950; Soil Association, 2002).

Creeping thistle may have allelopathic properties (Sindel, 1991). It can inhibit the growth of weeds and crop plants growing in the vicinity (Chon *et al.*, 2003). Field and glasshouse studies suggest that creeping thistle residues are phytotoxic to the growth of some crops (Wilson, 1981). Roots and shoots of creeping thistle that were mixed with soil reduced the growth of sugar-beet, wheat and alfalfa. The growth of common amaranth (*Amaranthus retroflexus* L.) and green foxtail (*Setaria viridis* L.) was reduced in soil containing leaf litter, roots or foliage from creeping thistle (Stachon & Zimdahl, 1980). Water extracts from the roots and foliage have inhibited the growth of its own seedlings and those of test species (Bendall, 1975). The presence of creeping thistle residues was also shown to inhibit further growth of the test species.

### **Persistence and spread**

Creeping thistle seed buried in soil retained 55% viability after 5 years (Kjaer, 1940). Seed stored dry gave 86% germination after 1 year but none was viable after 5 years. Chepil (1946b) found that seeds had a relatively short dormancy period of 1-3 years and considered there was little problem of the weed persisting in the soil seedbank. Most seeds emerged in year 1 when sown in the field and no seedlings emerged after year 2. Seed buried in soil at 0-2, 5 and 20 cm had viabilities of 1.4, 30.9 and 50.5% respectively after 3 years (Sindel, 1991). Guyot *et al.* (1962) give the longevity of seeds in soil as 5 to 6 years. Seeds can remain viable in soil for over 20 years (Salisbury, 1962; Weber, 2003; Porter, 1944). The half-life of seed at a depth of 15 cm has been estimated at between 5 and 10 years (Bostock, 1978). Persistence increases with burial depth and seed has remained viable for 20 years buried 105 cm deep. Other evidence though suggests that seed persists for much shorter periods under grassland or in surface layers of soil. Seeds of creeping thistle may be absent altogether or present in very low numbers in grassland soil (Roberts, 1981). In Duvel's seed burial experiment 6, 10 and 21% of seeds remained viable after 10 years burial at 8, 22 and 42 inches respectively (Toole & Browne, 1946; Goss, 1924). After 21 years, 5% of seeds were viable at 42 inches and 1% at shallower depths. No seeds remained alive after 30 years burial. In the laboratory, seed stored at 27°C and 80% humidity died within 6 months. The viability of seed stored dry at 20°C had declined to 12% after 2 years (Amor & Harris, 1975).

In set-aside fields in north-east Scotland, creeping thistle made up a significant proportion of the seed rain (Jones & Naylor, 1992). Seed was shed from early August to early September. Cutting time could influence the amount of seed returned to the soil. Soil seedbank estimates of 1,480 to 26,371 per m<sup>2</sup> have been made in Australia (Sindel, 1991). Heinmann & Cussans (1996) have suggested that reproduction by seed is important solely for colonising new habitats. Seedlings of creeping thistle are rarely seen in arable fields. Nevertheless, investigations into the genetic structure of creeping thistle patches in arable fields have shown that patches are made up of an aggregate of clones each with a diameter of around 5 m (Hettwer & Gerowitt, 2004). Ramets of the same genotype were found only in local patches within a few metres of each other. The results indicate that seedling establishment takes place regularly and is important in the persistence and spread of creeping thistle.

Seed from thistles in the headland can help to maintain an existing field population if seeding is not prevented by cutting (Håkansson, 2003). Each seed bears some forty feathery hairs forming a parachute that spreads open in dry air. Laboratory tests suggest maximum dispersal distances of 7.6 and 11.4 metres at wind speeds of 10.9 and 16.4 km/hour respectively but this would be affected by plant height (Sheldon & Burrows, 1973). Potentially, the seeds could be transported a considerable distance by a strong breeze but generally the seed is firmly held in the seed head while the parachute is readily detached, and most seeds land within a short radius of the parent (Salisbury, 1962). The thistledown seen blowing around in the wind is usually devoid of seed.

Creeping thistle seed has been dispersed as a contaminant of various crop seeds. Creeping thistle was introduced into the USA with crop seed (Mitich, 1988). In seed samples tested by the official seed testing station in 1960-61, creeping thistle seeds were found in 3% of perennial ryegrass seed samples of UK origin and up to 1% of other grass seed samples (Gooch, 1963). In clover and grass seed samples tested in Denmark for the period 1966-69, 1955-57, 1939 and 1927-28, creeping thistle seed was a contaminant in 1.9, 6.3, 9.6 and 7.4% of samples respectively (Olesen & Jensen, 1969). Up to 7% of Timothy seed samples from Sweden contained creeping thistle seed. The seed was also an important contaminant in red clover seed samples. At the Official Seed Testing Station for Scotland the incidence of creeping thistle seeds in certified and pre-certified barley seed 1996/97 showed that seed was present in 2.4 % of pre-certified samples but was absent from certified seed (Don, 1997).

Viable seeds of creeping thistle have been recovered from irrigation water (Kelley & Bruns, 1975; Wilson, 1980). The germination level of seed held at either 30 cm or 1.2 m depth in the water of an irrigation canal was 90 and 19% after 9 and 22 months respectively (Bruns & Rasmussen, 1953). Seed gave 50% germination after 36 months storage in freshwater but did not germinate after 54 months (Zimdahl, 1993).

The seeds have an elaiosome in the form of a peg of tissue inside the collar-like distal end of the fruit (Pemberton & Irving, 1990). This is attractive to ants that may further disperse the fallen seeds. A study in the US found significant numbers of apparently viable weed seeds, including creeping thistle, in manure samples from both heifer and

dairy herds (Pleasant & Schlather, 1994). Seeds of creeping thistle have germinated from the droppings of chaffinches fed on the seeds of a range of weed species (Holmes & Froud-Williams, 2001). However, the germinated seeds represented only a small proportion of the seeds consumed.

A single creeping thistle plant can cover several square metres and crowd out other vegetation (Weber, 2003). Plant colonies have been known to expand radially by 6-12 m per year (Salisbury, 1962). Creeping thistle spreads vegetatively by means of the horizontal underground creeping roots (Holm *et al.*, 1977). These can exceed 5 m long (Weber, 2003). The rate of elongation ranges from 1.5 to 4.0 m per year. The shoots that regenerated from a 7.5 cm fragment of root formed a thistle patch 7.2 m wide after 3 years (Donald, 1994). Patches spread laterally 0.8 to 1.3 m or more a year depending on the site, the year and the land management. Herbicide studies have demonstrated that there is a physical root connection and some translocation of materials between shoots within a clump. In Australia, the rate of spread varied from 4 cm to 3.41 m with an average of 1.50 m (Amor & Harris, 1975). Plant vigour tends to degenerate behind the advancing front. Shoot height and density is greatest within 3 m of the outer edge of a large thistle patch and least near the centre.

The roots are brittle and easily fragmented giving creeping thistle a great capacity for vegetative spread (Bostock & Benton, 1979). Cutting the roots into many small fragments rather than a few large ones increases the potential number of new shoots that will develop. Pieces of root buried in soil can remain dormant for long periods, shoots only appearing after soil disturbance (Moore, 1950; Soil Association, 2002). Fragments of root from creeping thistle plants encroaching from the field margins can be carried further into the field by cultivation. Collection and underground storage of vegetative portions of creeping thistle by rodents has resulted in the unexpected appearance of the weed in previously clean areas (Holm *et al.*, 1977).

### **Management**

The management and control of creeping thistle was reviewed previously by Donald (1990). The impact and control of creeping thistle in grassland was reviewed by Haggard *et al.* (1986). Donald (1990) in reviewing non-herbicidal methods of managing creeping thistle observed that with the exception of biological control, the methods being used were little different from those employed over 150 years earlier. One of the aims then was to destroy the top growth and starve out the roots. This also prevents seed production and limits further dispersal. However, at that time as now no single method was consistently effective in eradicating creeping thistle. It has often been noted that control by any means is erratic. Soil conditions may be responsible, cultural control can be poor on wet soils and is more effective in dry conditions. An integrated control program is best but even this will require 5 to 10 years of timely operations to eliminate the weed. Creeping thistle control is not a 'one-off' treatment.

Methods of cultural control include the use of clean crop seeds, ploughing, harrowing, mowing, grazing, mulching, the use of competitive crops and the cleaning of farm equipment. These approaches applied regularly weaken the plant and its capacity to

produce new shoots, they prevent seed production and reduce further spread. Plant competition can reduce flower production by a factor of 10 (Ang *et al.*, 1994). Both competition and defoliation will reduce creeping thistle biomass. The reduction in thistle growth increases with the level of defoliation but a single moderate defoliation may actually stimulate root growth initially. The effect of repeated defoliation at 14-day intervals is greatest in the presence of plant competition. Repeated mowing in a grass/clover mixture or barley stubble in the previous year reduced thistle biomass in the subsequent year (Melander, 2006). Regular inter-row hoeing in spring barley gave a similar reduction in thistle growth in the following year. Growing highly competitive crops such as grass/clover mixes and winter rye can reduce shoot number in creeping thistle (Böhm & Verschwele, 2004; Verschwele *et al.*, 2003). A 1-year clover-grass ley mulched 3 times gave a 50% reduction in shoot number. Ploughing in autumn and again in spring reduced shoot density to a similar extent. Stubble cultivations on up to 3 occasions followed by uncompetitive crops gave little control of creeping thistle. An increase in creeping thistle patches in fields during and after the transition to organic farming was associated with an emphasis on reduced tillage (Patriquin *et al.*, 1986).

Creeping thistle was found to increase in a series of spring-sown cereals on both harrowed and herbicide treated plots (Rademacher *et al.*, 1970). In Finland too there was an increase in the frequency of creeping thistle in conventional spring cereals in the period 1980 to 1990 (Hyvönen *et al.*, 2003). This may reflect a change in the rate or type of herbicides used. Creeping thistle shoot numbers increased in the first year of set-aside in fields managed under the permanent fallow option in England (Poulton & Swash, 1992).

Infestations of creeping thistle on grassland may be the result of poor management (MAFF, 1976). Under utilisation of the pasture when the thistle is actively growing combined with overgrazing in winter and early spring produces an open sward that is late starting into growth. The grass offers little competition to the emerging thistle shoots and stock generally avoids grazing the thistles, although young shoots are sometimes eaten (Moore, 1975). Close stocking or cutting at a young stage should reduce an infestation. Seedlings of creeping thistle emerge only in areas of soil disturbance such as molehills and adventitious shoot emergence is also greater in disturbed areas (Edwards *et al.*, 2000). Trampling by livestock can cause poaching which leads to ingress by creeping thistle (Wells, 1985). In Australia, studies showed that seedlings only become established in bare areas of dairy pasture, no seedlings emerged where the sward was intact (Bourdôt, 1996). Vegetative spread of creeping thistle was reduced under heavy grazing. The growth of creeping thistle was much less affected by competing pasture plants than growth of the biennial spear thistle (*C. vulgare*).

Over a 3-year period, tight autumn and winter grazing by sheep significantly increased the number of creeping thistle shoots compared with lenient grazing at that time (Pywell *et al.*, 2003). There was less competition from the sward when it was grazed short allowing the thistles to grow unhindered. Thistle shoot density also increased gradually over time in low-density swards. Cattle grazing reduced thistle numbers more than sheep grazing because the vegetation remained taller. Tight spring grazing failed to control

creeping thistle. Some thistles were defoliated but damaged shoots recovered rapidly and few died. Increased stocking rates will reduce the spread of creeping thistle (Amor & Harris, 1975). Sheep and ponies will eat young thistle shoots readily but mature stems are not palatable to stock. Sheep grazing may reduce the competition from neighbouring plants and allow greater survival of thistle seedlings (Sindel, 1991). Intensive grazing of the young, soft shoots in spring is said to control creeping thistle in pasture (Popay & Field, 1996). Late spring or early summer mowing followed by hard monthly grazing can also give good control. Goats tend to graze the thistles as well as the surrounding vegetation but prefer the flowers to the vegetative rosettes. Seeds may pass through their digestive system but less than 0.5% are viable compared with 1% in sheep. Donkeys and llamas will also eat creeping thistles, especially the flowers. Creeping thistle is not grazed by rabbits (Tansley, 1949). Rabbit grazing keeps competing vegetation short allowing creeping thistle to increase (Edwards *et al.*, 2000). Excluding rabbits can reduce thistle shoot density by about 90%.

There is an old country rhyme that goes:

Cut thistles in May, they grow in a day  
*Cut them in June, that is too soon*  
*Cut them in July, then they die*

Where topping is carried out for thistle control in grassland, the cutters need to be set low enough to remove all the thistle leaves. Topping must be repeated twice during the growing season over several years to have a permanent effect (MAFF, 1976). In pasture it is said that cutting early in the year followed by cutting for hay with a further late cut will reduce plant vigour. In grassland studies, repeated annual cutting of creeping thistle in June and September reduced thistle shoot numbers in the long term (Pywell *et al.*, 2003). Topping in early July and leaving the cut material in situ reduced creeping thistle density the following year in grass grazed continually by sheep at some sites but not others even after several years. In the early stages of restoring unimproved grassland cut annually for hay, there was a great increase initially in creeping thistle but annual hay cutting management gradually reduced the infestation. At another site, rotational cutting for hay one year in three was not effective in reducing creeping thistle. Sagar and Rawson (1964) were of the opinion that thistles had the lowest reserves and were most vulnerable just before the flower buds opened. Haggard *et al.* (1982) also thought that thistles were most vulnerable to mowing at the early flower bud stage. In pasture in parts of Australia, slashing the thistles twice per year was the commonest control measure used (Amor & Harris, 1974). In Victoria, mowing once or twice a year was the main alternative to herbicides, but thistle density after mowing once was shown to be no different from leaving the thistles uncut (Amor & Harris, 1977). Repeated mowing will weaken the plant and prevent seed production (Weber, 2003). Depletion of carbohydrates from the root system by mowing or crop competition will diminish the regrowth capacity of the plant (Graglia & Melander, 2005). Repeated hoeing early in the season also diminished the regenerative capacity of creeping thistle (Graglia *et al.*, 2004). Initially, a grass/white clover mix or a red-clover intercrop was undersown in spring barley and grown on after cereal harvest (Graglia *et al.*, 2006). In year 2 the grass/clover

mix was mown several times when creeping thistle shoots were 10 cm high. The red clover inter-rows were hoed several times with a 10 cm wide ducks foot hoe blades when the thistle shoots were 10 cm high. The frequency of mowing and hoeing showed a linear relationship with the reduction in biomass of the thistle in the spring barley grown the following year. In the past, good control was achieved by cutting the weed early, soon after it emerged, and repeating the cutting at frequent intervals throughout the season (Long, 1938). Burning was also said to give some control. In organic meadows, a single cut when the hay was harvested limited the increase in the creeping thistle population (Williams & Mercer, 2002). The inclusion of an aftermath cut led to a 15% reduction in the weed in the following year and the inclusion of a further cut in spring led to a 30% reduction in thistle frequency. Cutting frequency can be reduced as the creeping thistle population decreases.

Control by repeated cutting may take 3 or more years (Salisbury, 1961). In roadside verges, increased cutting frequency reduced the frequency of creeping thistle (Parr & Way, 1984; 1988). Creeping thistle populations gradually increased on land left uncropped and uncultivated but a single late mowing caused a decrease in the thistle population in the year that followed (Hodgson, 1958). In a fertility-building legume crop the effect of different mowing strategies over the year on shoot numbers of creeping thistle was monitored (Cormack, 2002). Mowing at legume height (45 cm) (4 times per year) was compared with mowing ever two weeks (8 times per year) and mowing when thistle buds were visible (3 times per year). The following year shoot numbers were reduced by 75% in all the treatments and it was concluded that maintaining a dense competitive crop was more important than mowing frequency in influencing creeping thistle survival. It is reported that several years of growing alfalfa with regular mowing can eliminate creeping thistle (Patriquin *et al.*, 1986). Mowing to 5 cm after each grazing period practically eliminated creeping thistle after 4 years (Holm *et al.*, 1977). In the USA sowing with alfalfa and mowing once in year one, and twice in the subsequent three years reduced creeping thistle to 14, 5 and 1% of the original population over the 4 year period (Hodgson, 1958). Once control measures cease, creeping thistle populations are likely to recover unless eradication has been complete.

Plants should be cut or pulled just before the flower buds show colour and this should be repeated each year (Soil Association, 2002). Pulling is more effective than cutting because it avoids shoots developing at base of a cut stem. The plants are forced to regrow from new adventitious buds on the underground roots and this is a greater drain on food reserves (Anon, 1937). Lifting in May/June is said to be best but repeated pulling will consume the reserves further. The 'Eco-puller' has been developed to mechanically remove perennial weeds such as creeping thistle from grassland (Soil Association, 2002). It has a working width of 1.5m and a ground speed of 5 kph at 540 rpm. Weeds should be at least 30 cm tall. It works best with a height difference between the weed and the grass. The weeds are fed between rollers that pull vertically to lift out the weeds with 5-10 cm of the vertical roots attached and deposit them into a collecting hopper for disposal. In a trial on grassland grazed by cattle, mechanical pulling in early July appeared to reduce thistle shoot numbers very little initially although stems were damaged (Pywell *et al.*, 2003). However, shoot numbers and percent cover were

significantly lower in the following year. Thistle shoots can be cut by hand just below the point of leaf formation using a chisel hoe. This is carried out in April/May and can be repeated if necessary. Shoots that emerge after chiselling in late May rarely reach maturity.

In experiments carried out at Rothamsted in 1925-7, thistles in cereal crops were pulled after rain in early June (Brenchley & Warrington, 1933). On land being fallowed, in addition to other cultivations, the thistles were cut with a thistle bar in early August and in October. Summer cultivation of fallows and the frequent hoeing of two successive root crops will help to reduce the weed (Morse & Palmer, 1925). The shoots must be destroyed early, soon after they appear, and cut down several times before the end of July. In the USA, repeated hand-hoeing in corn has proved effective in controlling creeping thistle (Donald, 1990). In the past in the UK, a field infested with creeping thistle would be put down to potatoes so that the scuffling, ridging and other operations both before and after crop emergence would reduce the weeds. Thistles that emerged in the crop row were pulled out by hand. In Canada, individual farmers have used spiked-tooth cultivators to loosen the soil around the thistles followed by a rod-weeder to pull out the thistles with around 15-30 cm of root attached.

It has long been known that creeping thistle cannot tolerate shade and smother crops have been seen as a way of managing creeping thistle. Dense fodder crops will help to choke out the weed. Both grass-clover green manures and the use of catch crops can reduce the occurrence of creeping thistle in an organic rotation (Olesen *et al.*, 2005). Heavy stands of forage grasses have been recommended for creeping thistle control but crop management such as the time of mowing can modify their effectiveness (Donald, 1990). In the USA, competitive grasses were as effective as herbicides for controlling creeping thistle (Wilson & Kachman, 1999). In Denmark, crop rotation had an important effect on creeping thistle biomass when the rotation included a grass-clover crop (Rasmussen & Askegaard, 2004). Catch crops appeared to limit the weed as much as intensive cultivations.

