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A review of non-chemical weed management

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Methods of non-chemical weed control that could be used in organic systems were reviewed previously as part of a desk study funded by MAFF (Bond & Grundy, 1998). Other reviews of developments in non-chemical weed control techniques and systems have included: Morgan, 1989; Parish, 1990a; Stopes & Millington, 1991; Rasmussen & Ascard, 1995; Rasmussen, 1996; Bond & Lennartsson, 1999 and Bond & Grundy, 2001. Bàrberi (2002) in an appraisal of recent organic weed management research questioned whether the right issues have been addressed anyway. The present review aims to update and consolidate the previous MAFF-funded review as part of the Organic Weed Management Project, OF0315, funded by DEFRA. It is intended that this review will be ongoing and based on recent scientific and grower related publications as these become available. The reference list should provide an extensive bibliography of papers relating to most aspects of non-chemical weed control.

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Introduction

Organic farmers cite weeds as the most significant production problem they encounter (Stopes & Millington, 1991), and total crop losses from weeds can occur under the organic system. In the UK, wheat crops have been ploughed in due to heavy weed infestations and there is evidence that perennial weeds increase under organic husbandry (East, 1993). One analysis of the relative frequency of weeds three years after conversion to organic growing showed that total seed numbers in soil had increased from 4050 m^{-2} to 17320 m^{-2} (Albrecht & Sommer, 1998). The 1991 ADAS organic wheat survey showed weed control to be the most important crop protection problem to be faced by organic wheat growers (Yarham & Turner, 1992). Chickweed (*Stellaria media*), mayweeds (*Matricaria* spp.), speedwells (*Veronica* spp.) and annual meadow grass (*Poa annua*) were among the most abundant of the 86 weed species recorded. Perennial weeds were more abundant in fields that had been under organic production for some years. In a survey of organic vegetable growers in the UK, weed control was considered to be one of the most serious problems (Peacock, 1990), and chickweed (*S. media*), couch grass (*Elymus repens*) and thistle (*Cirsium* spp.) to be the worst weed species. At the first stakeholder meeting of the current DEFRA project, the majority of the farmer and grower participants were of the opinion that docks (*Rumex* spp.) were the main problem.

UK organic growers surveyed in 1999 considered their current weed management to be adequate but few rated the available methods of direct weed control to be very effective (Beveridge & Naylor, 1999). Under the United Kingdom Register of Organic Food Standards (UKROFS, 1999), and similar national guideline elsewhere in Europe based on regulation No. 2092/91 of the European Community (EC, 1991), chemical intervention is not permitted for weed control purposes in organic farming systems. The use of pre- and post-emergence mechanical and thermal weeding methods, cultural control measures and the use of plastic and degradable mulches are allowed. However, direct intervention should be minimised to avoid undesirable effects within the farming system and on the environment (Woodward & Lampkin, 1990).

Even when using acceptable non-chemical control methods there may be some conflict between measures to control weeds and some of the other aims of the organic system. For example, early cultivation of pasture to improve weed control may increase the risk of nitrate leaching from the soil (Anon, 1997), as may other weed control strategies (Cussans, 1992). Intensive cultivation to control large weeds may damage soil structure (Mattsson *et al.*, 1990; Colquhoun & Bellinder, 1996). However, the increased mineralisation of soil nitrogen following cultivation can be used to advantage by organic growers for boosting crop growth (Smith *et al.*, 1994). Complete eradication of weeds is not the aim in organic systems (Blake, 1990), and under a regime of reduced management inputs the range of species may expand (Hall, 1995). Weeds increase the diversity of agricultural growing systems, but can be both a blessing (Zandstra & Motooka, 1978) and a nuisance (Streiberg, 1988). In Canada, the 'weed' black medick (*Medicago lupulina*) has been incorporated into the rotation of some alternative agricultural systems because it enriches the soil and discourages other weeds (McLaughlin & Mineau, 1995). In other instances, weeds have been planted deliberately within the crop as a trap for insect pests (Hokkanen, 1991), and so may play a part in integrated pest management systems (IPMS). Conversely, weeds may act as sources of infection or be alternative hosts for some pests (Norris, 1986).

Economic factors can have a considerable influence both on the crops that are grown and on the particular method of weed control that is applied within those crops. Certain methods may only be economic when used in high value crops (Leake, 1996); others are only applicable to crops grown in a particular way.

