The biology and non-chemical control of Creeping Thistle (*Cirsium arvense*).

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Creeping thistle
(Californian thistle, Canada thistle, creeping plume thistle)
***Cirsium arvense* (L.) Scop.**
(*Carduus arvensis, Cnicus arvensis, Serratula arvensis*)

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). However, it is less common on light, dry soils (Frankton & Mulligan, 1970). Creeping thistle is often limited to hedge bottoms and field margins or within 5 m of them into the cultivated field (Marshall, 1985). It can be a problem weed in gardens (Copson & Roberts, 1991). 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 high summer temperatures limits its southerly distribution in North America (Moore, 1975). As a C_3 plant it is less successful in hot, dry climates (Håkansson, 2003). In Canada, where creeping thistle can survive a winter temperature of $-27^{o}C$, land infested with the weed increased from 20,000 ha in 1975 to 200,000 ha in 1997 (Thomsen *et al.*, 2004). It is recorded up to 2,300 ft in Britain and has been found in prehistoric deposits (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 occurs in the latrine areas on horse grazed grassland (Gibson, 1997). 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. 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 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). It is able to survive in all but the most intensively cultivated arable fields, interferes with harvesting and reduces crop yield (Long, 1938; MAFF, 1976). 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).

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).

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). In a series of 4 national weed surveys made in Hungary between 1950 and 1997, it moved from 2nd to 5th 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. The adoption of set-aside may have allowed creeping thistle to increase in range and frequency (Dow AgroSciences, 2001).

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). The first population of creeping thistle resistant to the auxin type herbicides was recorded in 1979 (Dow AgroSciences, 2001).

Creeping and other thistles are food plants for several insect pests including bean aphis, 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). Creeping thistle seed is 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 (Clapham *et al*., 1987) sometimes into October (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 only by female flowers, 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 which 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 selfing.

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 seeds were viable if cutting took place 10-11 days after flowering. Haggar *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 in this study, even ripe seed was found to have very low levels of germination.

Research shows 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 germinate best at a relatively high constant temperature of 25-30^{o}C (Kumar & Irvine, 1971; Heinmann & Cussans, 1996; Salisbury, 1961), and at alternating temperatures of 20 to 30^{o}C and 30 to 40^{o}C (Wilson, 1979). At lower temperatures germination was aided by high light intensity. Pre-chilling at 4-7^{o}C also improved germination in the light and in the dark but was not essential in the light. When light was available, 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 3 were stimulatory, light and alternating temperatures have a synergistic effect. Fresh seed was deeply dormant, 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 on 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. Seedling thistles 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 but growth is limited by low temperature in winter. 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. The freezing resistance of overwintering root buds of creeping thistle has been evaluated in the laboratory (Schimming & Messersmith, 1988). The temperature required to reduce survival by 50% was –7°C, 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 bearing 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 under 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^{o}C reduces 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. 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 deeply 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 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). Creeping thistle residues were 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 (1946) 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 for 3 years had viabilities of 1.4, 30.9 and 50.5% respectively (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^{o}C and 80% humidity died within 6 months. The viability of seed stored dry at 20^{o}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^2 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 is usually devoid of seed.

Creeping thistle seed has been dispersed as a contaminant of various crop seeds. 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). Creeping thistle was spread to the USA as a contaminant of crop seed (Mitich, 1988).

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 faeces of chaffinches fed on the seeds of a range of weed species (Holmes & Froud-Williams, 2001). 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 20-40 ft 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 can remain dormant in the soil for long periods, shoots only appearing after soil disturbance (Moore, 1950; Soil Association, 2002). Fragments of root from creeping thistle encroaching from the field margins can be carried into the field by cultivation. Collection and 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 were reviewed by Donald in 1990. The impact and control of creeping thistle in grassland was reviewed by Haggar *et al.* in 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 one 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 bud 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).

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. It 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, 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 became 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, 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. Haggar *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 blade 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 spked-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 indicate 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 thistles seedling 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. However, Vanhala *et al.* (2003) found that creeping thistle was able to recover after a bare fallow. 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 and 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 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 were 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 & Zwerger, 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. A forage crop of hairy vetch (*Vicia villosa*) and winter rye (*Secale* *cereale*) was more effective at suppressing creeping thistle than a patchy grass-clover crop (Lukashyk, 2005). A single stubble cultivation before cover crop establishment was much less effective than repeated tillage. The improved level control with repeated stubble cultivation is similar regardless of the implement used (Lukashyk *et al.,* 2005). 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^{o}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^{o}C for 12 hours (Thompson *et al.,* 1997). At 56^{o}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^{o}C for 5 minutes was killed.

Wheat gluten meal (WGM) at 1 or 3 $g.dm^{-2}$ dusted over creeping thistle 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^{o}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 3rd 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 general 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 phytophagus 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 tips of shoots 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 which 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 reticulate* 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*).

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