In winter wheat in Canada, grain yield within a creeping thistle patch was reduced by 29 to 72% (McLennan *et al.*, 1991). In Greece, straw and grain yield of winter wheat declined as the stand age and density of creeping thistle increased (Mamolos & Kalburtji, 2001). The greater uptake of nitrogen by the weed was a critical factor in limiting crop yield. Shoots of creeping thistle are more frequent in spring-sown than autumn-sown cereals (Håkansson, 1995). In repeated spring barley cropping in the USA, an established population of creeping thistle increased 1.5-fold over a 4-year period (Hodgson, 1958). Where the barley was given nitrogen fertilizer the increase was 3-fold. Competition with spring barley reduced the height, shoot density and biomass of creeping thistle regenerating from root fragments compared with the weed growing alone (Kolo & Froud-Williams, 1993).

Competition with sown species suppressed the growth of creeping thistle in headlands sown with grass or wildflower/grass mixes in comparison with unsown headlands allowed to regenerate naturally (West *et al.*, 1997). The ingress of the weed from the

field margins was reduced but not prevented on sown headlands. Early results from a comparison of different boundary strips including; a cropped strip, a strip kept bare by rotary cultivation, sown grasses and sown wildflowers showed creeping thistle starting to ingress after 2 years (May *et al.*, 1994). Modelling studies of creeping thistle population dynamics suggest that field margin populations often contribute little to weed pressure in the field (Blumenthal & Jordan, 2001). For field margins to influence weed pressure in the field, the weed habitat in the field must be largely unoccupied or the dispersal rates in the margins must be much greater than those in the field. The results indicated that controlling field margin populations may have limited value.

In areas of grassland with high conservation value, dense creeping thistle patches can reduce botanical diversity but measures to control the weed can also harm the desirable plants. Controlled grazing can help to maintain botanical diversity. In a 6-year project begun in 2000, the results after 3 years suggested that the most effective means of non-chemical control on upland and semi-lowland grass was lenient autumn grazing in combination with topping (IGER, 200-). Tight autumn and winter grazing with sheep in upland pasture favoured the weed. In a limited comparison, cattle grazing reduced creeping thistle more than sheep grazing. In semi-lowland pasture, creeping thistle increased under tight grazing in spring, autumn and winter. Tight spring grazing is likely to expose the thistle shoots above the sward and achieve a height differential that will facilitate pulling or wiping with herbicides. The effect of cutting in June and September for the first 2 years had disappeared by year 6 (NERC, 2006). The effects of herbicide treatments applied in the first 2 years were also lost. Lenient grazing appeared to be the best long-term strategy for maintaining creeping thistle at a low density and help to prevent re-invasion.

Tillage can help to control creeping thistle but it can also spread the weed across a field. A single spring cultivation of grassland infested with creeping thistle led to a 25-fold increase in creeping thistle cover within 3 months due to fragmentation of thistle roots and rapid regeneration (Edwards *et al.*, 2000). Cultivation also destroys the competing vegetation giving creeping thistle seedlings an open site in which to develop free of competition unless a rapidly emerging cover crop is sown. Control through cultivation involves working as deeply as practicable with a series of operations spaced through the growing season. Deep ploughing may be the best means of loosening and bringing nearer to the surface the roots of creeping thistle. A cultivator or harrows can follow ploughing. The weeds brought to the surface can be left to desiccate in the wind and sun (MAFF 1949). The aim is to destroy or exhaust the roots by repeated destruction of the regenerating shoots. However, the creeping roots can withstand drying down to 20% of original moisture level (Chancellor, 1970).

In Denmark, perennial weeds are traditionally controlled by stubble cultivations in the autumn after a cereal or pulse crop followed by ploughing in late autumn on a heavy soil or early spring on a light soil but this can result in nutrient losses (Rasmussen *et al.*, 2005a; 2005b). A catch crop can prevent nutrient loss but will limit stubble cultivations. In a long-term crop rotation experiment established in 1996/7 under different soil types and climates, perennial weeds caused increasing problems during the two courses of the

rotation up to 2004 (Olesen *et al.*, 2005). There were lower numbers of thistle shoots and the least biomass after a grass/clover crop than after stubble cultivations with no cover crop. The increased nutrients from the cover crop may have aided crop growth in the following crop. Manure application also reduced thistle shoot density in the following crop.

In practice, where an infestation is very severe, bare fallowing is the only method of destruction by mechanical means (Long, 1938; MAFF, 1976). Regular cultivations should ensure the roots are desiccated. Regeneration under dry conditions is less likely to result in the establishment of new plants. Bare or bastard fallowing is practiced with good results on heavy soils. The baking of the soil clods in hot dry summers dries out the thistle roots (MAFF, 1949). Cultivation every 21 days during one growing season has resulted in a 99% reduction in creeping thistle (Patriquin *et al.*, 1986). There was no regrowth in the year after a series of cultivation had been made every 21 day over 1.5 years (Donald, 1994). It has been suggested that the schedule of cultivation should be kept flexible because the rate of emergence varies with the time of year and soil conditions. Operations should be timed to destroy creeping thistle shoots as they approach 7.5 cm tall (Donald, 1990). This will amount to 6-8 cultivations per growing season. In Canada, a summer fallow has given good control when the land is ploughed by the end of June and then cultivated regularly by surface tillage until autumn (McRostie *et al.*, 1932). Deep ploughing is considered of little benefit as much of the root system is well below the plough layer. The number and vigour of roots and shoots are reduced by persistent tillage. A rod weeder or duckfoot cultivator is more effective than a disc harrow.

In trials in the USA, land infested with creeping thistle was ploughed in April, followed between June and September with cultivations at 2, 3, or 4-week intervals with overlapping sweeps, one-way disking or tandem disking at 10 cm depth (Derscheid *et al.*, 1961). All the implements were equally effective and cultivations at 3-4 week intervals gave 99% control of the thistle in the following season. In other studies, 4 cultivations at 3-week intervals reduced creeping thistle by 88% and when seeded to alfalfa or bromegrass had eliminated the creeping thistle after 2 years of cropping. However, ecotypes of creeping thistle may differ in their response to cultivation (Donald, 1990). Delaying cultivation until the thistle is coming into flower appears to reduce control in the following year compared with tillage when shoot growth is at an early stage.

In the USA, established plots of different ecotypes were cultivated at 3-week intervals with duckfoot sweeps at a depth of 7.5 to 10 cm (Hodgson, 1970). There were 7 cultivations over the first growing season and some ecotypes were eliminated in the first year. Other ecotypes were more resistant but these were killed by a further 3 cultivations made between the start of the season in the following year and the end of July.

In field studies on organic land in Germany soil inversion in autumn or winter was vital for the control of creeping thistle (Pekrun & Claupein, 2004). The weed increased rapidly where non-inversion tillage was practiced but remained at a low level in ploughed areas. Deep ploughing was more effective than shallow in reducing the density of thistle

shoots. Stubble tillage in summer reduced the growth of creeping thistle but shallow ploughing was no better than stubble tillage with a rototiller or other cultivator. The inclusion of perennial fodder crops in the rotation also kept creeping thistle and other perennial weeds at a reasonable level. The abundance of creeping thistle was lowest where a high proportion of mulching crops were grown, especially grass/clover or grass/alfalfa that are mulched frequently (Verschwele & Häusler, 2004). The weed was more of a problem where the rotation included a high proportion of cereals. During the conversion of land to organic, the growing of summer crops and a reduction in the frequency of stubble tillage can increase the spread of local infestations. Creeping thistle increased and became a serious problem during a 9-year period on a trial area managed organically with a crop rotation of cereals and summer crops with legumes grown every 4 years (Verschwele & Häusler, 2005). The soil was ploughed annually in autumn and spring and stubble cultivations carried out with wing shares. The problem was due to ineffective weed control and poor crop competition.

Tillage, cutting and crop competition can be used within a rotation to target and control of creeping thistle but to be acceptable the strategy must be economically viable. A single shallow stubble cultivation immediately after cereal harvest followed by deep ploughing later in the autumn helps to contain populations of creeping thistle in an arable rotation (Pekrun & Claupein, 2006). Lukashyk *et al.* (2006) evaluated progressively deeper stubble cultivations after cereal harvest followed by mown forage crops and compared this with a grass clover ley undersown in the cereal and maintained and cut regularly over the 3-year study, and with a ley mown once in the autumn then ploughed and cultivated before sowing a forage crop. The stubble cultivations followed by forage cropping reduced thistle shoot density the greatest after 9 months and continued to be the most promising combination. However, by the end of the 3-year study all three strategies had reduced shoot density by around 90%. A dense crop cover was vitally important to prevent light reaching the emerging thistle shoots. In trials in Norway, fragmenting the roots into pieces 10 cm or less, burying them at least 15 cm deep and sowing a cover crop strongly reduced the above and below ground growth of creeping thistle (Thomsen *et al.*, 2004).

The effect of improved soil fertility on creeping thistle management is complex and depends on the crop and the rotation (Donald, 1990). There may be an increase in crop competitiveness but creeping thistle may also benefit from a higher level of nitrogen.

Heilman (1993) takes a holistic view and suggests that adopting a proper energy flow in the system will help to solve the problem of creeping thistle. Weed control is considered to be the treatment of symptoms. There is a natural energy flux that needs to be understood, used and managed as a cultural element for the natural regulation which keeps up the fertility of soil. Nevertheless, manual or mechanical removal when the thistles were beginning to flower was the control measure adopted by this author.

A preliminary study in Sweden demonstrated that the number of weed seeds left on the ground after combining oats was much higher than when the crop was harvested with a binder, dried in shocks and then threshed (Åberg, 1956). There were over 175 times

more creeping thistle seeds recorded on the soil surface after oats had been combine harvested.

Studies with soil clods of different sizes and hardness showed that seed germination and seedlings emergence of creeping thistle from larger clods was little different from that of small clods whether the soil was hard or soft (Terpstra, 1986). Seedling emergence is therefore unlikely to be reduced by leaving the soil in a rough state.

A decision-aiding model has been developed that predicts the start of emergence and the time when 80% of creeping thistle shoots are likely to have emerged and when control measures can be initiated if desired (Donald, 2000). Shoot emergence from adventitious root buds in spring has been modelled using degree-day heat sums based on air temperatures above 0°C. The model works well for both till and no-till situations but the depth and timing of primary tillage does have an effect. The starting day for heat sum accumulation will depend on the location. In North Dakota, USA, this is day 91.

In laboratory studies on the effect of heating on seed viability, imbibed seeds in trays of moist soil were no longer viable after being kept at 75 or 100°C for 12 hours (Thompson *et al.*, 1997). At 56°C the results were variable and seed viability was reduced by around 78-98% after 0.5-16 days. Seed held at 204 or 262°C for 5 minutes was killed.

Wheat gluten meal (WGM) at 1 or 3 g.dm<sup>-2</sup> dusted over seeds put to germinate on moist paper reduced germination by 92 and 100% respectively (Gough & Carlstrom, 1999).

There has been considerable interest in the biocontrol of thistles in Canada where they are introduced weeds. Techniques for thistle suppression in North America as a whole have involved the introduction of biocontrol agents from Europe and the Middle East (Trumble & Kok, 1982). The flea beetle *Altica carduorum* Guer. and the stem-mining weevil *Ceutorhynchus litura* F. have been studied in detail and released into the environment (Zwölfer, 1970). The flea beetle *A. carduorum* is native to mainland Europe. The larvae and adults weaken creeping thistle through defoliation and by feeding on the flower buds (Trumble & Kok, 1982). The adults feed throughout the summer, overwinter in the soil and then emerge to lay eggs on the underside of thistle leaves in spring. The adults continue to feed on the thistle after egg laying is complete. Attempts to establish the flea beetle in England and in North America have demonstrated that the life cycle of the insect is slowed by long periods when the temperature falls below 20°C. Delays in egg and larval maturation increase the level of predation during the early growth stages. In the UK, following releases of adult beetles from France egg production was low and mortality high at all stages (Baker *et al.*, 1972). It was concluded that the beetle was imperfectly adapted to the climate in Britain and is unlikely to become more than locally abundant. The beetle has a tendency to aggregate in the field and damage only a few plants in a stand which does not make it a promising biocontrol agent.

In Europe, creeping thistle is the primary host of *C. litura* (Trumble & Kok, 1982). The adults emerge from hibernation in spring and feed prior to laying eggs on thistle rosettes from March to May. The females feed on leaf tissue and deposit their eggs in the

feeding cavities (Rees, 1990). The larvae emerge from the eggs, mine into the leaf veins and move down the stem to the root crown. The mature 3<sup>rd</sup> instar larvae burrow out below soil level and pupate in the soil. The adults emerge in late summer to autumn. The low fecundity and poor dispersal of the species limits its usefulness as a biocontrol agent. The thistle generally survives damage caused by the weevil but the holes it creates provide sites of attack for other pests and diseases. In the USA, *C. litura* took 15 years to disperse 9 km from its release point (Rees, 1990).

The flower weevil, *Larinus planus* attacks creeping thistle flowers and reduces seed production (Sullivan, 2004). The larvae feed on the flowers and the adults consume the foliage. The Chrysomelid, *Spaeroderma testaceum* F. and the flea beetle *Lema cyanella* L. are other candidate species for biological control of creeping thistle in Canada (Zwölfer, 1969).

The thistle-stem gall fly, *Urophora cardui* L. is a phytophagous insect that is highly specific to creeping thistle. It may attack spear thistle (*C. vulgare*) but only if creeping thistle is absent (Trumble & Kok, 1982). It produces large, multi-chambered galls within the stems of creeping thistle (Peschken & Harris, 1975; Shorthouse & Lalonde, 1988; Lalonde & Shorthouse, 1984; Lalonde & Shorthouse, 1985). The female fly lays up to 11 eggs between the developing leaves at the shoot tips and when the larvae hatch in 7-10 days they tunnel down into the stem. Once the larvae reach an area of maturing vascular tissue they initiate a gall. The first swelling becomes apparent 12 to 20 days after egg laying. The gall grows for about 30 days and then becomes hard and woody. The larvae overwinter in the galls, pupation and adult emergence occur in late spring (Trumble & Kok, 1982). The severity of the effect on the thistle depends on whether the galls are on main or lateral shoots and whether the attack is early or late in the season. Gall size depends on the number of larval inhabitants. In the UK it has too restricted a distribution to have a major effect on creeping thistle (Masters & Ward, 2003). Nevertheless, these beneficial insects can provide some background control of thistle populations.

In New Zealand four insect species have been selected that could safely be used against creeping thistle. These are the flea beetles *L. cyanella* and *altica carduorum*, the stem-mining weevil *C. litura*, and the gall fly *U. cardui* (Jessep, 1997). The beetles and the weevil feed on the thistle leaves both as adults and larvae.

Larvae of the painted lady butterfly (*Cynthia cardui* (L.)) have defoliated the creeping thistle, and many other insects have been recorded on it (Moore, 1975). Creeping thistle is a food plant for several leaf-feeding micro-moth larvae.

Creeping thistle is attacked by the rust fungus *Puccinia obtegens* that weakens and stunts the plant, and prevents flowering (Morse & Palmer, 1925). The fungus occurs worldwide and has been evaluated in North America as a potential biocontrol agent (Turner *et al.*, 1981). Infection may cause a local or a systemic infection. If a systemic infection becomes established in the rhizome system the plant produces pale, stunted shoots that rarely flower. The fungus has caused epidemics that have eliminated creeping thistle

from local areas. Ecotypes identified by leaf shape and sprayed with a suspension of uredospores varied in resistance to the fungus. Penetration of the leaf surface by germinating uredospores occurred in both resistant and susceptible ecotypes. Resistance was expressed only after tissue invasion.

If a systemic infection can be established, the rust fungus *P. punctiformis* may cause premature death of creeping thistle or at least prevent it flowering. In Germany, inoculation with the fungus in June combined with the effect of a cutting treatment reduced the number of fertile flower heads that developed. Creeping thistle plantlets treated in late June and again in mid July with a suspension of spores from naturally infected thistles became heavily infected by the pathogen (Sørensen, 2003; 2004). All the infected shoots died. Infected roots exhibited increased sprouting and this combined with shoot death weakened the ability of the thistle to regenerate. The fungus affects the fragrance of the flowers and if they are less attractive to insects, this may decrease pollination levels (Donald, 1994). In North America there is an association between the fungus and the stem-mining weevil *C. litura* (Trumble & Kok, 1982). Insect damage may enhance infection rate and the combination of insect herbivory and fungal infection may add to the stress on the plant (Kluth *et al.*, 2001). It was suggested that the infection could carry over to affect growth in subsequent years (Kluth *et al.*, 2003). Local infections can occur on the leaves but only a systemic infection will have a major effect on thistle growth (Völker & Boyle, 1994). In nature, the systemic infection rate is less than 5% because few spores reach the underground organs. Teliospores washed into the soil infect the emerging thistle shoots which become pale and slender and rarely survive the season. The fungus is host specific and destroys the aerial shoots and weakens the root system, although root buds may be resistant to attack (Slonovschi *et al.*, 1999). The pathogen is ubiquitous, easy to distinguish and extract (Sørensen, 2003). It could form the basis of a mycoherbicide and methods of inducing teliospore production have been investigated (Völker & Boyle, 1994). For extraction to be commercially viable a large number of rust infected thistle plants need to reach the same stage of development simultaneously.

The soilborne fungus *Sclerotinia sclerotiorum* has also been investigated for the control of creeping thistle (TeBeest, 1996; Brosten & Sands, 1986). Applications of inoculum at different plant growth stages caused wilting and death, especially in June when the thistles were at a vegetative stage. The fungus has killed 20 to 80% of thistle shoots but it has a wide host range that includes important crop plants such as lettuce. Studies of ascospore dispersal suggest that airborne numbers decline to natural levels at around 8 m downwind from the point of release (Bourdôt *et al.*, 2001). However, severe meteorological conditions may affect this.

In pot studies, indigenous fungal pathogens isolated from creeping thistle have been tested alone and in mixtures as potential biocontrol agents (Guske *et al.*, 2004). Of the tested inocula, a mixture of *Phoma hedericola*, and a '*Mycelia sterila*' significantly reduced the reproductive capacity of creeping thistle. There appeared to be a synergism between the different organisms that could prove advantageous in the development of future mycoherbicides. In successional fallow field conditions spore suspensions of *Phoma destructiva* and *Puccinia punctiformis* were applied alone or in combination to

natural populations of creeping thistle over a 3 year period (Kluth *et al.*, 2005). There were only minor effects from the single treatments, again there appeared to be some synergism with the combined treatment but reductions in the weed were only transient.

Phytoparasitic bacteria have also been considered as potential biological weed control candidates. Spray applications of *Pseudomonas syringae* with surfactant added have caused severe disease symptoms in creeping thistle (Johnson *et al.*, 1996). In the UK, thistles exhibiting bleached foliage thought to be due to this bacterium were seen on roadsides and grassland in 2006.

Pre-dispersal seed predation is a major reason for low seed output in creeping thistle (Heimann & Cussans, 1996). In October in England, 43% of seedheads have been found to contain insect larvae (Donald, 1994). The main predators are the midge *Dasyneura gibsoni* Felt. (Diptera: Cecidomyiidae) and the fly *Orellia ruficanda* (Diptera: Trypetidae). The larvae of *D. gibsonii* suck the juices from the young seeds, those of *O. ruficanda* burrow into the seeds and consume the contents. Predation levels of up to 26% have been recorded in Europe. In Canada, *O. ruficanda* occurs in 20-85% of seed heads and damages 20-80% of the seeds in an attacked head (Forsyth & Watson, 1985). However, *O. ruficanda* is not considered to be a severe predator.

A rare parasitic plant, the thistle broomrape (*Orobanche reticulata* Wallr.) is said to weaken and kill the weed (Anon, 1997). The broomrape is native to the UK but very rare and local in its distribution which is predominantly in Yorkshire (Stace, 1997; Clapham *et al.*, 1987).