There is a view that only research conducted within a 'wholly organic system' has any significance to organic growers (Marland, 1989). While this may be so for some measures aimed at reducing the weed problem by cultural means, direct, or physical, weed control is likely to have a similar effect whatever the system. The output from weed biology and weed competition research should apply equally well to both organic and conventional systems. In the absence of sufficient research made solely within the organic system, the present review includes relevant work from other growing systems, avoiding only those studies made solely on chemical methods of weed control. The direction that organic research should take to make up the deficit has been reviewed by Lockeretz (2000).

In this review, cultural weed control is considered separately from methods of controlling weeds directly. In addition, the main sections have been sub-divided to define and discuss more closely the different areas of interest that lie within them.

DIRECT WEED CONTROL

Physical weed control

Weeds differ from most pests and diseases in that killing or removing them by direct physical means is a practical option. The problem is in removing the weeds selectively without injuring the crop. The choice of weeding method and of implement depends in part on practical aspects such as the crop and the soil type, but economic elements like purchase price, operating costs and labour requirements are often the over-riding factors. On small areas or where sufficient work force is available hand-weeding remains a possibility, particularly in high value crops, but on most farms, crops are grown on too large a scale, and labour is expensive and often of limited availability. An overview of the applications and relative costs of the main mechanical weed control implements used in the UK was given by Lampkin (1990).

Mechanical weed control

Mechanical weed control may involve weeding the whole crop, or it may be limited to selective inter-row weeding. In a well spaced crop planted 'on the square', a second inter-row weeding may be made at right angles to the first to cover a greater percentage of the soil surface (Kouwenhoven *et al.*, 1991; Kouwenhoven, 1994; 1997). In addition, inter-row implements have been designed that control weeds within the crop row by directing soil along the row to cover small weeds (Klooster, 1982). Mechanical weeders range from basic hand tools to sophisticated tractor driven devices. These may include cultivating tools such as hoes, harrows, tines and brush weeders, cutting tools like mowers and strimmers, as well as implements like thistle-bars that may do both. Custom-made basket or cage-wheeled weeders, with gangs of rolling wire cylinders, offer another way to deal with seedling weeds in a friable soil (Bowman, 1997; McGrath, 1999). The mode of action, operating speeds and limitations of a number of mechanical weeding tools were reviewed by Tillett & Home (in Welsh *et al.,* 2002).

The choice of implement, and the timing and frequency of its use may depend on the crop and on the weed population. Some implements, such as fixed harrows, are thought more suitable for arable crops, while others like inter-row brush weeders may be considered to be more effective for horticultural use. The optimum timing for mechanical weed control is influenced by the competitive ability of the crop (Turner *et al.*, 1999). A single inter-row cultivation at any time may provide excellent weed control in a crop like transplanted broccoli that rapidly develops a broad, shading leaf canopy (Colquhoun & Bellinder, 1996). Control from a single weeding may be poorer in crops like sweet corn *(Zea mays*) where early growth is slow, or in green beans (*Phaseolus vulgaris*) where the growing season is relatively long. In the UK, the optimum timings for mechanical weed control have been defined for onions and for carrots grown in both organic and conventional systems (Bevan *et al.,* 1993 & 1994; Bond & Burston, 1996; Bond *et al.*,1998a). In organic winter cereals, Welsh *et al.*, (1996), using a spring-tine weeder, found that corn poppy (*Papaver rhoeas*) was more effectively controlled in the autumn whilst chickweed (*S. media*) was controlled best in spring.

In experiments to determine the type of physical damage that gave the most effective control of a range of seedling weeds, Jones *et al.*, (1995 & 1996), found that burial to 1 cm depth was the most effective treatment, closely followed by cutting at the soil surface. Plants need to be buried totally to be controlled but plant size, angle and growth habit influence the depth of covering required (Baerveldt & Ascard, 1999). At high weed densities, even with the most effective mechanical weeders, sufficient weeds are likely to survive control measures and profoundly reduce crop yield in cereals (Rasmussen, 1993a). Direct control needs to be linked with long term preventative measures to maintain the weed population at a manageable level.

With most mechanical weeding implements, operator skill, experience and knowledge are critical to success. Drawbacks to mechanical weed control include low work rates, delays due to wet conditions, and the subsequent risk of weed control failure as weeds become larger. Pullen & Cowell (1997), reviewed the merits of six different mechanical weeding mechanisms, and quantified their performance in controlling inter-row weeds at different growth stages and at different tractor speeds. Weed control was not necessarily better at earlier weed stages and weeding too early often missed late germinating weeds. Increasing forward speed did not improve the performance of all the implements equally.