### **Legislation**

The Minister has powers under the Weeds Act 1959 to require an occupier of land to prevent the spread of spear thistle (*Cirsium vulgare*) and creeping thistle (*Cirsium arvense*). Set-aside land is not exempt.

### **Chemical control**

Creeping thistles are a problem in arable and horticultural crops and in grassland. Chemical control of creeping thistle should be part of an integrated management approach, combining effective cultural options where possible (Pollak & Bailey, 2001). Creeping thistles generally have a varied response to herbicide treatment, as there is such variation within the species including the rooting system and growth habit. Spot spraying is a highly effective method of applying herbicides, using a wick applicator or knapsack sprayer.

Dow Shield (clopyralid) is one of the most effective selective herbicides available for controlling creeping thistle (Singh and Malik 1992 & Defra Project Report, 2003) in grassland and arable and horticultural crops. This can be used in a tank mixture with other products depending on the weed flora at the specific site. Herbicide application should occur when the plants are actively growing, usually in late June or July.

There are many other products available for controlling creeping thistle listed in Table 1. The manufacturers' handbooks or the UK Pesticide Guide should be consulted for full details of rates and application details.

Table 1. List of main herbicides available for controlling creeping thistle

<b>Active ingredient</b>	<b>Herbicide product</b>
2,4-D	Various products including Depitox, Dioweed 50, Herboxone
2,4-D + dicamba + triclopyr	Broadsword, Nu-Shot
2,4-D + MCPA	Headland Polo, Lupo
Aminopyralid + fluroxypyr	Forefront
Asulam	Asulox, Spitfire, Greencrop Frond
Clopyralid	Dow Shield, Torate, Greencrop Champion
Clopyralid + fluroxypyr + triclopyr	Pastor
Clopyralid + 2,4-D + MCPA	Lonpar (grassland use)
Glyphosate (wick applications)	<i>Numerous products</i>
MCPA	Various products including Campbell's MCPA 50, Headland Spear, Agritox 50
MCPB	Tropotox, Butoxone, Bellmac Straight
Mecoprop-P	Various products including Duplosan KV, Landgold Mecoprop-P 600

### **Discussion**

Creeping thistle is a problem weed on both cultivated land and in uncultivated areas such as grassland. The introduction of set-aside may have encouraged the weed to increase over the last few years.

Seed is often considered to much less important than vegetative reproduction. Seed predation and the limited persistence of seed in cultivated soil together with the sensitivity of young seedlings to competition limit the likelihood that a seed will produce a mature plant. However, it was as a seed contaminant in cereal grain that creeping thistle spread to North America. It is vital therefore to prevent seed production and early seedling establishment. Many growers consider that creeping thistle seed carried in from adjacent areas is the source of new infestations. It would be helpful to investigate the likelihood of this.

Seed may be a source of long distance dispersal and new infestations but it is the extensive root system that is responsible for the local spread and persistence of creeping thistle. There have been many investigations of the regeneration of root and shoot pieces and the factors that affect this but much of this has been done in controlled conditions. Creeping thistle shoots are a common site in the headlands and margins of arable fields. While this appears to be a source of vegetative spread into the cultivated field it is unclear how important the field margins are for maintaining infestations.

In grassland, most research has investigated the effect of different grazing strategies combined with mechanical or chemical treatments. In general the mechanical and chemical treatments have provided a rapid but short-lived solution while lenient grazing at the correct time has given better control in the long term. More research is needed on how infestations are initiated and how an initial invasion can be prevented. In grassland this may relate to sward density, local disturbance, urine/dung patches, nutrients.

In cultivated soil, combinations of tillage, cutting and crop competition achieve the best control but there is no short-term solution for dealing with creeping thistle. Pulling rather than cutting may prolong the period of regeneration and drain reserves further. In grassland where grazing had left thistle shoots exposed, mechanical pulling would be a practical option.

There has been a great deal of interest in the biological control of creeping thistle particularly in North America where there have been releases of several insects from European sources. Natural biocontrol occurs in the UK and there may be some merit in identifying strategies that enhance the effect of native insects and other biocontrol agents but success is unlikely to come in the short term.

## **The biology and control of broad-leaved dock (*Rumex obtusifolius* L.) and curled dock (*R. crispus* L.)**

### **Occurrence**

The docks (*Rumex* spp.) are a group of native plants that occur in a wide range of habitats and soil types and at altitudes up to 2,000 ft in the UK. Their biology and non-chemical control was reviewed previously by Foster (1989). More recently their ecology and non-chemical control was reviewed by Zaller (2004). Only two species are considered of major concern in agriculture, namely broad-leaved dock (*Rumex obtusifolius* L.) and curled dock (*R. crispus* L.) (Holm *et al.*, 1977). Curled dock is capable of behaving as an annual, biennial or perennial but plants only persist for several years when regularly cut down and prevented from setting seed (ADAS, 1977).

Three subspecies of broad-leaved dock have been distinguished in the UK and four varieties of curled dock but the variation in the two species is further complicated by hybridisation (Williams, 1971b). Intermediate forms of the two species were noted in the British Flora published in 1887 (Bentham & Hooker, 1887). Hybrids between curled dock and broad-leaved dock are quite common and may occupy whole fields (ADAS, 1977; Harper & Chancellor, 1959). They exhibit a range of intermediate characteristics (Lousley & Kent, 1981) and may be more vigorous than the parents. The hybrids are thought to produce little viable seed (Chancellor, 1956; Cavers & Harper, 1964), although the infertile panicles may still develop and turn red in autumn (Lousley & Kent, 1981). However, the presence of fertile hybrids has been reported and there is evidence that backcrossing has occurred to the extent that some plants of hybrid origin are almost indistinguishable from the parent species (Williams, 1971b; Stace, 1997). Both the curled and broad-leaved docks also hybridise with the wood dock (*R. sanguineus*) and the clustered dock (*R. conglomeratus*) when growing in the same area. These hybrids are not thought to be fertile. Hybrids with other docks, such as the water dock (*R. hydrolapathum*), are known but are generally of local occurrence (Lousley & Kent, 1981). In North America, populations of curled dock exhibit considerable genetic variation and this has allowed them to adapt to local conditions (Hume & Cavers, 1982b). Plants from cooler regions are short and compact with large numbers of stomata per unit area, an adaptation to reduce heat loss and optimise CO<sub>2</sub> exchange.

The docks are currently considered by farmers to be among the most important problem weeds in organic farming systems. However, in a 1993 survey of the most important weeds according to European weed scientists, docks were among the top 15 weeds of only one out of ten of the crop groups under consideration (Schroeder *et al.*, 1993). Docks are said to be the most common perennial weed in grassland on dairy farms, especially in young swards (Haggar *et al.*, 1982). A survey of 502 grassland farms in England and Wales found that 40% of farmers thought *Rumex* spp. to be a problem (Peel & Hopkins, 1980). In other surveys, dock infestations were recorded on 8% of grassland. In a postal survey of *Rumex* incidence in UK grasslands, Haggar (1980) found that the highest infestations of docks were in Devon and Sussex. Factors closely associated with the presence of docks were the application of slurry, farmyard manure and nitrogen.

Uneven or excessive application of slurry can smother grass and leave bare patches ideal for dock establishment (SAC, 1986). Cutting for silage was also linked with high dock numbers possibly due to the openness of the sward after cutting. In some surveys, docks were common on soils deficient in potassium, and on soils rich in nitrogen (Haggard *et al.*, 1982). However, in other studies increased potassium levels were associated with greater densities in dock populations (Humphreys *et al.*, 1999). Recent studies in the Netherlands concluded that increasing the potassium status did not favour dock development (Van Eekeren *et al.*, 2006). Few docks were found on fields subject to flooding, cutting for hay or grazing by sheep, but studies in the Netherlands suggest that docks have some resistance to flooding. In a survey of 156 organic farmers in Germany, 80% had a problem with docks. Around 85% of grassland farmers had problems with docks, 20% of them had docks on 30% of the grassland (Böhm & Verschwele, 2004).

Broad-leaved dock is a highly variable perennial species and many forms, varieties and subspecies have been described worldwide (Trimen, 1873; Cavers & Harper, 1964). Broad-leaved dock is found throughout the British Isles and there does not seem to be any climatic limitation to its distribution in Britain. It is less frequent in the north of Scotland but neither the length of growing season nor the winter cold is thought to be responsible. Mature plants can withstand severe cold and drought although seedlings may be killed. Absence from high altitude areas is thought to be due to a lack of disturbed ground at these heights (Cavers & Harper, 1964). Broad-leaved dock is found in widely different plant communities and habitats including woods, arable fields, field margins, short-term leys, permanent pasture, and waste places (Clapham *et al.*, 1987). An open habitat is needed for seedling establishment but mature plants can survive competition. It is often found around gateways and on trodden ground in pastures. It is the most abundant dock in grassland (ADAS, 1977). In a survey of UK cereal field margins recorded as part of Countryside 2000, broad-leaved dock was one of the most frequent species recorded (Firbank *et al.*, 2002). In a survey of weeds in conventional cereals in central southern England in 1982, broad-leaved dock was found in 4, 2 and 2% of winter wheat, winter barley and spring barley respectively (Chancellor & Froud-Williams, 1984). Broad-leaved dock is able to grow on a range of soils except the most acid, although, Brenchley (1913) found it only on sandy soils. While abundant on most soils it to some extent avoids chalk (Morse & Palmer, 1925). In flooded soils, the primary lateral roots of broad-leaved docks do not die but the root system extends due to the formation of new laterals (Laan *et al.*, 1989). Large numbers of horizontal laterals and adventitious roots are formed. In addition, broad-leaved dock develops very thick and unbranched downward growing laterals. Greenhouse studies on climate change showed that broad-leaved dock made enhanced growth at elevated CO<sup>2</sup> levels as long as nitrate and water were not limiting (Arp *et al.*, 1998).

Curled dock occurs in arable and meadowland, sand dunes, shingle and in waste places (Clapham *et al.*, 1987; Tansley, 1949). It has been described as the commonest British dock and is one of the five most widely distributed plants in the world (Cavers & Harper, 1964). Curled dock is found as often among one arable crop as another (Brenchley, 1920). It is found throughout Great Britain but is less frequent in the north according to Harper & Chancellor (1959). Brenchley (1911) characterises it as universally distributed

but more a plant of clay, chalk or gravel than light sandy soils. Curled dock is said to have a preference for level, stone-free, fine-textured, poorly-drained soils (Dale *et al.*, 1965). In Norfolk, farmers considered curled dock to be their worst weed and only constant action kept it in check (Brenchley, 1913). Brenchley (1920) described curled dock as being found as often among one crop as any other. It was found in 41% of crops surveyed including cereals, roots, seed crops and legumes. In a study of seedbanks in some arable soils in the English midlands sampled in 1972-3, curled dock seed was recorded in 3% of the fields sampled in Oxfordshire and 34% of those in Warwickshire but never in large numbers (Roberts & Chancellor, 1986). Curled dock seed was poorly represented in the soil seedbank beneath contrasting pasture types (Champness & Morris, 1948). It often dies after flowering and tends to disappear from permanent grass if new seedlings fail to establish (ADAS, 1977). Individual plants have the ability to survive in a range of environmental conditions through plasticity and genetic heterogeneity (Hume & Cavers, 1982a), while whole populations have become adapted to different climatic and edaphic conditions through resource allocation and reproductive strategy (Hume & Cavers, 1983a). Variants of curled dock grown under the same conditions have been shown to retain some of their distinct characteristics but other differences became less clear-cut outside the natural habitats (Akeroyd and Briggs, 1983a).

Curled dock has a high tolerance of UV-B radiation (Hübner & Ziegler, 1998). Leaves exposed to smog or ozone develop a red coloration due to the formation of anthocyanin pigments (Koukol & Dugger, 1967). Dock numbers may increase in crops weakened by waterlogging (Popay *et al.*, 1994b). Studies in the Netherlands have shown that curled dock is resistant to flooding even at the seedling stage (Voesenek *et al.*, 1993). Older plants can survive 8 weeks of submergence in the dark due to a dormancy strategy characterized by the slower consumption of carbohydrates stored in the taproot (Laan & Blom, 1990). Within a few hours of submergence, the orientation of the leaves becomes more vertical and the petioles lengthen by up to 80% (Voesenek & Blom, 1989). Plants subjected to flooding, were able to adapt to lower light levels by increasing leaf area and developing elongated leaves (Vervuren *et al.*, 1999). In well-drained conditions much of the root growth is concentrated in lower soil layers (Voesenek & Blom, 1987). In response to waterlogging curled dock develops new flooding-resistant roots (Voesenek *et al.*, 1989). The primary lateral roots survive under flooded conditions but the root system becomes extended by the formation of new laterals and adventitious roots (Laan *et al.*, 1989). The primary roots of curled dock were able to recover after aerobic conditions were restored due to the high porosity of the roots enabling internal oxygen diffusion to take place under anaerobic conditions (Laan *et al.*, 1990; 1991).

In the UK, broad-leaved dock is a weed host for the potato tuber eelworm, *Ditylenchus destructor* (Holm *et al.*, 1977; Franklin, 1970). Docks also serve as alternate hosts for bean aphid and mangold fly, and encourage subterranean larvae such as those of the swift moths (Morse & Palmer, 1925). *Mantura rustica* is a nationally scarce species of flea beetle associated with the broad-leaved dock (Crofts & Jefferson, 1999). The larvae are leaf miners.

## **Biology**

Broad-leaved dock flowers from June to October but flowering is delayed by early shoot removal (Clapham *et al.*, 1987). Seedlings of broad-leaved dock generally do not flower in the first year (Chancellor, 1956; Harper & Chancellor, 1959). The few plants that do flower in their seedling year produce an inflorescence from July onwards. A large mature broad-leaved dock can produce up to 60,000 ripe seeds (achenes) per year (Cavers & Harper 1964; Foster 1989). The seeds are shed continuously from late summer through to winter, and can germinate in any month of the year if conditions are favourable.

The seeds are viable from an early stage of development (ADAS, 1977). In grassland, dock seeds harvested at weekly intervals from mid May to late June exhibited low germinability at the time of haymaking (Pekrun *et al.*, 2002). As the plants matured germinability increased. Seeds of broad-leaved dock continued to increase in dry weight and percentage germination even after inflorescences were cut from the plant (Weaver & Cavers, 1980). A few viable seeds developed from flower stems cut just 6 days after flowering. Seeds from inflorescences cut 14 days after flowering and left in the field to mature had germination levels little different from seeds left on the plant to ripen. Seed size does not influence percent germination but the rate of germination decreases with increasing seed size (Cideciyan & Malloch, 1982). Initial seedling growth is slower from smaller seeds but there is no noticeable difference at later growth stages. Defoliation, including grazing by the chrysomelid beetle *Gastrophysa viridula* on broad-leaved dock, reduces seed numbers and seed weight.

Curled dock generally flowers earlier than the broad-leaved dock. Inflorescences are first initiated in April or early May and flowering takes place from June to October (NAAS, 1949). The flowers are usually wind pollinated but visits by bumblebees have been observed (Akeroyd & Briggs, 1983a; Grime *et al.*, 1988). It is reported that 25 to 100% of plants are self-fertile. There is some evidence that both outbreeding and inbreeding may occur in curled dock (Akeroyd & Briggs, 1983b). Plants in open habitats generally flower and set seed in the first year, but in densely crowded populations flowering may be delayed to year 2 or even 3. Under good growing conditions a seedling may flower just 9 weeks after emergence. Sometimes plants flower twice in the year, flowering in May and then again after the first seeds are shed. Unlike in Britain and the rest of Europe, plants of curled dock in most North American populations require overwintering before flowering can occur (Hume & Cavers, 1983b). In short days (8 hrs) curled dock plants were short and took 70 days to flower, in long days (15 hrs) they were tall and flowered after 35 days (Holm *et al.*, 1977). Inflorescences that develop in the autumn on plants that have been cut down earlier in the year are therefore shorter due to daylength as well as the growth check. Some curled dock plants die after setting seed others overwinter as rosettes that develop new lateral shoots in spring from axillary buds on the root crown. Prevention of flowering by mowing or cutting may encourage perennation in curled dock.

In curled dock, the upper part of a flower panicle may be in bud while the lower is forming fruit. The seeds from the top of a panicle are lighter and have thinner seed coats

than seeds from lower down. When a proportion of the flowers were removed from a flowering stem at anthesis, the weights of the individual seeds produced were greater and the seed coats thicker than those from untreated plants. Seeds with thicker coats did not germinate as readily as those with thinner coats (Maun & Cavers, 1971b). Defoliation of the flower panicle at anthesis had little effect on seed numbers but reduced total seed weight per panicle and the proportion of larger seeds. Seeds from defoliated plants had thinner seed coats and absorbed water readily. These seeds germinated more rapidly and had less precise germination requirements than seeds from untreated plants (Maun & Cavers, 1971a). The percentage germination was lower for smaller seeds but seed size had no effect on seedlings growth (Cideciyan & Malloch, 1982). The results could have implications for seeds produced on plants whose leaves or flowers are consumed by insects or partially destroyed by disease. Various figures are given for seed numbers per plant from less than 100 to over 40,000 seeds per year.

Curled dock shoots cut down in flower may not ripen seed, but plants in which the seeds have begun to form and are in the milk stage will form viable seeds. Weaver & Cavers (1980) found that seeds of curled dock continued to increase in dry weight and percentage germination even after the inflorescences were cut from the plant. A few viable seeds developed from flower stems cut just 6 days after flowering. Seeds from inflorescences cut 14 days after flowering and left in the field to mature had germination levels little different from those left on the plant to ripen. Maun (1974) found that cut panicles that were dried immediately did not produce viable seed but panicles placed among mown herbage or buried in soil produced viable seeds even when cut 2-6 days after flowering began. Seeds reached physiological maturity at 18 days from anthesis, around the period of milk ripeness and gave the highest germination from this point on.

There have been wide variations between the findings of different researchers in the germination requirements of dock seed. Cavers & Harper (1966) attempted to clarify the situation by carrying out germination tests on curled and broad-leaved dock seed from different sources. They found no consistent differences in response between the two species. The seeds mostly required light or alternating temperatures for germination. There were, however, differences in the germination response of seeds from different sites, from different plants within a site, from different panicles on the same plant and from different positions within the same panicle. There was no consistent difference in germination due to the maturity of the seed when harvested. Some seeds were heavier and had different requirements for germination than lighter seeds. The heavier seeds were often the last to be shed. After shedding, heavy seeds were likely to remain dormant in soil for a longer period than small, light seeds. When the heavier seeds germinated they gave rise to larger more vigorous seedlings. The variability in the responses of seeds has contributed to the success of docks as weeds. Laboratory studies suggest that diurnal fluctuations in temperature with an amplitude of 2°C promote germination in broad-leaved dock seeds (Thompson *et al.*, 1977). Recent studies on the germination of broad-leaved dock seed have demonstrated a link between the germinability of seed at the time of dispersal and the date of flowering of the parent plant (Honek & Martinková, 2002). Even when the original shoots were cut down this maternal effect was active in the seeds produced at the later flowering. Thee

germination characteristics were correlated with the date when plants would have flowered originally. Fresh seeds of broad-leaved dock may require a short after-ripening period of up to a month but the first seeds that ripen in the year are ready to germinate and produce seedlings by July (Benvenuti *et al.*, 2001).

Freshly matured curled dock seeds are non-dormant and buried seeds exposed to natural seasonal temperature changes for 22 months remained non-dormant (Baskin & Baskin, 1985). Seeds exhumed at monthly intervals gave 80-100% germination in a range of alternating temperature regimes. Seeds collected from individual plants and stored under different conditions of temperature and humidity for 6 months to 5 years all germinated under alternating temperatures and light (Cavers, 1974). In darkness at constant or alternating temperatures, however, there were significant interplant differences in the number of seeds that germinated following different storage conditions. Mature seed of curled dock germinated within a month of shedding under conditions of fluctuating temperature and illumination (Gill, 1938).

In an unpublished HDRA preliminary study, the viability of seed in samples from naturally occurring dock hybrids in the field ranged from 3 to 89% with an average of 41%. The hybrids were identified by the morphological appearance of the plants and their seed integuments. The variation in seed viability may reflect the level of backcrossing that had taken place in the parent plants.

In common with other species colonizing bare ground, seeds of curled and broad-leaved dock germinate better in the light than in shade or in darkness (Grime & Jarvis, 1976). Germination was inhibited under a leafy canopy compared with under diffuse natural light (Taylorson & Borthwick, 1969). Light filtered through leaves is much richer in far-red light which is known to inhibit germination (Górski *et al.*, 1977). When seeds were put to germinate under a leaf canopy or diffuse white light there was no germination under the canopy and 87-93% in the diffuse light. In the USA, freshly shed curled dock seed germinated in the light at alternating temperatures but did not germinate in the dark. Milberg (1997) found that broad-leaved dock seed germinated best in full light or following a 15 second light flash. In darkness or with just a 1 second flash of light, germination was poor. The seed appeared to require light levels above a certain threshold to stimulate germination. The results suggest that cultivation in the light would produce a concentrated flush of emergence while dark cultivation would result in only sporadic seedling emergence. Maun & Cavers (1971a) found that curled dock seed germination in the dark at a constant temperature was poor but seeds germinated rapidly once transferred to the light with alternating temperatures. In broad-leaved dock, under alternating temperatures, increasing the amplitude of temperature fluctuations increased germination in both the light and dark up to an amplitude of 25°C (Thompson & Whatley, 1983). Illumination with red light will induce germination at constant temperature, illumination with far red light will reduce germination in alternating temperatures (Taylorson & Hendricks, 1972). These treatments have contrasting effects on the phytochrome levels that control seed germination.

It was established that at a constant 25°C, 15 minutes illumination with red light was the minimum required to stimulate the germination of fully-imbibed broad-leaved dock seeds (Vicente *et al.*, 1962). To determine the period during water uptake when light was most effective in stimulating seed germination, seeds were put at various constant temperatures between 18 and 30°C and illuminated for 15 minutes at varying times after the start of water uptake. Germination increased with the length of imbibition but the period varied with temperature. Peak germination was achieved when seeds were illuminated after 96, 48, 24 and 20 hours at 18, 21, 24 and 25°C respectively. At 27°C peak germination followed illumination after 72 hours and at 30°C germination was low, showing that higher temperatures are less good for germination. The stimulation of germination was reversible by exposure to far red light for 30 minutes, but this became less effective with time and had no effect after 36 hours. In curled dock, the germination response to irradiation with red light was altered by the imbibition temperature of the seed (Taylorson & Dinola, 1990). Maximum germination followed imbibition at 15°C, while the minimum followed imbibition at 32.5°C. Germination levels fell rapidly following imbibition above 17.5°C.

Broad-leaved dock seed with the seed coat cut or damaged germinated in the dark and was not affected by far-red light (Noronha *et al.*, 1971). Scarification of curled dock seed markedly improved the response to light, moist-chilling and temperature shifts (Hemmat *et al.*, 1985). Removal of the entire seedcoat induced 69% germination in the dark. When scarified seed of curled dock was imbibed and held at 25°C or above for 3-7 days, secondary dormancy was imposed that could only be broken by chilling (Deunff & Chaussat, 1968). Pre-chilling of seed removed the requirement for alternating temperatures, and germination occurred at constant temperatures in the light (Vincent & Roberts, 1977). Pre-chilled seed would also germinate at alternating and certain constant temperatures in the absence of light if nitrate was present. Germination in the light or in darkness occurred at constant temperatures following stratification in the light at temperatures between 1.5 and 15.0°C (Totterdell & Roberts, 1979). However, too long a period of stratification at the higher temperatures re-imposed dormancy. Stratification in the light fulfilled subsequent light requirements but dark stratification did not (Baskin & Baskin, 1978). Therefore seed stratified on the soil surface before burial would probably germinate *in situ* while seed buried and then stratified would not germinate until the soil was disturbed. It appears that losses from the seedbank are possible in the absence of light, leading to a decline in seed numbers even in undisturbed soil.

In Petri-dish tests, a single temperature fluctuation from 20 to 30°C in darkness induced 30 to 40% germination of broad-leaved dock (Van Assche & Van Nerum, 1997). A minimum shift of 5°C was needed but a 15°C change was optimal, and rapid warming gave greater germination. There was some stimulation of germination after a period of just 15 minutes at the higher temperature but 1 hour was better. Although a single shift worked, a cycle of three alternations gave the best result. Warming alone will also stimulate germination. The exposure of imbibed seeds to temperatures of 40°C for 1 hour or 35°C for 10 min stimulated the germination of broad-leaved dock seed (Vicente *et al.*, 1968; Takaki *et al.*, 1981; Hand *et al.*, 1982). Seeds put to germinate at 22°C in darkness or continuous white light gave 30% germination in the dark and 90% in the light (Tretyn

*et al.*, 1988). Meneghini *et al.*, (1968) found that broad-leaved dock seed germinated in the dark if imbibed and subjected to a higher temperature (35-44°C) than the optimum germination temperature of 25°C for 2 hr or lower temperatures (4-15°C) for 32 hr. Exposure to red light for 10 min would also stimulate germination (Takaki *et al.*, 1981; Hand *et al.*, 1982). The stimulating effect of high temperature and red light can be reversed by irradiation with far-red light immediately after treatment. Taylorson & Hendricks (1973) found that imbibed seeds of curled dock held in darkness at temperatures above 5°C developed secondary dormancy and became increasingly less responsive to red light the higher the temperature and the longer the exposure. The dormancy could be overcome by a prolonged period at a low temperature or a brief high temperature shift. In laboratory studies, increasing the amplitude of the fluctuation in day/night temperatures also increased germination levels (Benvenuti *et al.*, 2001). Germination increased following a period of dry storage (Grime *et al.*, 1988). In laboratory tests with dry-stored curled dock seed sown on moist paper or soil in the light there was around 60% germination at a constant 18-20°C (Cross, 1930-33). At alternating temperatures of 20 / 30°C or 8 / 20 / 30°C seeds gave over 80% germination.

Both species germinate readily on the soil surface (Mohler, 1993). In pot tests, the percentage germination of curled and broad-leaved dock seed was reduced if the seed was buried just 10 mm deep in soil (Weaver & Cavers, 1979a). With curled dock, seedling emergence was significantly greater when seed was left on the soil surface rather than buried (Boyd & Van Acker, 2003). Nineteen days after sowing, emergence was 48, 21, 10 and 5% for seeds sown at depths of 0, 10-20, 30-40, and 60-70 mm respectively. This suggests that seeds may be better left on the soil surface after shedding to encourage germination and predation, but germination will only occur if sufficient moisture is present. Burial of curled dock seed beneath a 6 mm layer of sand reduced germination levels or greatly prolonged the period of seedling emergence, and is cited as an example of enforced dormancy (Maun & Cavers, 1971b). Benvenuti *et al.* (2001) found 80 mm to be the limiting depth beyond which no germination occurred. Recovery of the seed demonstrated that this lack of emergence was not due to fatal germination. In a loam soil more than 90% of dock seedlings recorded in the field had emerged from the top 15 mm of soil (Unpublished results). The maximum depth of emergence was 25 mm.

In broad-leaved dock seed buried 25 mm deep in soil cultivated at monthly intervals, seedlings emergence occurred throughout the year with a peak flush in April that tailed off through to July/August (Chancellor, 1979). Roberts & Neilson (1980) found that odd seedlings emerged throughout the year from seeds buried at 75 mm deep in soil that was cultivated three times per year. Peaks of emergence occurred in April and from July-October. Seeds mixed into soil in February from seed heads that had stood through the winter began to emerge from March (Unpublished data). The soil was stirred at monthly intervals, and emergence was greatest in April/May and July/August then tailed off in September/October. In this limited study with a clay loam soil the depth of seedling emergence ranged from 0 to 70 mm. In the peak periods of emergence seedlings emerged from deeper in the soil than earlier or later in the year.

In curled dock germination was mainly from March to April and from July to August (Chancellor, 1970). Roberts & Neilson (1980) found that emergence of curled dock occurred mostly from March to September but with odd seedlings emerging throughout the year. In common with many weeds, flushes of curled dock seedlings emerge soon after periods of heavy summer rainfall. Under natural conditions seeds near the soil surface are subjected to periods of wetting and drying, alternating temperatures and light which primes them to germinate rapidly after substantial rainfall (Vincent & Cavers, 1978). Seeds buried deeper in the soil are not subjected to this combination of factors and remain dormant.

Dock seedlings have a low competitive ability and find it difficult to become established in closed vegetation. Seeds of curled and broad-leaved dock sown in December in different habitats showed flushes of emergence in March-April and July-August but few of the seedlings survived more than a few months (Cavers and Harper, 1967a). In pot studies, broad-leaved dock sown at the same time as perennial ryegrass (*Lolium perenne*) suffered competition from the grass (Keary & Hatcher, 2004). When the dock seed was sown 21 or 42 days in advance of the grass the dock seedlings were able to establish a leaf canopy. In other pot experiments, twice as many curled dock seedlings became established in a clay than in a silty-loam soil (Harper & Chancellor, 1959). Seedling establishment was poor in waterlogged soils and in the presence of ryegrass. Seedlings often emerge in the open on cultivated ground or in pasture where the turf has become damaged. When curled dock seed was sown in field plots where the existing vegetation had been dug in to represent disturbed patches, sowing density had no effect on emergence (Weaver & Cavers, 1979a). More seedlings survived over-winter where a larger area of soil was disturbed perhaps because encroachment by the existing vegetation was less complete.

Dock seedlings can emerge in dense patches but the level of seedling mortality increases with seedling numbers (Chancellor, 1956). Seedlings emerge at different times through the year but time of emergence has little effect on survival (Pino *et al.*, 1997). Survivorship has more to do with seedling age and size. Mortality is greater in small, young seedlings. Unpublished preliminary studies suggest that the microbiological and nutrient status of the soil can have a significant effect on dock seedling vigour. In Canada, it was found that fewer than 10% of curled dock seedlings survived into the following year (Weaver & Cavers, 1979b). Young transplants survived for 12 months in the same habitats and some plants of curled dock flowered but many suffered leaf losses on transplanting and subsequent growth was poor. Transplants of broad-leaved dock actively competed with other herbage plants and were better adapted to long term survival than curled dock. However, less than 2% of month old seedlings of broad-leaved dock transplanted into an old reseeded grassland survived for up to 4 years (Hongo, 1989b). In newly sown grassland, dock seedling survival was enhanced by frequent cutting of the sward (Hongo, 1989a). Broad-leaved dock is better adapted to survival in grassland than curled dock but the latter has a better capacity to multiply in unstable arable habitats.

Once broad-leaved dock has developed a deep taproot it has an advantage over shallow rooted crops and grasses and becomes difficult to eradicate. The roots may extend to a depth of 1 to 1.5 m on some soils. Established plants can withstand trampling and mowing. New shoots are sent up soon after decapitation and flowering is merely delayed until autumn (ADAS, 1977). Repeated regeneration may lead to the development of large clumps. Broad-leaved dock overwinters as a rosette with small dark leaves and a stout rootstock. In spring new leaves develop rapidly and there is a vegetative phase of elongation. A vertical underground stem is developed around 5 cm long. The flowering stem arises from the apex of a shoot and may grow to 1.2 m tall and is well branched. Further shoots may originate from adventitious buds on the underground stem, particularly after damage. Flowers are initiated in early May and the first flowering occurs in late-May or June and the second in August-September according to Cavers & Harper (1964). However, the NAAS Advisory leaflet (1949) gives the flowering period as just August to September.

Individual plants of broad-leaved dock, especially in pastures, can be very long-lived forming compound crowns with multiple taproots. Secondary taproot production occurs in the second flowering year when the stem system begins to branch (Pino *et al.*, 1995). After three years, the taproots increase in size and the underground organs begin to fragment. Older plants become heavily divided and secondary taproots turn into the main root system which then produces further secondary taproots. Eventually a dense population from a single clone will occupy a large area. Clonal growth is the main method of regeneration in dense vegetation where seedling establishment is unlikely to occur. When grassland is ploughed, seedling recruitment and re-establishment from fragments become more important in the regeneration of the dock population.

There is some confusion about the ability of broad-leaved dock to regenerate from underground organs. The vertical underground stem may reach 5 cm in length and the crown is presumably kept at ground level by root contraction (Cavers & Harper, 1964). The roots beneath this are large, fleshy and fanged. Several authors claim that regeneration is possible from any part of the underground organs even if cut into short pieces (Hunt & Harkess, 1968). However, detailed studies have also shown that only fragments from above the root collar are able to produce new plants (Roberts & Hughes, 1939; Pino *et al.*, 1995). In pot tests with pieces of broad-leaved dock 'root', no regrowth occurred from pieces taken from 9-15 cm depth. It was reported that this was because buds did not develop on dock 'root' tissue taken from below 9 cm deep (Dierauer, 1993). While detached portions of the true root are said not to grow into new plants (MAFF, 1956), Hudson (1955) obtained regeneration from a small percentage of true root segments taken in March. In general though, true root cuttings do not regrow and it may be that a small portion of stem tissue was present on the few roots that did regenerate. It is now 'commonly agreed' that only the upper 7.5 cm of the underground organs of broad-leaved dock will regenerate and that regeneration occurs more readily early in the season (Holme *et al.*, 1977b). However, some farmers would disagree, and shoot regeneration has been noted on the lateral root of a decapitated taproot (personal observation). It takes around 50 days from emergence for a seedling to develop a rootstock that will regenerate if the seedling is decapitated (SAC, 1986; Monaco &

Cumbo, 1972). It has also been observed that the flower stems of broad-leaved dock that have been trampled down into contact with the ground can form new plants at the leaf axils (personal observation).

Most authors agree that curled dock does not regenerate vegetatively as extensively as broad-leaved dock but again there is some confusion. A thick fleshy underground stem 3-4 cm long surmounts the vertical taproot. Root contraction keeps the crown of the plant at or beneath the soil surface. According to MAFF (1956), detached portions of the true root do not regrow. It is 'generally agreed' that only the upper 4.0 cm of the underground organs of curled dock will regenerate and this occurs more readily early in the season (Holme *et al.*, 1977b). Hunt and Harkess (1968) state that curled dock only regenerates from the top 2.5 cm or so of root. However, Chancellor (1956) found that curled dock regenerated from 1 cm segments taken from 12.5 cm below soil surface. Seedlings take around 40 days from emergence to develop a rootstock that will regenerate if a seedling is decapitated (Monaco & Cumbo, 1972). Regrowth of curled dock from the rosette stage begins very early in spring with the first warm weather.

### **Persistence and Spread**

Estimates put dock seed numbers in soil at five million seeds per acre in the top 15 cm of soil (Hunt & Harkess, 1968). The seeds are said to be capable of surviving in the soil for 50-60 years (Healy, 1953). Seeds of both curled and broad-leaved dock contain high concentrations of *Ortho*-dihydrophenol (Hendry *et al.*, 1994). The chemical is thought to inhibit microbial decomposition of the seeds as well as defending them against herbivory. In Duvel's buried seed experiments, 3-5% of broad-leaved dock seed survived after 39 years burial in uncultivated soil below 55 cm. Earlier in the experiment, after 20 years burial at 10, 55 and 105 cm deep, over 80% of the seeds were able to germinate (Toole & Browne, 1946; Goss, 1924). Seeds in dry storage remain viable for 8 years (Brenchley, 1918).

Curled dock seed that had been buried 25 cm deep in soil for 5 years retained over 80% viability (Kjaer, 1940). Goss (1924) recorded levels of germination of 9, 24 and 14% respectively in seed buried in soil for 20 years at 20, 55 and 105 cm deep. In Duvel's seed burial experiment 12% of curled dock seeds buried in soil at 105 cm survived after 30 years and 6% after 39 years (Toole & Browne, 1946). In Beal's seed burial experiment curled dock seed remained viable after 50 years burial in soil at 50 cm deep (Crocker, 1938). Curled dock was one of only three species with seeds that survived after 70 years burial in the experiment (Darlington & Steinbauer, 1961). Two percent of the seeds remained viable after 80 years but none survived 90 or 100 years burial (Kivilaan & Bandurski, 1981). Seed buried in mineral soil at 13, 26 or 39 cm depth and left undisturbed retained 30, 26 and 0% viability respectively after 20 years (Lewis, 1973). Seed buried in a peat soil at 26 cm for 20 years retained 13% viability. In studies with seeds buried at 2.5, 10.0 or 17.8 cm deep in soils with different water tables, seeds of curled dock did not deteriorate as quickly as those of other species (Lewis, 1961). Most seeds survived 1 month of burial but germination levels were somewhat less after a further month. Waterlogging appeared to induce dormancy and prevent sprouting in situ.

Dock seeds buried in the soil, can germinate rapidly following soil disturbance if conditions are favourable (Roberts & Totterdell, 1981).

There is no obvious natural seed dispersal mechanism but the seeds are said to be light enough to blow in the wind (Cavers & Harper, 1964). Spines on the perianth segments may also facilitate distribution on clothing and in animal fur. Nevertheless, dock seedlings often occur in patches around the parent plant. In the USA, viable dock seeds have been found in irrigation water taken from open waterways (Shull, 1962; Kelley & Bruns, 1975; Wilson, 1980). Seeds of both curled and broad-leaved dock have been shown to float for up to 2 days in water (Cavers & Harper, 1967b). The winged integuments around the seeds help to keep them floating. Seeds of the maritime form of curled dock will continue to float for several months. Most seeds of curled dock decomposed after 9 months submergence in water (Bruns, 1965). Around 77% were still viable after 6 months and a few seeds remained firm and possibly viable for 36 months.

Docks have been introduced onto clean land as impurities during the sowing of cereals or pastures (Long, 1938; MAFF, 1956). The incidence of dock seeds in samples of wheat, barley, oats and rye tested by the Official Seed Testing Station from 1961 to 1968 was 2, 2, 3-8 and 2-10% of samples respectively (Tonkin, 1968). Curled dock seed was by far the commonest contaminant being found in around 1% of wheat and barley seed samples tested by the Official Seed Testing Station each year between 1961 and 1968. In oats the frequency was 2% and in rye between 0.4 and 5.0% of samples contained curled dock seed. In cereal seed sampled in the period 1978 to 1981, curled dock seed was found in up to 5% of wheat and up to 4% of barley samples tested (Tonkin, 1982). At the Official Seed Testing Station for Scotland the incidence of curled dock and other weed seeds in certified and pre-certified seed 1996/97 showed that seed of curled dock was present in 3.5% of pre-certified samples but was absent from certified seed (Don, 1997). Most of the contaminated samples contained just a few seeds but the highest figures for dock seeds in an 8 oz sample were 131 seeds in wheat, 157 in barley and 69 seeds in oats. In a survey of cereal seed drilled in 1970 on UK farms, curled dock seed was found in 15% of samples from home saved seed but none in merchants' seed (Tonkin & Phillipson, 1973). Broad-leaved dock seed was found in 10% of samples from home saved seed with none found in the merchants seed. The results emphasise the need for cleaning and testing of home saved seed before use. Curled dock seed was shown to survive storage under granary conditions for up to 4 years (Lewis, 1958).