On a cautionary note, there may be some disadvantages to the greater use of mechanical weed control. The additional cultivations associated with mechanical weeding could harm soil structure and possibly encourage soil erosion (Colquhoun & Bellinder, 1996). The increased mineralisation of soil nitrogen due to cultivation may be seen by some growers as a problem and by others as an advantage (Smith *et al.*, 1994, Welsh *et al.*, 2002). There is concern about the impact of mechanical weeding on ground nesting birds and management practices may some alteration to minimise disruption at critical times (Welsh *et al.,* 2002).

Hand tools

Although hand hoes, push hoes and other traditional hand weeding tools are still used on small-scale horticultural crops in the UK this is often seen as a last resort. In developing countries, where hand labour is more readily available, there is a greater incentive to evaluate the ergonomics and weeding efficiency of different hand tools (Chatizwa, 1997). Hand weeding is of particular importance where the terrain and climate are unsuitable for mechanised systems, or local technical knowledge is lacking (Anobah, 1993). Whatever the level of sophistication of the farming system, there will be times when hand-roguing of the odd plant or patch of a particular weed is the most effective way of preventing that weed from proliferating or spreading and becoming a serious problem (Marshall, 1992; Putnam, 1990). In the UK, the uprooting of perennial weeds in grassland is still carried out with hand tools. A recent development in the hand-weeding of row crops has been the use of self-propelled and tractor-drawn platforms or flat-bed machines that move slowly through the crop carrying up to eight workers lying prone, and weeding the crop rows as they pass over them (McGrath, 1999; Turner, 2000). Hand weeding may be combined with mechanical inter-row weeding to deal with weeds left in the crop row. Ionescu *et al.*, (1996), found that in corn and soybean crops the combination of the two practices prevented crop losses and reduced the time spent hand-weeding.

The Eco-puller has been developed to mechanically remove perennial weeds such as common ragwort (*Senecio jacobaea*) from grassland (Soil Association, 2002). It works best with a height difference between the weed and the grass or crop. A prototype mechanical weed puller that is intended to replace hand weeding in row crops is also being tested (Anon, 2002). The tractor-mounted device comprises contra-rotating rollers designed to pull up weeds such as fat hen. A work speed of 4-5 mph is forecast.

Harrows

Harrowing is a traditional form of mechanical weed control for dealing with annual weeds but is ineffective against perennial and established deep-rooted weeds. In cereals, 'blind' or pre-emergent harrowing may be carried out after drilling but before crop emergence in order to kill the first flush of small emerging weeds. Spring-tine, chain or drag harrows may be used (Lampkin, 1990). The aim is to give the crop an early advantage over the weeds to aid selectivity in subsequent harrowing operations.

Dry weather is critical to the success of early harrowing operations but adequate soil moisture is needed initially to encourage early weed emergence. Blind harrowing has little effect if few weeds have emerged, and may sometimes delay crop emergence (Heard, 1993). Post-emergence harrowing may cause crop injury too, but selectivity depends on many factors including the soil covering mechanism (Kurstjens & Perdok, 2000). Increased working depth and forward speed in a drier soil gave increased soil covering (Kurstjens, 2002). The impact of uprooting has been shown to cause higher mortality than soil covering in weeds harrowed at or 3-4 days after emergence (Kurstjens & Kropff, 2001). Increasing the working depth from 10 to 30 mm doubled the number of uprooted plants, and was further improved by higher soil moisture and faster working speeds (Kurstjens *et al.*, 2000). Drier soil at harrowing decreased weed survival (Kurstjens, 2002).

Chain harrows with round and/or shuttle shaped links bury the weeds but do not pull them up. However, Rasmussen (1991a), found that only 37 to 50% weed control was obtained even with 5 passes at one cultivation. For best results, the soil should be crumbly, not too wet or crusted. When used post-emergence in cereals the chain harrow is more effective against weeds below the 3-leaf stage (Böhrnsen, 1993).

Tine weeders with either rigid or spring-loaded tines, superficially cultivate the whole soil surface. They are considered less damaging to the crop than chain weeders (Lampkin, 1990). At early weed stages the harrowing action buries seedlings under loose soil rather than uprooting them, and does not pull up established cereal plants beyond the 3-leaf stage (Rasmussen, 1994). The choice of tines depends on soil type and structure, but adjustment of the implement, especially the angle of penetration of the tines, is important (Böhrnsen, 1993). On some implements the downward force on the tines can be adjusted. Weed control in winter wheat ranged from 69 to 95%, depending on seed rate, following 2-4 harrowings at one cultivation using stiff tines (Rasmussen, 1991a). The particle sorting and throwing action of tines varied with particle size and moisture content of the soil (Kouwenhoven & Terpestra, 1979). Sorting action increased with wider tines and slower forward speed, while throwing action increased with forward speed, working depth and tin width. Tine weeders are more successful on lighter soils and less suitable for heavy land (Lampkin, 1990). They come in a several working widths and their use in brassicas and other vegetables is increasing (Williams, 2003).