Long (1938) commented that curled dock was much commoner than the broad-leaved dock in areas where clover seed was produced, and that its seeds were likely to be found in samples of English clover seed. In 1960/1 and 1963/64, it was common in samples of both English and New Zealand red clover (MacKay, 1964). In seed samples tested by the official seed testing station in 1960-61, curled dock seeds were found in up to 8% of grass seed samples of UK origin and up to 16% of Scandinavian origin (Gooch, 1963). Up to 22% of red and up to 17% of white clover seed samples contained curled dock seed. In general, the frequencies were lower than those recorded in 1951-52, perhaps due to greater herbicide use. Dock seed was an important contaminant in up to 18% of forage, root and vegetable brassica seed, 4% of leek and 3% of carrot seed samples

tested. Curled dock seed was also likely to be found in seed of rye-grass, cock's-foot and Timothy (ADAS, 1977). The level of dock seed contamination of herbage seed samples in 1956 from a range of countries suggests that in the past docks with varied genetic backgrounds are likely to have been introduced into the UK (Wellington, 1959). The contamination of some grass and clover seed samples in 1956 was little better than in 1922-23 despite improvements in seed cleaning.

Dock seed is likely to be shed and spread during cereal harvesting both in the cropped area and further afield. It can be carried on farm machinery and in the straw as well as among the harvested grain. Curled dock seed that had been combine harvested germinated 4 to 24% more than hand harvested seed (Currie & Peeper, 1988). This was probably due to scarification of the seed coat during mechanical harvesting. Scarified seed responds more readily to germination enhancing stimuli such as moist chilling treatments than intact seed (Hemmat *et al.*, 1985).

In a weedy alfalfa crop (*Medicago sativa* L.) much of the dock's seed was removed from the field as ripening seed heads bailed with the crop (Pino *et al.*, 1993). Hagggar *et al.* (1982) thought one cause of a dock build up was the feeding of contaminated hay and concentrate feeds to cattle followed by the application of their infested manure to the fields. Dock seeds are able to pass through the digestive tract of cattle unharmed (Hance & Holly, 1989). Viable seeds have been found in cattle droppings and are said to remain alive for at least 3 weeks in dung compost. A study in the USA found significant numbers of apparently viable weed seeds including docks in manure samples from both heifer and dairy herds (Pleasant & Schlather, 1994). In other studies, curled dock seeds gave 58% germination after 47 hours digestion by cattle and 3% germination if then stored for 3 months in the manure (Zimdahl, 1993). Dock seeds were destroyed when fed to chickens (Holm *et al.*, 1977). However, while the viability of curled dock seeds consumed by the chickens was destroyed, dropped seeds could still contaminate the poultry manure (Copper *et al.*, 1960). Dock seedlings have been raised from the droppings of other birds (Salisbury, 1961). In laboratory tests, only low numbers of dock seeds were ingested by earthworms but intact and viable seeds were found in worm casts (McRill, 1974). While not a very effective method of dispersal it may provide a site for the establishment of seedlings in a grass sward.

Trials have shown that dock seeds can survive long periods of immersion in slurry. Germination levels of 10% after 16 weeks at 20 °C and 26% after 24 weeks at 8-10 °C have been reported (UKMANI, 1974). Immersion of broad-leaved dock seed for 6 weeks in untreated cattle slurry had little effect on percentage germination at any temperature. The germination decreased to a low level in aerated slurry and in slurry fermented for methane production, viability was lost after 4 weeks (Besson *et al.*, 1986). The effect was much greater in untreated pig slurry where viability was low after 6 weeks at 4 °C and was nil after 4 weeks at 14 °C. Dock seeds were killed after 1 week in aerated pig slurry.

The viability of mature dock seeds was reduced in silage particularly where 0.5% formic acid was added to the silage to aid fermentation (Masuda *et al.*, 1984). Broad-leaved

dock seeds ensiled in grass silages of different dry matter percentages showed a decline in vitality with time (Van Eekeren *et al.*, 2006). Seed viability was lost after 6 weeks in silage with a dry matter of 23% and after 8 weeks when the dry matter content was 34%. At 60% dry matter, 30% of seeds were still viable after 8 weeks ensilage.

Studies of the effect of temperature on the viability of imbibed weed seeds suggest that seeds of broad-leaved dock require relatively high temperatures to destroy viability (Thompson *et al.*, 1997). Temperatures up to 56°C for 16 days did not affect subsequent germination. This is around the temperature at which sewage sludge may be maintained to avoid killing beneficial micro-organisms. Dock seeds held at 75 or 100°C for 16 days were killed. A few minutes exposure to a temperature of 83°C was sufficient to prevent dock seed germination.

### **Management**

There are some who would argue that docks are not true weeds of grassland because they contribute to the herbage and hence do not need to be controlled. They may also contribute trace elements to a grazing animals diet. The leaves of curled dock, for example, contain an unusually high amount of zinc (Karlsson, 1952). Studies of the nutritive value of a range of grassland species indicated that broad-leaved dock was relatively high in P and K levels in the leaves, and particularly high in Mg (Wilman & Riley, 1993). There are potential advantages in enhancing the concentration of important elements in the diet of livestock through the presence of dicotyledonous weeds (Wilman & Derrick, 1994). However, curled dock has a relatively high content of oxalic acid that can affect dietary calcium bioavailability (Guil *et al.*, 1996). In addition tissue analysis shows it is low in calcium. The high oxalic acid to calcium ratio, with a mean value of 32, could exacerbate the adverse impact on calcium nutrition.

In the USA, studies of the forage quality of curled dock showed that at the early vegetative stages it had a comparable quality to cultivated forages (Bosworth *et al.*, 1985; Marten *et al.*, 1987). Its value as forage and the palatability to grazing lambs rapidly decreased as the plants matured. In feeding studies with sheep the voluntary intake of dried broad-leaf dock was high and it was readily broken down during maceration (Wilman *et al.*, 1997). The rate of intake of the fresh leaves was low, particularly when chopped, probably because of the taste or smell (Derrick *et al.*, 1993). When 10% broad-leaved dock leaves were included in the Lucerne/grass diet of stall fed cattle, the animals suffered no bloat (Waghorn & Jones, 1989). Cattle fed on herbage without the added dock leaves did suffer bloat. Tannins in the dock leaves precipitate out soluble protein in the rumen liquor. Omrod (1966) considered that in grassland even a severe dock infestation was likely to occupy less than 5% of the pasture. Nevertheless, the presence of broad-leaved dock in grassland at densities of 5 to 10 docks per m<sup>2</sup> reduced the weight of harvested grass by 30%, although the total weight of herbage remained constant (Oswald & Haggard, 1983). It was estimated that a 20-30% ground cover of docks would result in a 20% reduction in grass growth.

In a study of changes in the botanical composition of grassland fields during the organic conversion period, docks appeared to increase in young swards to a plateau of 40% of

fields in which docks were visible. However, the docks were only becoming a problem in 20% of fields. About 10% of swards still had an actual dock problem after 5 years (Haggar & Padel, 1996). The number of long-term pastures in which docks were a problem fell from 20% at the start of conversion to 5% by year 4. In a survey of the impact of sward management practices, dock density increased during conversion on fields cut for silage but decreased on grazed fields. A simple mathematical model to study the economics of controlling broad-leaved dock in grassland has been constructed based on data from several sources (Doyle *et al.*, 1984). The model was designed for determining the merits of herbicide use but with further research input it might provide some insight into the economics of other control strategies.

Broad-leaved dock was said to be avoided by cattle, sheep, horses and rabbits but was apparently eaten readily by deer (Cavers & Harper, 1964). However, Courtney & Johnston (1978) found that in grassland grazed intensively by dairy cattle the consumption of broad-leaved dock was the same as that of the grass, and that the dock had comparable digestibility. Docks also made a substantial contribution to the total herbage under a system of cutting for conservation silage, and were acceptable to stock (Courtney, 1972b). Sheep are more selective grazers than cattle but horses are the most fastidious (Haggar *et al.*, 1982). Horses should therefore graze with sheep or cattle to prevent a build up of docks. It has been suggested that sheep are used to graze off seedling docks in the autumn and mature docks in March–May when they are most palatable. Sheep will eat young dock plants if grazed tightly and will take out the crowns but care is needed to avoid damage to the pasture. Cattle will graze young docks with less risk of overgrazing and if grazed periodically at intervals of less than 3 weeks the docks are kept in check. Unlike cattle and sheep, horses tend to confine their droppings to one area of a field and this can lead to ingress by docks where the dung is concentrated (Wells, 1985). In Germany, grazing pasture with small ruminants reduced dock populations within 2 years (Böhm & Finze, 2003). Sheep reduced the docks by 42% and goats reduced them by 71%. Where the pasture was grazed by cattle the population increased. The increase was greater with strip grazing than with rotational grazing. Nuoffer (1993) found that goats were selective in grazing curled dock in field beans and potatoes. It is known that different breeds of livestock vary in their grazing or browsing preferences and abilities and this may need to be taken into account for improved dock control (Soil Association, 2002). Pigs grazing on grassland may not eat the dock roots but will uproot them (Short, 2005).

A newly sown ley, being very slow to develop a dense sward, is vulnerable to dock infestations from seeds in the seedbank (Hopkins & Bowling, 1998). Initially the dock seedling are sensitive to competition from the grass and increasing the sowing rate of perennial ryegrass can have a marked effect on dock development. In resown grass/clover infested with broad-leaved dock seedlings, cutting reduced seedling numbers (Van Eekeren *et al.*, 2006). Increasing the cutting frequency from every 6 weeks to every 2 weeks reduced root biomass but did not increase seedling losses over a 25-week period. Once out of the seedling stage, docks growing in grass are resistant both to grazing, cutting and to competition from the grass (ADAS, 1977). No system of mowing is fully effective (MAFF, 1956). Broad-leaved dock seedlings were favoured when swards were

cut frequently whereas mature docks grew better in grass cut infrequently (Hughes *et al.*, 1993). Frequent cutting encouraged regeneration of taproots and branching of the shoots, increasing the potential for future growth. In trials, the cutting height, cutting frequency and fertilisation regime were all found to affect docks to some extent (Hopkins & Johnson, 2002). The results may assist in containing an infestation, but none of the treatments presented a possible method for controlling docks completely. Cutting needs to be low enough to take off all the leaves and frequent enough to prevent the regrowth flowering but timing may depend on the system of pasture management. Cutting grass shorter may give the docks an advantage. Courtney (1986) reported that when a grass sward was cut frequently (5-7 cuts per year) the presence of docks had little effect on yield. When the sward was cut less frequently (3-4 cuts per year) total yields were reduced and the herbage contained a high proportion of dock foliage. Niggli *et al.* (1993) found that cutting at 6-week intervals favoured the docks more than cutting every 4 weeks. The docks were also favoured by increasing nitrogen rates, but the composition of the grass sward affected dock growth too. Pure swards of Italian ryegrass hindered the growth of young docks more than pure swards of perennial ryegrass, smooth meadow-grass or meadow foxtail. However, the regrowth potential of the docks increased when grass competition was reduced by cutting. The relative growth rate of broad-leaved dock was shown to exceed that of perennial ryegrass (Jeangros & Nösberger, 1992). The dock allocated more dry matter to the leaves and was less sensitive to a reduction in light intensity under shading. In curled dock, the starch content of the root declines after defoliation and may take 3 weeks to return to previous levels (Hatcher, 1996). Repeated defoliation within periods shorter than 3 weeks may eventually lead to plant death.

Trials have been carried out to determine the effect of using a mechanical soil aerator in spring on the development of docks in a dock-infested silage field (Hopkins, 1999). The treatment applied in April had some benefit over the non-aerated area perhaps through improved sward growth or disruption of the dock roots but after three years no significant difference was detected.

While NPK fertilizers had no effect on the germination of broad-leaved dock seed in grassland, increased levels of N reduced dock seedling establishment due to improved grass growth (Humphreys, 1995). The rapid achievement of a dense ground cover in sward establishment also reduces dock numbers. Dock longevity is favoured by a longer interval between cutting or mowing of the sward. Grass has a lower requirement for K than docks and grows better when the N level in soil is relatively higher than P & K. Cattle slurry has a high content of K compared with the levels of N & P and docks are able to take advantage of this, especially at high application rates. Applications of slurry in late summer or autumn favour dock seedling establishment. Cow slurry has been shown to supply K in excess of the requirement of the grasses in the sward allowing it to accumulate in the soil (Christie, 1987). It is better to apply the slurry earlier in the year and at moderate rates or as split applications. It is better to apply the slurry earlier in the year and at moderate rates or as split applications.

In grassland a high dock seed bank population in soil does not necessarily lead to a high infestation of docks (Pekrun *et al.*, 2005). The establishment of seedlings can be minimised by avoiding gaps in the vegetation. In pasture, it is prudent to avoid sward damage from trampling and poaching, particularly overwinter (ADAS, 1977; Hopkins & Bowling, 1998). Winter grazing and winter cutting regimes should be avoided (Philipps *et al.*, 2003). Dock plants in and around the field should be prevented from seeding. Slurry should be applied evenly to avoid creating patches where dock seedlings can emerge.

Established plants should be removed by pulling, spudding or using a docking-iron when the soil is soft (NAAS, 1949; Morse & Palmer, 1925). In an arable field, the level of control increased with the extent of removal of individual dock plants (Pekrun *et al.*, 2002). The maximum amount of root should be extracted. Removal must take place before flowering and all plant parts should be burned. Pulled docks must not be thrown on headlands or in ditches where they are likely to survive. However, it has been observed that sheep will eat pulled dock plants left on the headland (Personal communication). The time taken to extract docks with hand tools depends on the growth stage of the dock, the terrain, the density of the dock population, the density of other vegetation and the level of soil moisture. Large docks taken longer to uproot than young plants. Removal is easier on flat sites in well grazed vegetation. Docks are pulled out more readily from moist soil. Young docks at a low density may take around 8 man-hours per ha to clear using docking tools while older, established plants at a high density could take over 130 man-hours per ha to clear (Trevelyan, 2001). Docks in grass can be pulled in winter and early spring with a follow-up in May. Hand removal is effective for local infestations but where a large area is affected, ploughing and resowing may be the best option (Hopkins and Bowling, 1998). Plants should be pulled once the flower stem lengthens, usually in June (Soil Association, 2002). This is best done when the soil is moist. Apparently, regeneration is less likely to occur in wet soils. In an unpublished HDRA preliminary study of regeneration from dock roots left in situ after the removal of the upper 1, 5, 10 or 15 cm including the crown, there was no regeneration from roots cut at 10 cm or 15 cm depth. After 21 weeks there was 60% regeneration of roots that had been cut at 1 cm and 25% of roots cut at 5 cm depth. In a separate study 13% of roots cut at 7.5 cm depth had regenerated after 6 months. The curled dock generally has a straighter taproot and is easier to uproot intact. Docks are said to be easier to pull up when the seeds begin to swell. It is thought that the roots shrink as the resources are drained into the seeds. In Germany, manual weeding reduced the dock population by 75% but was time consuming. A self-driven 'dock rooting machine' reduced the dock spread by around 57%. Burning off the foliage had little effect on dock numbers. The 'Eco-Puller' is a tractor trailed, PTO driven machine developed for mechanically pulling perennial weeds out from grassland (Crofts & Jefferson, 1999). It is said that docks should be pulled after the seeds have been shed but this would limit the benefit of removal.

On set-aside land, Aquilina (1992) and Aquilina & Clarke (1994) applied cutting treatments at different times and frequencies to control broad-leaved dock. The docks were cut at early flower bud stage and/or full flower and/or viable seed stage. At one site

the treatments were made with a reciprocating knife mower, at a second site a vertical flail mower was used. All the cut material was left in situ. At the first site, the dock population increased following treatment over a 3-year period. At the second site the dock population was reduced by between 50 and 72% over the same period. It was not clear whether this difference was due to the plant populations at the sites or to the implements used. Broad-leaved dock was common in unsown set-aside land in Scotland but numbers were lower where a sown cover had been established (Fisher *et al.*, 1992).

Wheat and barley yields were unaffected by seedling broad-leaved docks but yields of wheat were significantly reduced by docks that regrew from buried roots (Popay & Daly, 1994). Curled dock was found to increase in a series of spring-sown cereals on both harrowed and herbicide treated plots (Rademacher *et al.*, 1970). Regenerating docks may be a problem in cereals that follow a ley (Lampkin, 1998). When old leys are put back into cultivation the docks should be topped regularly prior to cultivation to reduce plant vigour. The sward should be cultivated in June following tight grazing from April giving time for further cultivations prior to autumn cropping. Ploughing and rolling break up the soil and release the dock roots for collection and destruction or to expose them to desiccate at the soil surface. Some farmers have tried modified subsoilers with extra legs connected to a chain to try to bring the dock roots to the surface for collection and disposal. Others have used potato lifters (Short, 2005). It has been suggested that the roots can be shredded and composted with farmyard manure.

The population dynamics of broad-leaved dock were studied under alfalfa / winter cereal crop rotations (Masalles *et al.*, 1997; Pino *et al.*, 1998). Alfalfa (lucerne) is normally left to grow for 5-6 years during which it is harvested at a height of 4-5 cm every 30-40 days from April to October. During the cereal cropping period, the old alfalfa crop is ploughed down and a winter cereal established. After harvesting and ploughing-in the cereal a new crop of alfalfa is sown. Analysis and modelling of the results suggest that dock populations increased during the alfalfa cropping period and decreased under the cereals. There was an increase in curled dock seedling emergence following mowing 1 year after alfalfa establishment (Huarte & Benech Arnold, 2003). Nevertheless, curled dock germination was reduced in the presence of the crop particularly when crop density was high. In the soil under alfalfa the thermal amplitude was less than that of bare soil, mainly because the maximum temperature was much higher on the bare soil. However, the amplitude increased after mowing. Established docks were able to survive the cutting regimes in the alfalfa but suffered losses when the land was ploughed for the cereal. In established alfalfa crops where there was little soil cultivation to incorporate shed dock seed into the soil, Pino *et al.* (1993) found that many of the dock seeds germinated giving seedling flushes in late summer to autumn. Where seed shedding was prevented by shoot removal the seedbank in the top 4 cm of soil was reduced from 2,357 to 245 seeds per m<sup>2</sup> after one year. However, with dock seed production recorded at over 60,000 per m<sup>2</sup>, seedbank numbers could easily be restored if further seeding occurred.

It is vitally important to sow only pure crop seed, free of weed seed contaminants (Long, 1938). Dock seeds collected during combine harvesting of cereals should be retained and denatured, not scattered back onto the stubble. Straw containing mature dock seedheads

should not be spread as mulch. Farmyard manure should be composted to ensure that dock and other weed seeds it contains are killed.

In New Zealand, undersowing cereals with clover reduced the number of docks reaching maturity. Where undersowing is used to establish a ley in the understory of an arable crop, the ground cover remains in the stubble after crop harvest and into the winter (Measures, 2000). It ensures the ley is well established and able to suppress further weed seedling emergence. A summer fallow during which the soil was rotary hoed three times, eliminated docks while a single rotary hoeing followed by a green feed crop did not (Popay & Stiefel, 1994). There was no benefit from deep ploughing after the first rotary hoeing (Popay *et al.*, 1994b). A single shallow stubble cultivation immediately after cereal harvest followed by deep ploughing later in the autumn helps to contain populations of curled dock in an arable rotation (Pekrun & Claupein, 2006). Seed shedding in cereals results in numerous dock seedlings emerging in subsequent crops. The seedling do not grow well under a competitive crop and in small numbers can be hand rogued but if they become a serious problem it may be best to cut the cereal for whole crop silage to prevent further seeding. Docks that remain in the stubble after cereal harvest can grow rapidly if the stubble is left uncultivated. The stubble may be grazed or cultivated to prevent flowering.

In the past, seedling docks were hoed off in spring and autumn. Young seedlings can also be destroyed by thorough cultivations or ploughing (MAFF, 1956; Hughes *et al.*, 1993). Control of established plants was by removing the docks bodily during ploughing (Long, 1938; NAAS, 1949) or during bare or bastard fallowing (MAFF, 1956). Ploughing followed by fallowing and repeated cultivations during spring and early summer exhausts the older roots and controls young seedlings of broad-leaved dock (SAC, 1986). Hunt & Harkess (1968), however, considered deep ploughing to be only a temporary solution against mature docks as the docks can grow through after being ploughed well down. Any docks left on the soil surface will readily re-root. In an unpublished HDRA preliminary study of the period of drying needed to prevent regeneration of uprooted dock roots of different lengths with their crown still attached, no docks regenerated after a period of 4 to 8 weeks drying. An average of 21% of roots regenerated after a 1-week drying treatment. In a separate study dock roots left on the soil surface and covered with black plastic sheeting for 8 weeks did not survive. Roots buried at 30 cm deep did not re-emerge in the period of the study. Dock roots can be collected up and burned (Morse & Palmer, 1925).

Established docks may be shallowly undercut with sweeps or a turf cutter (Philipps *et al.*, 2003). There is little soil disturbance but the crowns remain in situ and are likely to regenerate without further action. Another suggestion for the control of established docks is a series (3-4) of rotary cultivations preferably in April-June. The rotovations begin at a shallow depth and become progressively deeper with time to around 6 inches. Each time the docks begin to resprout a further rotovation takes place. The succession of carefully managed rotovations is intended to exhaust the reserves of the roots. Pino *et al.* (1995) proposed that docks should be severed below the root collar by rotovation and the severed shoot portions buried to below 15 cm (preferably 30 cm) by ploughing.

Dierauer (1993) tried a range of non-chemical control methods against broad-leaved dock including: drilling down into the roots, cutting plants at ground level, at 5 cm and at 10 cm deep, flaming, mowing, applying a bio-dynamic preparation of the ash of dock seeds, exposing the plants to the eggs and adults of *Gastrophysa viridula* beetles, and tearing out the entire root. Most of the treatments were only successful in the short term. The drilled roots for example had resprouted within six weeks of treatment, and cutting off the leaves had little effect. Cutting at 5 cm deep gave a 27% reduction in docks, cutting at 10 cm gave an 80% reduction, which was as good as the effect of tearing out the whole root.

In field studies, mulching the soil with residues of hairy vetch (*Vicia villosa*) and of rye (*Secale cereale*) reduced the emergence of curled dock seedlings (Mohler & Teasdale, 1993). Weed emergence declined with increasing rate of residue, however, the natural amount of residue that remained after a cover crop was killed off was insufficient for good weed control. A low rate of residue could encourage greater weed emergence.

In greenhouse tests, corn gluten meal (CGM) applied as a surface and incorporated treatment to soil sown with curled dock seed has been shown to reduce plant development (Bingaman & Christians, 1995). Application rates of 324, 649 and 973 g per m<sup>2</sup> reduced curled dock seedling survival by 75, 94 and 97% respectively. Shoot length was reduced by over 90%. Corn gluten hydrolysate (CGH), a water soluble material derived from CGM, was found to be more active than CGM when applied to the surface of pots of soil sown with curled dock seed (Liu & Christians, 1997). Wheat gluten meal sprinkled over curled dock seeds on wet blotter paper reduced germination by 70% at 300g per m<sup>2</sup> (Gough & Carlstrom, 1999). The treatment reduced primary root and shoot length by 99 and 91% respectively.

Cavers and Harper (1964) list a range of fungi and insects that attack, feed on or occur on docks but this not an indication of their efficacy as control agents. The potential for the biological control of curled and broad-leaved dock using insects was reviewed in some detail by Grossrieder & Keary (2004) with particular reference to organic farming in Switzerland. Insect control agents both native and non-native were evaluated including the weevils *Hypera rumicis*, not recorded in Europe, and *Lixus cribricollis*, originating Morocco, the larvae of 4 *Sesiid* moth species, known to feed on *Rumex* in Europe, and the aphid *Brachycaudus rumexicolens* whose origin is uncertain, as well as the UK native insects described below. The authors considered that the augmentation of native species was the best approach for *Rumex* control at present.

The use of the stem boring larvae of the native weevils *Apion violaceum* and *A. miniatum* for controlling broad-leaved dock has been investigated (Hopkins & Whittaker, 1980; Freese, 1995). The females of both species deposit their eggs onto the midrib of leaves and the larvae bore into the stems. The larvae then eat into the stem and roots leading to plant death. *Apion miniatum* lays its eggs two weeks earlier than *A. violaceum* and the larvae inhabit the lower parts of the stem. The larvae of *A. violaceum* are more widely distributed along the stem. Both species are themselves attacked by a range of parasitoid

species that feed on the larvae and reduce their effectiveness as biological control agents (Hopkins *et al.*, 1984).

Larvae of the leaf-mining fly *Pegomya nigitarsis* cause blotch mines on the leaves of broad-leaved, curled and wood docks (Whittaker, 1994). The damage reduces photosynthesis and increases water loss from the leaves. A badly infested plant may have more than half its leaves attacked by mines which can cover the entire surface area of the leaf. In the UK, larvae are found from May to November. The fully grown larvae emerge from the leaf and pupate in the upper layers of the soil.

In the UK and elsewhere, there has been research on the chrysomelid beetle (*Gastrophysa viridula*) as a biocontrol agent for both curled and broad-leaved dock (Bentley *et al.*, 1980). The small leaf feeding beetle is restricted to curled and broad-leaved dock plants. It overwinters as an adult and emerges in April. Males and gravid females are found on docks in May (Whittaker *et al.*, 1979). Eggs are laid on the underside of leaves in batches of around 30. The egg laying beetles show a preference for broad-leaved docks over curled docks in the ratio of 9 to 1 (Bentley & Whittaker, 1979). Mean egg numbers of 800 per plant have been recorded on broad-leaved dock plants. The black larvae that emerge from the eggs pass through 3 instars and pupate within 3-4 weeks. The pupae enter the soil surrounding the dock plants and later emerge as adults that climb back up onto the plants. Adult beetles are most numerous in May, July and September. A generation may be completed in 4-6 weeks and 3 generations are possible each year. The eggs and larvae, but not the adults, may be eaten by *Anthocoris nemorum* and are preyed upon by syrphid larvae. Syrphid eggs are laid one per clump in the middle of the beetle eggs. The white egg is clearly visible among the yellow *Gastrophysa* eggs. The emerged syrphid larva can consume 200 eggs or larvae during its development. Around 50% of eggs are lost to the larvae. The predator pressure increases with increasing plant diversity in the vegetation cover (Smith & Whittaker, 1980a).

The application of the herbicide Asulam to docks can reduce beetle numbers depending on the growth stage of the beetle at the time of application (Speight & Whittaker, 1987). The effect of the herbicide on the morphology of the docks, particularly the foliage, is responsible for the reduction. All stages of the beetle are vulnerable to flooding, particularly the older larvae, and local populations can be wiped out (Whittaker *et al.*, 1979). Cutting and mowing of docks at critical stages can also have a major effect on beetle populations due to the limited dispersal of the adults. The beetles disperse by crawling and none are observed to fly. The average distance moved is 3 m and the maximum is 7 m. Re-invasion of cleared areas is therefore very slow.

In some habitats the beetle is sufficiently numerous to defoliate the host plants, in others it occurs at a very low density. In the field, a natural population of beetles can remove 45% of the leaf area of a dock (Bentley & Whittaker, 1979). When given a choice, the beetles show a preference for feeding on broad-leaved dock but this also depends on the dock species the beetle was raised on. Heavy grazing by the beetle can significantly reduce whole plant dry weight of both dock species, potentially resulting in a 65% reduction. When growing together, curled dock is less competitive than broad-leaved

dock. Beetle grazing can reduce its competitive ability further and may affect the frequency and distribution of curled dock in mixed populations.

Beetles seem unwilling to leave a dock clump and search for feeding sites elsewhere (Smith & Whittaker, 1980a). If the larvae defoliate the host they may be required to search for a new food source and mortality at this time can be high due to predation and the risk of starvation. After flowering, leaf production by a dock clump ceases for up to 2 months so the beetle population can experience a drop in food source especially where the flowering of dock plants in a given habitat is synchronised. This can affect the number of generations produced and the proportion of gravid females. As the dock plants begin to flower and the stem leaves die back the beetles move up the plant and ultimately feed on the flowers and seeds. When the next flush of basal leaves is produced the beetles move down again to feed on them. Adults avoid laying eggs on old senescent leaves and in preference will lay them on the new basal leaves when these are produced. In hay meadows, periodic mowing or grazing prevents dock flowering and hence leaf loss becoming synchronised. This allows *G. viridula* to survive better through the season. There is evidence that as the diversity and maturity of the vegetation increases the hostility of the habitat towards the beetles also increases preventing populations achieving their full potential of 3 generations per year (Smith & Whittaker, 1980b).

Twenty two separate species of rust fungus infect *Rumex* spp. (Inman, 1970). The rust fungus *Uromyces rumicis* is non-systemic but can cause serious foliar injury and has been shown to have some potential as a biological control agent (Inman, 1971; Schubiger *et al.*, 1986). The primary host range appears to be restricted to *Rumex* spp. Selections of curled dock have demonstrated a wide range of disease reactions following inoculations with urediospores of the fungus (Inman, 1969). The rust is widespread in Europe, it infects the dock foliage in August-September causing the affected leaves to die but not the whole plant. Symptoms begin as a red spot that expands to form the typical rust pustule. It is not known if the primary inoculum each year comes from overwintered spores or from spores on overwintered mycelia. During the growing season the rust spreads by wind blown urediniospores that require a moist surface for germination. The alternate host in the life cycle of the fungus is lesser celandine (*Ranunculus ficaria*) but this only plays a minor part in the life cycle of the pathogen. There has been particular interest in its use in the USA (Inman, 1971; Frank, 1971). Various naturally occurring flavour-related compounds were shown to stimulate germination of both curled dock seed and urediniospores of *U. rumicis* (French *et al.*, 1986). Benzonitrile, found in cocoa aroma, was the most active compound tested on both seeds and spores.

Among other fungi that frequently cause disease in *Rumex* spp., *Ramularia rubella* (a necrotrophic Ascomycete) and *Venturia rumicis* (a hemibiotrophic Ascomycete) are present throughout the year. *Ramularia rubella* causes red spots around 1 cm diameter to develop on dock leaves. It endemic to Europe, the host range is restricted to *Rumex* spp. and it is considered to have potential as a mycoherbicide against weedy *Rumex* (Huber-Meinicke *et al.*, 1989). Symptoms appeared within 3-5 days of the application of a suspension of conidia. Severely affected leaves with 50% of leaf area infected died within 7-10 days. Leaves less affected by the fungus survived but photosynthetic

capacity was reduced. Infected plants could produce more leaves and, despite reducing food reserves in the rootstock, the fungus alone had no major effect on plant survival. *Venturia rumicis* (Syn. *Mycosphaerella rumicis*) also causes a leaf spotting disease of *Rumex* spp. and has been widely recorded in Great Britain (Kerr, 1961). The fungus thrives in cool wet conditions but is less prevalent in hot dry weather. Leaves become infected by ascospores which may germinate within 8 hours of being shed. Moisture is needed for germination and for subsequent ascospore release, which can occur 20 days after an infection has developed. The spores may be discharged up to 1.5 cm, may simply fall on a nearby leaf or may be carried further afield on wind currents. *Ovularia obliqua* also causes a leaf spotting disease of *Rumex* spp. The spots often enlarge under moist conditions to cover a large area of a leaf.

Experiments have indicated that infection by one pathogen predisposes a leaf to infection by another (Hatcher & Paul, 2000). However, it has been shown that leaf damage by the beetle *G. viridula* leads to a reduction in infection by the pathogens both on the grazed and undamaged leaves of a plant (Hatcher *et al.*, 1994a). Herbivory appears to induce a systemic resistance to the pathogens. The response suppressed the development of pustules of *U. rumicis* and reduced the penetration of fungal hyphae into the leaf (Hatcher *et al.*, 1995). Conversely, when the beetle and the rust fungus *U. rumicis* occur together on dock leaves, the presence of the fungus increases mortality of beetle larvae at early stages of development and reduces the fecundity and longevity of the adult beetles (Hatcher *et al.*, 1994b). When the effects of the rust fungus and beetle grazing were compared singly and combined on curled dock, beetle grazing or rust alone had the greatest effect (Hatcher *et al.*, 1994c). When combined, the order of attack was important in the level of damage caused. Beetle grazing followed by rust infection was no worse than the rust alone. Rust followed by beetle grazing caused the greatest reduction in biomass in curled but not in broad-leaved dock. A model was developed to help in predicting the amount of damage likely from the rust and beetle.

In studies of the beetle-rust interaction on the autumn growth and overwintering of curled and broad-leaved docks the effects were monitored from August onwards (Hatcher, 1996). The rust fungus *U. rumicis* infects the docks mainly from August to October, at the same time that the beetle is present. There is some separation as the fungus is poor at infecting young leaves while these are the leaves favoured for egg laying by the beetle. Between August and October, the beetle alone removed 79% of the leaf area. The rust was slow to develop but caused a 50% decrease by October. A combination of the two had an additive effect and leaf area was reduced by 92% on curled and 88% on broad-leaved docks. Root and shoot weight of both dock species was also reduced more by the combination. Herbivory and fungal infection will limit the competitive ability of docks in grassland.

In other experiments the addition of nitrogen fertilizer increased dock growth but did not allow it to escape the effects of the beetle and fungus (Hatcher *et al.*, 1997a). The density of rust pustules decreased with increasing nitrate as did beetle herbivory and egg laying (Hatcher *et al.*, 1997b). It is suggested that there may be an optimum nitrogen fertilization level for *G. viridula* development (Hatcher *et al.*, 1997c). Singly, nitrogen

deficiency and the rust fungus reduce dock growth. When combined, they may put an additive stress on the plant (Hatcher & Ayres, 1998).

Natural colonization by insects and fungi may take several years to build up but can cause significant damage to dock populations (Hatcher, 1999). The artificial introduction of additional beetles increases the level of damage. Site conditions have a big effect on weed recovery.

Exposure to an arbuscular-mycorrhizal fungal inoculum has been shown to cause a 60% reduction in biomass in the broad-leaved dock, a non-host weed species (Jordan *et al.*, 2000). Broad-leaved dock has been shown to be susceptible to infection by the honey fungus *Armillaria mellea* (West *et al.*, 2000). The foliage of infected plants became wilted or senesced. Although there may be potential for biocontrol of docks, infected plants could spread honey fungus to nearby trees and shrubs.

### **Legislation**

The Weeds Act, 1959, requires an occupier of land to prevent the spread of broad-leaved dock and curled dock. Set-aside land is not exempt.

The 1951 regulations made under the Seeds Act 1920, defined the seed of all *Rumex* species as injurious weed seeds. The Plant Varieties and Seed Act, 1964 section 16(3)(c), gives the Minister the power to prohibit the sale of seeds containing more than a prescribed proportion of docks and sorrels.

### **Chemical control**

Docks are generally not a problem in arable cereal rotations due to the widespread herbicides available. They are however a big problem in rotational grassland and permanent pasture and many herbicides are available for their control, either as single product or in mixtures (Table 2). The manufacturers' handbook or the UK Pesticide Guide should be consulted for more detail of product rates and application timings. Herbicide application should occur when the plants are actively growing, usually in late June or July.

Table 2. List of main herbicides available for controlling broad-leaved dock

<b>Active ingredient</b>	<b>Products</b>
2,4-D + dicamba + triclopyr	Broadsword, Nu-Shot
2,4-D + MCPA	Headland Polo, Lupo
Amidosulfuron	Various products including Eagle, Squire, Landgold amidosulfuron
Aminopyralid + fluroxypyr	Forefront
Asulam	Asulox, Spitfire, Greencrop Frond
Clopyralid + fluroxypyr + triclopyr	Pastor
Dicamba (often used with 2,4-D + fluroxypyr + triclopyr)	<i>various products</i>
Dicamba + mecoprop-P +/- MCPA	<i>various products</i>
Fluroxypyr	Starane, Hatchet, Tomahawk, Crescent
Fluroxypyr + triclopyr	Doxstar
MCPA	Various products including Campbell's MCPA 50, Headland Spear, Agritox 50
MCPB	Tropotox, Butoxone, Bellmac Straight
Mecoprop-P	Various products including Duplosan KV, Landgold Mecoprop-P 600

### **Discussion**

The broad-leaved and curled docks are considered by many UK farmers to be the main broad-leaved weeds. Docks cause problems in both grassland and in cultivated soils. Broad-leaved dock is more important in grassland while the curled dock is considered to be commoner in arable crops. However, farmers rarely distinguish between the different docks and where both species occur together hybrids are often present. It can prove difficult to determine the extent of hybridisation in the field. While there has been much investigation of seed development and germination, the importance of hybridization in dock seed biology and seedling dynamics has received less attention. Preliminary studies have shown that hybrid dock seed can exhibit a range of viability. The vigour of seedlings and mature plants from hybrid seed was not tested but could be important in competition with crops.

Seed is the main source of spread of docks both locally and over longer distances. Dock seeds are produced in large numbers and are able to persist in the soil for a considerable time. It is therefore most important to prevent seeding, seed dispersal and seedling establishment, although many growers still fail to appreciate this. The combine harvester and home-saved seed remain important agents of seed spread in arable crops. Slurry, silage and manure are other potential sources of introduced dock seeds. Seedling establishment of docks often receives less attention than vegetative regeneration, particularly in grassland but is nevertheless important. In grassland, as with other perennial weeds, maintaining a dense sward will prevent seedling establishment. Achieving the right nutrient balance also appears to be important in making the grass more competitive over the docks that do develop. There may be an opportunity for dock

seedlings to emerge in the disturbed area left after the removal of adult docks from grassland. The microbiological and nutrient status of soil can have a significant effect on the growth of seedling docks. In cereals and other competitive crops, dock seedlings may not affect the yield of the current crop but can persist as small plants that continue to develop after crop harvest and form roots able to survive and regrow more competitively in the next crop. In cereals, undersowing with clover reduces dock seedling establishment.

Mature docks are able to persist and reproduce vegetatively due to the stout taproots even if the aerial shoots are cut down to prevent seeding. Undisturbed plants can form large clumps when the crown of the plant splits to form two or more ramets. Roots fragmented by cultivation can also regenerate and develop into new plants. There has been a great deal of investigation of dock regeneration from roots but there remains some confusion on how deep roots need to be cut to prevent regrowth. In grassland, hand removal of dock remains an option that is relied on where sufficient labour is available. Unpublished observations showed that dock roots left in situ and from which the upper 1, 5, 10 or 15 cm were removed did not regenerate if cut at 10 cm or below. The removal of mature docks may leave a bare area in the sward where seedling docks could establish.