Weeders fitted with flexible tines (flexi-tines) can be used selectively at the late tillering stage of cereals when the dense crop foliage forces the tines into the inter-row (Rasmussen, 1994). Flexi-tine weeders are also used in broad-leaved crops, but may injure poorly established crop plants in dry conditions, reducing crop yield (Colquhoun & Bellinder, 1996). In drilled pinto bean (*Phaseolus vulgaris*), flexi-tine harrows damaged the stems and hypocotyls of the beans and reduced crop stand when used at crop emergence and later growth stages (Vangessel *et al.*, 1995). Torsion weeders, with pairs of tines set either side of the crop row offer more precise inter-row weeding (Bowman, 1997). Rotary-tine weeders, with two ground-driven 'star' or 'spider-tine' rotors covering each row, also allow inter-row weed control (Pullen & Cowell, 1997). The angle of the rotors can be set to move soil away from, or towards the row; the latter ridging up the crop to bury small intra-row weeds. For vegetable crops, finger-weeders with flexible rubber tines on ground-driven cone-wheels have been developed that follow inter-row cultivators and uproot then bury the loosened weeds next to, and within, the crop row (Turner, 2000; Williams, 2000). In tree crops, rotating heads of vertical metal tines are used to cultivate around and between plants in the row either manually or automatically via a sensor (Bowman, 1997).

The timing and frequency of harrowing is important both for the effect on the weeds and on the crop (Rasmussen & Svenningsen, 1995), it may be more important than the type of harrow used (Rasmussen *et al*, 1989). Wilson. (1993), found that harrowing in autumn thinned a wheat crop more than in spring, and the effect was more severe with two passes at right angles. The effect on the weeds depended on the species. The growth of *Brassica napus* was only reduced by harrowing in autumn; by the spring the weed had developed a deep taproot and was not readily uprooted. Similarly, Welsh *et al.*, (1997), found that corn poppy (*Papaver rhoeas*) and shepherd's purse (*Capsella bursa-pastoris*) which also develop a taproot, were more effectively controlled with tines in autumn than in spring. The shallow rooted weeds, chickweed (*S. media*) and cleavers (*Galium aparine*), were better controlled in spring when there was more foliage to catch on the tines. For good control of cleavers (*G. aparine*) in winter wheat, a combination of early and late harrowing gave the best results

(Steinmann & Gerowitt, 1993). Soil moisture and environmental conditions at the time of harrowing influence both the effectiveness of the weeding operation, and the selectivity between crop and weed. Kirkland (1995), found that moisture conditions, at and immediately after harrowing, had a differential effect on the recovery of wheat and wild oat (*Avena fatua*).

Tractor speed at different stages of crop and weed development is important for weed control but the effect maybe influenced by other factors (Rydberg, 1993; Kouwenhoven, 1997). Crop burial was severe when oats were harrowed at the 1-leaf stage, and weed control was poor then because few weeds had emerged at that time. Both weed control and crop yield were better following harrowing at the 2- or 3-leaf crop stage. When oats were at the 3- to 4-leaf stage, a faster driving speed increased the amount of soil covering the crop plants. Harrowing across the rows caused greater soil covering than harrowing along the rows. At higher tractor speeds, crop yield was adversely affected in two of the three years of testing (Rydberg, 1994). Good weed control was obtained by harrowing at 5 km/hour but the direction of harrowing did not matter.

A model to describe crop yield responses to weed harrowing has been developed for cereals (Rasmussen, 1991b). It takes into account crop damage, weed density and weed reduction. Modelling procedures have also been developed and tested to determine the optimum intensity for harrowing peas at early crop growth stages (Rasmussen, 1992b; 1993b). Selectivity with rigid and with flexible tines is improved when the crop has a size advantage over the weeds (Rasmussen, 1994, Rasmussen & Svenningsen, 1995). Different types of harrows have been tested for selectivity in terms of weed burial versus crop burial in soil using a model that describes the relationship between crop soil cover and weed control (Rasmussen, 1992a). Many factors influenced the degree of selectivity including site characteristics and the composition of the weed flora (Rasmussen, 1990). Control of the working depth with a sensor control system minimised the variation in soil covering under various soil conditions (Søgaard, 1998).