In arable crops, dock regeneration from roots fragmented by cultivation is a serious problem. Unpublished investigations have demonstrated that uprooted dock roots left to dry out for 0, 1, 4 or 8 weeks before being planted did not regenerate after 4 or more weeks of drying. While mechanical methods for separating the roots from soil have been tried using harvesting machinery this has not been completely successful.

While there has been great interest in and study of the biological control of docks, no single agent has proved fully effective but natural control at a background level may help with dock management in the field. Enhancing the effect of natural control agents is likely to prove beneficial.

## The biology and control of Field horsetail (*Equisetum arvense L.*)

### Occurrence

Field horsetail occurs throughout the world and is widely distributed in the UK (Marshall, 1984a; Holm *et al.*, 1977). In early surveys of Bedfordshire, Hertfordshire and Norfolk, field horsetail was universally distributed on most types of soil (Brenchley 1911; 1913). It was frequently found in association with coltsfoot (*Tussilago farfara*). Competitive crops like cereals were thought to discourage it (Brenchley, 1920). In a survey of weeds in conventional cereals in central southern England in 1982, field horsetail was found in less than 1% of winter wheat and not at all in winter barley and spring barley (Chancellor & Froud-Williams, 1984). It is a weed of horticultural importance being a particular problem in fruit and other perennial crops and in nursery stock. It grows strongly on arable and grassland (Long, 1938). Horsetail is also found in meadows, gardens, hedgebanks and waste land (Clapham *et al.*, 1987; Stace, 1997). It is a serious garden weed and flourishes on damp soils (Copson & Roberts, 1991). Field horsetail has a preference for stone free, abandoned sites (Dale *et al.*, 1965).

Field horsetail has the ability to accumulate gold in its tissues, 4.5 ounces per ton of fresh plant material have been recorded (Holm *et al.*, 1977). It will also accumulate heavy metals such as cadmium, copper, lead and zinc (Cody & Wagner, 1981). Extracts of horsetail make an effective fungicide and have been used to treat blackspot on roses, rust on mint and mallow and mildew on many other plants (Mitich, 1997). It has herbal uses for treating bladder disorders and skin inflammations. The silica rich sterile stems have been used to scour cooking pans, sand wood and polish metal.

Field horsetail is toxic to sheep, cattle and horses. Horses are particularly sensitive (Forsyth, 1968). The plant is poisonous both in the green state and dried in hay due to an enzyme present in the tissues (Willis, 1954). Hay containing the weed is potentially more dangerous than horsetail growing in pasture (Frankton & Mulligan, 1970). The related marsh horsetail (*E. palustre*), a perennial weed of wet, low-lying grassland is also poisonous to livestock.

### Biology

A rhizomatous perennial, field horsetail is dimorphic, producing non-photosynthetic spore-bearing fertile stems in March-April followed by green vegetative stems in late-spring. The cone bearing fertile stems develop from subterranean buds formed the previous summer and persist for about 10 days after emergence (Grime *et al.*, 1988).

The single cone on each fertile stem can produce 100,000 spores but these are very short lived (Salisbury, 1962). The spores remain viable for 48 hours after release (Doll, 2001). Spores germinate quickly on moist substrates to produce male and female gametophytes that mature only within a narrow range of conditions. After fertilisation, cell division results in the formation of a shoot apex and roots (Marshall, 1984a). Once established, the sporelings soon become rhizomatous and quickly develop successive layers of horizontal rhizomes at 30 cm intervals as growth continues downwards (Holm *et al.*,

1977). Spores that do not germinate after release lose viability rapidly (Cody & Wagner, 1981). The gametophytes too are susceptible to desiccation and few achieve fertilisation.

The vegetative stems have a rough texture due to deposits of silica. Maximum vegetative growth occurs in July (Marshall, 1986). Stored food reserves are depleted from late-April to mid-May, and from mid-May to August the reserves are replenished (Holm *et al.*, 1977). Dry matter accumulation in the rhizomes may continue until October and then decline through the winter (Marshall, 1986).

The rhizome system can be extensive both horizontally and vertically and may reach over 1.5 m deep depending on substrate and water table level. More than half the rhizomes are found in the upper 25 cm of soil (Williams, 1979). In fallow soil and where there is little crop competition more rhizomes are found at shallower levels. The rhizomes grow rapidly in June-July and continue to elongate beyond October. The underground rhizome tips are covered with scale-like leaf sheaths. Roots arise at the nodes of the rhizomes. Tubers are also produced at the nodes of the rhizomes and may be present singly or in strings of two to four (Marshall, 1984a). Tubers are initiated in July and formation is thought to be influenced by soil pH and soil type. Tuber formation is more frequent in sand rather than clay soil. Tubers initiated in August may continue to grow in size and number until November, well beyond the period of active shoot growth (Marshall, 1986). Rhizomes may produce numerous tubers (300-1000/m<sup>3</sup>). Most of the tubers are found below 50 cm depth. Once detached the tubers can grow into independent plants (Salisbury, 1962).

### **Persistence and Spread**

Vegetative reproduction via rhizomes and tubers is probably the most important means of spread and perennation. It has been calculated that horsetail has the potential to infest a one hectare area within 6 years of introduction (Cloutier & Watson, 1985). The plant also reproduces by spores but the importance of sexual reproduction is unclear.

Vegetative reproduction and regeneration is by detached rhizome sections or tubers. Rhizome buds may remain dormant or develop into aerial shoots or new rhizomes (Marshall, 1984a). Regeneration of single node fragments is mainly in March-May & October-November. A 1.3 cm long segment planted 15 cm deep easily produces a new plant (Doll, 2001). Larger fragments have been shown to regenerate anytime except when high temperatures make the rhizome pieces susceptible to desiccation. In growth room tests, a 10 cm length of rhizome has produced a total of 64 m of rhizome in 1 year (Cody & Wagner, 1981). Tubers germinate when separated from the rhizome system and can remain viable for long periods in soil. Tubers immersed in water for 42 days remained viable but tubers kept dry in the laboratory for 14 days did not. Tubers that remained attached to the parent rhizome did not germinate (Williams, 1979).

### **Management**

Field horsetail is difficult to control by cultivation because new stems regenerate from rhizome fragments and tubers. It is essential therefore to avoid introducing horsetail into clean fields. Horsetail regrew equally well whether cut back once or sixteen times

during the growing season (Cloutier & Watson, 1985). Keeping an area free of the weed for one year did little to reduce horsetail growth in the following year.

Black plastic sheeting has been found to kill rhizomes in the upper layers of soil (Cody & Wagner, 1981). However, the emerging vegetative stems can penetrate some woven polypropylene mulches (Personal experience). Regular mowing over a period of years may eliminate horsetail (Marshall, 1984b). It is said to not persist in lawns that are mown regularly. Control in arable land includes draining, liming, deep cultivation, improvement in soil texture and persistent cutting of vegetative and spore bearing shoots (Long, 1938).

Annual cultivations and a herbicide regime that controls competitive broad-leaved weeds favour field horsetail which can become dominant (Andersson & Lundergådh, 1999a). Soil compaction and prolonged cereal rotations result in increased abundance. It can be controlled by improved cultivation regimes and more competitive crops and cultivars.

It has been shown that horsetail can survive periods of flooding and burning but may be sensitive to water stress in drought conditions especially when growing in competition with other plants (Cloutier & Watson, 1985). Improved land drainage can also affect horsetail vigour and its competitive ability (Morse & Palmer, 1925). A good dressing of lime is helpful in reducing the weed.

Field horsetail is adapted to sunny habitats. The vegetative shoots lack functional leaves and this is possibly the reason that horsetail cannot tolerate shading (Holm et al., 1977). At lower light levels the shoots become taller while at a high light intensity the shoots lie prostrate (Andersson & Lundergådh, 1999a). Tuber production increases at higher light levels. It seems that the weed is not always competitive with crops (Cody & Wagner, 1981). Horsetail was only a serious weed in cereals growing on low fertility soil where the light penetrated to ground level in May when the horsetail shoots were emerging (Thurston, 1976). Cereals are better able to take advantage of increased nitrogen levels giving them a competitive advantage over field horsetail which does not respond as rapidly to increased soil fertility (Håkansson, 2003; Andersson & Lundergådh, 1999a). Rhizome tissues contain sufficient reserves of nitrogen and the plant has a relatively low requirement for soil nitrogen at least initially. The growth rate of field horsetail responds linearly to increasing levels of potassium but only at higher nitrogen levels (Andersson & Lundergådh, 1999b).

No biological agents that are useful in the control of field horsetail have been found.

### **Chemical control**

There is a very limited amount of information available regarding the chemical control of field horsetails. They are generally not a problem in arable crops due to rotations, but are more of a problem in horticultural crops and occasional problem in grassland. The following herbicides are available for controlling field horsetail. Amitrole is currently

being trialed on a natural population of field horsetail in an HDC-funded project (June 2005-2009) ‘Controlling weeds in nursery stock’ led by ADAS:-

- **Amitrole** (Weedazol-TL, Aminotriazole Technical) – this is a foliar-acting, non-selective herbicide. Repeated treatments would be required for long-term control. Preferred application times are summer and autumn.
- **Dichlobenil** (Casoron G4) – this herbicide is applied in winter or early spring when conditions are moist and cool. It acts by inhibiting new shoots. It has a recommendation for use in woody crops and non-crop areas.
- **Glyphosate** (*various products*) – apply in late summer when weed growth active. If the area of field horsetail is relatively small mechanical damage, such as trampling, before spraying can aid herbicide uptake as the leaf cuticles are bruised (RHS 2007).
- **MCPA** (*various products*) – various MCPA formulations may be recommended for controlling the top-growth within grassland and cereal crops.

### **Discussion**

Field horsetail can be a problem both in cultivated and uncultivated soils. Field horsetail does not produce seeds but reproduces by spores that require very specific conditions to develop. It is not clear how important spores are in the development of new infestations in the field because vegetative reproduction by the extensive rhizome system and its tubers is so successful. In a short-term project it would be difficult to ascertain the importance of spores in the establishment of new infestations

Control by cultivation is difficult to achieve due to the depth of the rhizomes. Treatments may give a short-term reduction but the weed has considerable capacity for regeneration even when vegetative shoots are removed through the full growing season. The weed is susceptible to competition and a dense crop stand can help to suppress the weed especially on fertile soil. Controlling other weeds may favour field horsetail and this suggests that undersowing could help to reduce the weed in some crops. Field horsetail does not respond to increased fertility as much as a crop. Optimising crop growth prior to horsetail emergence would appear to be the best way to keep horsetail in check.

Although field horsetail can occur in grassland its management has received little attention. Control by grazing is not an option due to the toxic nature of the shoots. In lawns that are cut regularly to maintain a short sward, field horsetail is kept in check.

The literature search has not identified any recent investigation of the non-chemical control of field horsetail. Neither is there any evidence that biological control of field horsetail is considered a realistic option.

## The biology and control of rushes (*Juncus* spp.)

### Occurrence and biology

Only a few of the 25 or so British species of rushes are of importance as weeds (ADAS, 1972). In most situations rushes form a valuable part of the natural flora and do not need to be controlled. Many species provide cover for wildlife especially wading birds (Wolton, 2004). Some rushes have a spreading habit others are tuft forming (Salisbury, 1961). There are species with a very short rootstock and others that have extensively creeping rhizomes (Richards & Clapham, 1941d). The main problem species are the tuft forming rushes (Lazenby, 1953).

Rushes occur mainly but not solely on poorly drained soils of low pH. Rushes are common on flat pastureland with a heavy soil that is often waterlogged, (Tansley, 1949b). Poor drainage is a common factor in rush establishment. Rushes often arise in disturbed areas or where the sward is weak. Rush infestations were a particular problem when large acreages of poor grassland were ploughed out for cropping during the 2<sup>nd</sup> World War (Moore, 1949). A survey of the West Riding of Yorkshire in 1946 showed that over 10,000 acres were badly infested in that county alone. A similar problem on a smaller scale had followed the 1<sup>st</sup> World War.

The soft rush (*J. effusus* L.) and compact rush (*J. conglomeratus* L.) were originally classified together as *J. communis* but are now considered separate species (Lazenby, 1953). Several genotypes are recognised. The soft rush is probably the main weedy species, it is widespread and forms tussocks that extend by means of a short creeping rhizome from which new shoots and ultimately new plants arise (ADAS, 1972). It is native in marshes, ditches, bogs, wet meadows, damp woods and by water, mostly on acid soils (Stace, 1997; Clapham *et al.*, 1987). Soft rush is abundant throughout the British Isles and is ubiquitous in moist situations and regions of high humidity. It can become established on a range of soils but is most frequent on base deficient soils and on thin peat (Elliott, 1957). It does not thrive on soils that remain waterlogged throughout the year or ones that dry out in summer. Soft rush is usually found in open situations but will flourish in partial shade. It readily invades undergrazed hill pasture (Richards & Clapham, 1941b). It is not found on arable land (Grime *et al.*, 1988). Undisturbed plants grow into clumps over 1 m tall but mowing or heavy trampling alters this to a more uniform spread of individual shoots. The dense tussock structure and persistent layer of leaf litter deter the establishment of other plants. Soft rush flowers from early June to July in the south and July to August in the north. Seed ripens from July or August onwards but is shed over a long period. In general, plants do not flower until the second year. Flowers are wind or rarely insect-pollinated or are cleistogamous. Seed capsules contain an average of 82 seeds and a plant may produce 700,000 or more seeds (Salisbury, 1961). On average 8 million seeds can be produced on a square yard in one season (Moore, 1949). Laboratory tests have shown that light is required for a high level of germination (Grime & Jarvis, 1976). Red light is effective but blue or green wavelengths are not. Diurnal fluctuations in temperature with an amplitude of 1.5°C promote seed germination in the light (Thompson *et al.*, 1977). Seeds do not germinate

until the April following their ripening but can remain dormant for 60 years. In the north of Britain, seedling emergence may not begin until May or June (Richards & Clapham, 1941b). Large numbers of soft rush seeds were present in the soil under coppiced and coniferous woodland (Brown, 1979). Waterlogged conditions are not essential for establishment but a high water table increases seedling emergence (Lazenby, 1953). Seeds require moisture and light for germination, and fields can become infested with seedlings after ploughing. Rush seedling numbers are highest when growing without competition from other species (Lazenby, 1955a; 1955b). The seedlings are extremely susceptible to competition. At first, seedlings are susceptible to drying-out, shading and mechanical damage but once established they become more resistant. Increased soil fertility can promote rush growth but because of the effect on companion species the level of plant competition can also increase. The soft rush rhizomes form a dense horizontal mat 6 to 50 mm below the soil surface (Richards & Clapham, 1941b). Fine freely branched roots extend sideways and upwards from the rhizomes while stout, straight roots penetrate vertically downwards to 25 cm. Shoots begin vigorous growth in March.

The hard rush (*J. inflexus* L.) is the other main weedy species and it occurs on neutral or calcareous clays and alluvial soils often with the compact rush (Richards & Clapham, 1941a). It is rare on acid soils but is tolerant of saline conditions. The tussocks are more open and the rhizome system more extensive than the soft rush. It is native in marshes, dune slacks, wet meadows or by water on neutral or base rich soils and is common through most of the British Isles (Stace, 1997; Clapham *et al.*, 1987). It is a tuft forming rush with the shoots borne on underground stems (Salisbury, 1961). The hard rush flowers from June to August (ADAS, 1972). The average seed number per capsule is 67 and there may be 200,000 or more seeds per plant. Hard rush may not set seed every year (Richards & Clapham, 1941a). It forms sterile hybrids with the soft rush but backcrosses to the parents may result in viable seeds. Hard rush seeds require light for germination. The shoots, if grazed, may cause poisoning in sheep and cattle. Cattle that acquire a taste for it may suffer blindness and death (Salisbury, 1961).

The compact rush (*J. conglomeratus* L.) is a rhizomatous perennial native in marshes, dune slacks, wet meadows or by water on neutral or base rich soils (Stace, 1997; Clapham *et al.*, 1987). It is common through most of the British Isles, although the impression is sometimes given that compact rush is restricted to acid soils. It resembles the soft rush and is often associated with it (Richards & Clapham, 1941c). It is more tolerant of dry conditions but less tolerant of flooding. It is a tuft forming rush with the shoots borne on underground stems (Salisbury, 1961). It occurs in pastures on less heavy soils poor in nutrients. It flowers from early May to July (ADAS, 1972). The seed capsules ripen from July to September (Richards & Clapham, 1941). A plant may produce 500,000 seeds (Salisbury, 1961). The seeds germinate in April-May in disturbed ground (Richards & Clapham, 1941c). Flowering stems may fall to the ground allowing seeds to germinate in situ.

The jointed rush (*J. articulatus* L.) is widespread in waterlogged areas in hilly districts (ADAS, 1972). It is a perennial with an extensive rhizome system and forms a sward

rather than tussocks but is a very variable plant. Where it has a prostrate habit it may root at the nodes to form clonal patches (Grime *et al.*, 1988). It is frequent on unreclaimed areas (Salisbury, 1961). It is common throughout Britain and is native in damp grassland, heaths, moors, marshes and dune slacks (Stace, 1997; Clapham *et al.*, 1987). It occurs on wet acid soils usually on grazed areas and is absent from dry habitats. The jointed rush flowers from June to September and seed is set from September to October (Grime *et al.*, 1988). Flowers are wind pollinated and jointed rush may hybridise with other species. Even in a grazed site it produces numerous seeds that germinate in spring. Laboratory studies have shown that seed requires high light levels for germination (Grime & Jarvis, 1976). Red light is effective but blue or green wavelengths are not. In a survey of seeds in pasture soils in the Netherlands in 1966, while the jointed rush was uncommon in the sward it was well represented in the soil seedbank (Van Altena & Minderhoud, 1972).

The heath rush (*J. squarrosus* L.) is a tough wiry perennial with a rosette of leaves borne at the end of a horizontal rhizome (Welch, 1966). It shows little variation in characters and is sharply distinct from other rush species. It is common only in the North and West of Britain. Heath rush is a sward forming moorland plant with a compact, slow-spreading rhizome (ADAS, 1972). It is common on acid soils throughout Britain (Stace, 1997; Clapham *et al.*, 1987). It is confined to uncultivated ground and is absent from arable land. It is intolerant of shade both as a seedling and when mature, and is absent from woodland and tall vegetation. Heath rush is restricted to wet heaths, upland moors and rough grazing where it is sought out by grazing animals early in the season, so it is a useful food plant rather than a weed. The leaves are tough and fibrous but are eaten by cattle, horses and sheep in winter and spring when other food is scarce. Sheep also eat the developing inflorescences. Heath rush is favoured by grazing and it is common where sheep grazing is heavy. Without grazing the grasses increase and suppress this poorly competitive rush. The growth of new shoots begins in March and increases through April and May. Plants are often 5 years old before they first flower. The flowers are wind pollinated and flowering occurs in late June and July. The seed capsules contain around 50 seeds and ripen from August to October. The capsules open in dry weather and many seeds are dispersed a short distance by the wind. Heath rush has relatively large seeds compared with many other rushes and fewer of them (Cavers, 1983). Some seeds may not be dispersed until the flower stem decays and falls to the ground in spring, resulting in a small patch of seedlings emerging (Welch, 1966). Germination occurs in May and June but a bare area is needed for successful establishment. In closed communities regeneration is mainly by rhizome growth (Grime *et al.*, 1988). Heath rush cannot withstand competition from the fast growing species in base-rich habitats. For this reason it is usually confined to acidic soils or peat but it can grow on a range of soils. It grows on coarse sands and stiff clays but is absent or stunted on dry soils. Heath rush can withstand water logging but not submergence. Burning and treading have little effect. A variety of insects feed on the heath rush and a number of pathogens attack it too.

The blunt-flowered rush (*Juncus subnodulosus* Schrank) and sharp-flowered rush (*J. acutiflorus* Ehrh. Ex Hoffm.) are sometimes a problem in pasture (Wolton, 2004). The

blunt-flowered rush is a rhizomatous perennial native in fens, marshes and dune slacks (Stace, 1997; Clapham *et al.*, 1987). It is locally frequent in England and Wales especially in unreclaimed areas (Salisbury, 1961). The horizontal rhizome is far-creeping (Richards & Clapham, 1941e). The blunt-flowered rush has a narrow habitat range and occurs where the groundwater is alkaline. It is characteristic of calcareous peat and has some tolerance of brackish conditions. It flowers in July/August and seed is shed in September/October. In cultivation, seedlings emerge in April/May. The seeds require light for germination. The sharp-flowered rush has a spreading habit and is common in wet pastures (Salisbury, 1961). It is native in bogs, marshes, damp grassland and the margins of rivers and ponds throughout Britain (Stace, 1997). It has a stout, far-creeping rhizome. It flowers from July to September and is the last of the common rushes to flower (Clapham *et al.*, 1987). There are 12 seeds per capsule.

The slender rush (*J. tenuis* Willd.) is a perennial introduced from North America and first seen in Britain in 1883 or, according to some, in 1795/6 (Stace, 1997; Richards, 1943). It was observed in Europe in 1824 (Salisbury, 1961). Within 60 years of introduction it had spread to 50% of the British counties and is now locally frequent throughout Britain. It occurs on damp barish ground on roadsides, tracks and pathways (Stace, 1997). It is a relatively short-lived perennial depending on the habitat (Richards, 1943). Slender rush grows in small tufts with a short upright rootstock but does not form large stands. The erect shoots die down in winter leaving a rosette of green leaves. It has a preference for areas of high rainfall. It does not thrive in closed vegetation but can tolerate shade. It may even flower in dense shade and can flower in its first year. The slender rush flowers from June to September (Clapham *et al.*, 1987). The average number of seeds per plant is 33,000. The average number of seeds per capsule is 268 (Richards, 1943). The seeds swell when wet and burst out of the capsule. The seeds may germinate soon after shedding and can do so while still retained in the capsule.

The most important annual rush is the toad rush (*J. bufonius* L.) (Stace, 1997; Clapham *et al.*, 1987). The species now also includes *J. minutulus* (Grime *et al.*, 1988). It is common throughout the UK and is native in all kinds of damp habitats both natural and artificial. It is found on rutted tracks liable to temporary flooding and in areas of arable land with impeded drainage (Salisbury, 1961). Toad rush flowers from May to September and fruits from July to October (Grime *et al.*, 1988). Plants may flower within 4 weeks of establishment. The flowers are cleistogamous and there are around 100 seeds per dehiscent capsule. Stevens (1932) gives the average seed production per plant as 5,300. Others give the seed number per plant as 34,000 (Stevens, 1957). Seed dormancy is broken by dry storage (Grime *et al.*, 1988). In a study of seedbanks in some arable soils in the English midlands sampled in 1972-3, toad rush seed was recorded in 34% of the fields sampled in Oxfordshire and 3% of those in Warwickshire but never in large numbers (Roberts & Chancellor, 1986). Toad rush seeds were the most frequent in a seedbank survey of arable soils in Denmark in 1964 (Jensen, 1969). The average number of viable seeds recorded was 26,500 per m<sup>2</sup>. In a survey of seeds in pasture soils in the Netherlands in 1966, while toad rush was uncommon in the sward it was well represented in the soil seedbank (Van Altena & Minderhoud, 1972). In a comparison of the ranking of arable weed species in unsprayed crop edges in the Netherlands in 1956 and 1993, toad

rush moved from 22<sup>nd</sup> to 17<sup>th</sup> place (Joenje & Kleijn, 1994). It is thought to germinate over a limited period in the year, mainly from April to December with peaks in April and September-November (Chancellor, 1964; 1965). More seedlings are likely to emerge in a soil that has not been cultivated. Laboratory studies have shown that light is required for seed germination (Grime & Jarvis, 1976).

### **Persistence and Spread**

Once established the rushes spread vegetatively and/or by the small seeds that are produced in vast numbers. The seeds are blown or carried elsewhere and germinate from April onward. Rushes are major contributors to the seedbank in a range of grasslands but only low numbers are recorded in the better types of British grassland (Roberts, 1981). When buried the seeds can remain viable in soil for 20 years (Wolton, 2004). It is reasonable to assume that land adjacent to a rush infested area, even if it shows no evidence of rushes, will nevertheless carry a high content of rush seed (Moore, 1949). Rush seeds have been recorded in enormous numbers in the soil beneath pastures even though the plants may be poorly represented in the vegetation (Chippindale & Milton, 1934; Champness & Morris, 1948).

In a study of seeds in the seedbank of soils under neglected coppice and conifer woodlands, soft rush was the most abundant seed recorded (Brown, 1979). Seeds of hard rush can remain viable for 7 years in dry storage (Richards & Clapham, 1941a). Those of slender rush remain viable for at least 2 years in dry conditions (Richards, 1943). Seeds of blunt-flowered rush did not germinate after 8 years in the laboratory (Richards & Clapham, 1941e). Thompson *et al.* (1993) suggest that based on seed characters, soft rush seed should persist for longer than 5 years in soil. It has been reported that seeds may remain viable for 60 years or longer (Lazenby, 1955a). In a 7-year study of the annual percent decline of seeds in cultivated soil there was no apparent decline in toad rush seeds (Popay *et al.*, 1994a). In Belgium, toad rush was one of the main species that remained in the seedbank of a reclaimed heath that was under arable cropping since 1924 and under grassland from the 1960s (Stieperaere & Timmerman, 1983). In studies of seedbanks of arable soils in Denmark in 1964 and 1989, toad rush seeds represented approximately 56% of viable seeds in both years (Jensen & Kjellsson, 1992). Seeds of toad rush recovered from excavations and dated at 30 and 300 years were found to germinate (Ødum, 1974). Viable toad rush seeds were still present in the soil after 100 years under forest (Crocker, 1916).

The production of numerous seeds with high viability and extensive dispersal gives heath rush an advantage in colonising newly available areas (Welch, 1966). Buds in the shoot bases give rise to new shoots on the edge of the rosette and large patches can form which may be over 100 years old. Soft rush is strongly rhizomatous and may form extensive clonal patches (Grime *et al.*, 1988). In dense communities of soft-rush, vegetative spread is the primary method of reproduction with seedlings developing around the margins (Richards & Clapham, 1941b). The blunt-flowered rush spreads by rapid rhizome extension and new colonies may form when pieces of rhizome are torn off and carried away (Richards & Clapham, 1941e).

Rush seeds are dispersed by wind and water (Salisbury, 1961). Further spread is by animals, birds, on machinery or in manure (Elliott, 1957). The wind disperses the seeds of soft rush a short distance from the parent, the greatest concentration falling on the leeward side of the plant but few are blown more than 2.5 m (Agnew, 1954). Surface water spreads soft rush seeds down hillsides. Seeds of soft rush, hard rush, jointed rush and North American rush become mucilaginous and sticky when wet and this may aid dispersal in wet conditions. In dry conditions wind dispersal is more likely. The seeds of slender rush also become slimy when wet and adhere to boots and tyres, hence its distribution along trackways. Blunt-flowered rush seeds are not mucilaginous and are dispersed by wind and water. Toad rush and soft rush seeds do not float but the young seedlings float and may be carried to new sites by flooding (Grime *et al.*, 1988). The seeds of hard rush are dispersed by wind and rain splash, also on the feet of birds and on shoes. Toad rush seeds have been found in cattle and horse droppings. Where rushes are used as animal bedding the seeds are spread with the resulting farmyard manure.

### **Management**

The soft, the hard and the compact rush are of the greatest significance on cultivated grassland. Control is limited to cutting, cultivating and drainage (Wolton, 2004). Cutting before flowering will prevent further seed shed but there will be many seeds remaining in the soil seedbank (Salisbury, 1961). Cutting may help to stop spread but is unlikely to give good control. Grazing may also help but is unlikely to be effective alone. The hard rush tolerates annual mowing and moderate trampling (Richards & Clapham, 1941a). The compact rush is resistant to trampling (Richards & Clapham, 1941c). The jointed rush can withstand mowing and grazing. The slender rush is very resistant to trampling, cutting and grazing (Richards, 1943). Neither cattle nor sheep have much effect on hard and soft rush in open pasture. Sheep confined to small areas at high stocking rates can give improved control of rushes (Popay & Field, 1996). Goats will provide even better control at a minimum stocking rate of 12 goats/ha. In Wales, 20 to 60 goats/ha grazing red fescue/white clover pasture from June to October reduced soft rush tussocks. The greatest reduction was in shorter pasture, and the suppression was maintained for 3 years. Topping in early August followed by grazing with hardy breeds of cattle or ponies over 2 years gives good control in uplands (Soil Association, 2002). In lowlands, cutting followed by grazing is effective. In lowland areas that flood naturally, topping followed by flooding is effective on wet grassland. Pulling of clumped rushes is another method of control. The application of lime, and keeping rushes cut down or grazed by horses are other measures that may be taken (Morse & Palmer, 1925). The blunt-flowered rush is very tolerant of frequent cutting or burning and of grazing (Richards & Clapham, 1941e).

Control must aim at eradication and preventing re-establishment. Rushes do best on wet soils so improved drainage will help with any control measure. According to Morse & Palmer, (1925) only good drainage is permanently effective in controlling rushes. However, the presence of rushes is also an indication of an impoverished soil. All rushes are controlled by ploughing or rotary cultivations (ADAS, 1972). A preliminary rotary cultivation may be needed to break up the tussocks before ploughing. On shallow soils ploughing may not be possible anyway. Rushes are prolific seeders, and ploughing or other cultivations may stimulate the emergence of further infestations unless the new

sward establishes rapidly. Sowing to a short-term crop followed by further surface cultivations may be best before re-establishing a long-term sward. In an established sward, common rush is considerably reduced by regular annual mowing for hay. Rush seeds require light for germination and seedlings are only likely to emerge in open areas. Rushes will establish rapidly on ground left bare due to poaching etc. Seedlings are sensitive to competition and to moisture deficit but become tougher once established. Detached young shoots of toad rush can re-root after disturbance (Grime *et al.*, 1988).

Mechanical control of soft rush is by ploughing or mowing. Ploughing and reseedling is possible on a drier, level site. Ploughing should be in spring or early summer with good inversion. Plants that are not completely buried are able to re-establish themselves (Lazenby, 1953). Where an uncut field of rushes has been ploughed-in it has been known for the rushes to reappear between the furrow slices. The vegetative tillers grow out into the light and the plants re-establish themselves. Mature plants left fully exposed on the soil surface are susceptible to drying out by the wind and sun. Fourteen days exposure is likely to be fatal.

Mowing should be between July and September, and should be repeated in consecutive years. Cutting to ground level twice a year or once after flowering will reduce plant vigour (Crofts & Jefferson, 1999). If only one cut is possible then cutting in August after flowering is most effective. Where possible the cuttings should be removed. Soft rush is tolerant of annual cutting for animal bedding and is moderately resistant to trampling.

Soft rush is grazed by cattle and rabbits but is not eliminated by this (Richards & Clapham, 1941b). Goats will eat soft rush in grassland, however, high stocking rates are needed to achieve control. Voles kill tussocks of *Juncus* spp. but also destroy grasses (Tansley, 1949a).

Where rushes are being maintained as a habitat for birds such as lapwings, redshank, snipe and curlew, the cutting regime should aim to give a patchwork of grassland and rushes (Arkle, 2007; Crofts & Jefferson, 1999). This is achieved by mowing one third of the area each year between August and November to avoid harming chicks, with a second cut 4 to 8 weeks later. Stocking rates should be kept low to avoid damage to nests during the breeding season and to the sward.

### **Chemical control**

- **MCPA** (Headland Spear) – for use in permanent grassland, where this species is generally only a problem.
- **Glyphosate** (*various products*) – can be used in wick applicators as a spot treatment, but needs to be very accurately applied to prevent kill of the surrounding vegetation.

**Discussion**

Rushes are not a problem on cultivated land and even on grassland are generally restricted to poorer pastures where land management is less intensive. Grassland where rushes can be a problem is often not considered of sufficient agricultural value to justify costly intervention. On such land, a reduction in rush frequency is most likely to result from changes in management that improve the sward and prevent overgrazing. Ploughing is seldom an option and rush seed reserves in the soil are likely to produce a further infestation unless cultivation is continued for several seasons.

While direct control is said to be limited to cutting, cultivating and drainage this is based mainly on anecdotal information, observations and on studies made many years ago. Stock grazing also influences the growth of rush infestations but some of the more effective options may not be practical. There appears to have been little new research on rush control. Much of the current interest in rush management comes from their value to wildlife on heathland and other important habitats.

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## Appendix

### Research projects in Europe of relevance to perennial weed management

A DEFRA funded review of current European research on organic farming was made from 1998 to 2000 (OF0171) (ADAS, 2000). Key research institutes, major projects and individual researchers were identified. Current and recently completed research projects were included. A total of 724 projects was identified. The greatest activity was in Sweden. An overview was provided of the range, content and organisation of organic research. It was proposed that research directories should be refined and updated on an annual or biennial basis. In addition, the review incorporated 5 study tours including a European study tour of weed control in organic horticultural and arable systems. A further project, (OF0338, DEFRA 2003), identified and collated information on organic research projects in the UK. There was also a project (OF0350, DEFRA 2005) to assess the issues and aspirations stakeholders felt should be addressed by publicly funded research in organic farming.

A preliminary overview of organic farming research in Europe based on contributions from several experts was published in March 2002 (Zerger & Willer, 2002). Little detail was given of the research projects and weed control was only specified as a general research area for Great Britain and Hungary. Current research topics in Hungary at that time included ecological weed management and the development of machinery for mechanical control (Frühwald, 2000). The influence of climate, crop rotation and tillage on the weed flora and soil seedbank were also being investigated.

An updated consolidated report of organic farming research in Europe was prepared in 2004 (Slabe, 2004). In Austria, a project was investigating the occurrence of the dock leaf beetle and its potential for biological control of the broad-leaved dock (2003-2007). A second project led by Andreas Bohner was investigating the biological control of broad-leaved dock in grassland (2004-2006). In Belgium there were two projects on mechanical weed control optimization and innovation (2003-2005). In Cyprus, there was a study of the biological control of insects and weeds. In Denmark, the management of perennial weed species in organic farming was the title of a project led by Bo Melander. The project focussed on creeping thistle (*Cirsium arvense*) and common couch (*Elytiglia repens*). Effective control was obtained but the level of treatment intensity was unacceptably high (DARCOF II, 2002; 2006). Mechanical control was applied alone or in combination with suppressive cover crops. Other Danish projects on cultivation in ridge and mixed cropping, and on band-heating for intra-row weed control were led by Jesper Rasmussen and Martin Heid Jørgensen respectively. In Lithuania, weed control theoretical background and technology optimization in agriculture was being evaluated (Slabe, 2004). The effectiveness of mulches for weed control was also being investigated. In Poland, ecological methods of weed control were under investigation. Weed infestations and the weed seed bank of winter wheat were being studied too. In Sweden, a number of research projects on weed management in organic farming were being led by Håkan Fogelfors. There was a project on the management of couch grass utilising plant competition and cutting that ran from 2002 to 2004. The aim was to

investigate the extent to which couch can be inhibited or eliminated by cutting together with competing crops. In Switzerland, the development of novel technologies for the control of pests, diseases and weeds was a priority. A project on the biocontrol of creeping thistle led by Eric Wyss ran from 2003 to 2005. The Netherlands had several projects within the theme of plant protection and weed control. In the UK, there was a participatory investigation of the management of weeds in organic production systems (OF0315). There was also a desk study on using weeds to reduce pest insect numbers (OF0329).

A MAFF funded contract (OFT0115T 1995-1998 & extended for a further year) evaluated the effects of mechanical aeration, cutting height and cutting frequency on the control of docks in grassland (Hopkins, 1999). Also in the UK, there was a MAFF Open Contract (OF 0143) entitled: The effect of break crops on weed control in organic arable ley crop rotations (Robson, 2003). A four year experiment was set up to investigate the impact of break crops in an organic ley-arable rotation on the weed burden in the break crop and subsequent cereal crop. A 3-year Defra funded project (BD1437), undertaken by IGER and NERC from 2000 to 2003 had the overall aim of developing and testing integrated weed management systems to control creeping thistle and other injurious weeds (Pywell *et al.*, 2003). A 3-year Defra funded project (BD1449), undertaken by IGER, CEH and CABI Bioscience, aimed to determine the effect of grazing on the growth and spread of creeping thistle in lowland and semi-upland pasture (IGER, 200-; NERC, 2006). Field experiments were set up in 2000 to assess grazing treatments and other weed control measures. A Hortlink project 'Mechanical weeding for sustainable salad and brassica production in a zero or limited herbicide environment (HL0173)' that finished in 2007 has developed a prototype in row mechanical weeder. A synchronised control system enables the deployment and retraction of a shallow undercutting blade.

There is a current 5-year project at the Danish Research Centre for Organic Farming entitled Effective control of perennial weeds and intra-row weeds in organic cropping through novel technology and new management strategies (DARCOF III, 2007). The proposal will seek to optimise tillage and cutting treatments by gaining a better understanding of source/sink allocation of resources in *Cirsium arvense* and *Tussilago farfara*. The work will also seek to develop new technologies for effective uprooting and destruction of the vegetative organs of *Elytrigia repens* and *Rumex crispus*. Within the project is a PhD Scholarship to research the phenology and source-sink dynamics in relationship to the management of *C. arvense* and *T. farfara* (EWRS, 2006).

In the Finnish Research Network on Organic Agri-Food Systems there is a project entitled 'perennial weeds threat to cereal production' (Finland, 2006).

Among the organic farming and related projects carried out under the European commission's Fifth Framework Programme for research was the theme 'Strategies of weed control in organic farming (Contract No. QLK5 2000 1418) (EU-Agrinet, 2002). It is also listed as QLRT-1999-31418 (organic-europe.net, 2006). The aim of the WECOF project was to improve the efficiency of weed control in organic farming with winter wheat as the model crop (WECOF, 2000; Davies *et al.*, 2002). A series of core trials

with winter wheat were established in Germany, Poland, Scotland and Spain. Studies within the project included variety trials to evaluate crop architecture. The allelopathic potential of certain crop residues to reduce weed emergence was investigated. The impact of light-less cultivations on the emergence of light sensitive weeds was also determined. The results are intended to assist in the development of a Decision Support System (DSS) that will aid the formulation of site specific strategies for weed control.

The Crop and Weed Ecology Group (Bastiaans *et al.*) at Wageningen University list a number of weed related research themes but none are specified as organic (WageningenUR, 2005). These included integrated and low input weed management, population dynamics, biodiversity, the use of cover crops and precision weed control.

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