Tractor hoes

Tractor hoes have ‘A’ or ‘L’ shaped fixed, vibrating or revolving shares that cut through the soil at 2-4 cm depth (Bowman, 1997). The important design features and nomenclature of hoe blades is explained in detail by Tillett & Home (in Welsh *et al.*, 2002). The goose-foot (or ducks-foot) share may be mounted on individual parallelogram linkages or fitted to individual spring tines. Increasing the working depth does little to improve weed kill, but higher forward speed increases soil covering of weeds and reduces survival (Pullen & Cowell, 1997). Soil structure is important; in rough soil weeds may continue to grow in the lumps of soil lifted by the hoe (Mattsson *et al.,* 1990). Desiccation on the soil surface is a critical factor in preventing weed regeneration, and wet conditions after hoeing can decrease the level of control. Hoeing is particularly effective against mature weeds (Böhrnsen, 1993).

Hoe weeders control weeds within the inter-row; the shares undercut everything so it is necessary to steer the hoes very carefully between the crop rows. A good seedbed and precise drilling of the crop are prerequisites for successful hoeing. The technique of harrowing-in cereal seed after drilling may displace the seed out of the row leading to crop damage during hoeing. Seed rates should be increased to compensate for any likely losses (Lampkin, 1990).

Steerage may be the sole responsibility of the tractor driver, with or without the aid of some form of self-steering mechanism, or a second operator may control the steering (Bowman, 1997). In narrow row spacings poor machine guidance can remove a significant number of crop plants (Stopes & Lippiatt, 1993). In order to protect the above ground parts of plants from mechanical damage, and from being covered with soil, different types of protectors can be fitted. These may take the form of discs, plates or protective hoods (Bowman, 1997; Mattsson *et al.,* 1990). In crops like carrot and sugar beet, implements may incorporate ridging bodies to bury weeds along the row with a band of loose soil (Baumann & Slembrouck, 1994, Lampkin, 1990). The hoe-ridger is specifically designed to do this in sugar beet (Parish, 1990a), giving a mixture of inter- and intra-row weed control. However, root development of the weeds may influence soil movement and thus the success of intra-row weed control. A shallow working depth and relatively steep position of the hoe blade gives the best results (Terpstra & Kouwenhoven, 1981).

The powered rotary hoe is PTO (power take-off) driven and fitted with rotating L-shaped blades on a horizontal axle. The width of the rotor can be adjusted to different row widths. It gives more intensive cultivation of the soil and can deal with larger weeds. A further development has been the rotary ground driven weeder or rolling cultivator with usually two ground driven 'star' or 'spider tine' rotors covering each row (Pullen & Cowell, 1997; Williams, 2000). The angle of the rotors can be set to move soil away from, or towards the row. The latter, ridging up the crop to bury small inter-row weeds. Increasing the forward speed of the rotary hoes does not improve the level of weed control. The machines work best on light, stone free soils.

In cereals, increasing the row spacing can improve inter-row cultivation without affecting yield (Rasmussen, 1994; Tillett *et al.,* 1999; Welsh *et al.,* 2002). Inter-row hoeing may itself lead to some reduction in crop density particularly following early weeding treatments but again this may not affect yield (Welsh *et al.,* 1997). Inter-row cultivations with a rotary hoe in pinto beans (*Phaseolus vulgaris*), gave adequate weed control without reducing plant stand or injuring the crop (Vangessel *et al.,* 1995). There is always concern that hoeing itself causes crop losses due to mechanical injury. In carrots, inter-row cultivation with a conventional hoe did not reduce yield in the absence of weeds. At similar speeds and depth settings it gave comparable weed control to a brush weeder but in weedy fields the brush weeder had a more destructive effect on the weeds (Ascard, 1993). There was no yield loss either in weed-free, drilled onions that were hoed close to the crop row with a conventional hoe with goose-foot shares (Melander & Hartvig, 1997). Discs protected the onions from undesired lateral soil movement and allowed an untilled strip of variable width (5-12.5 cm) to be left alongside the crop row.

Brush weeders

The brush weeder, or brush hoe, is primarily intended for inter-row weeding of vegetable crops such as carrots, onions and beetroot etc. (Lampkin, 1986;1990), although it has been tested in cereals (Richards, 1991). With leafy vegetables there is a greater risk of causing crop damage. As the name suggests the weeding action comes from strong nylon brushes that rotate and brush the weeds onto the soil surface. It has the advantage that it can be operated under moister soil conditions than a tractor steerage hoe. A second person, in addition to the tractor driver, or some form of self-steering mechanism is needed to ensure careful guidance of the brushes between the crop rows.

Two main types of brush hoe have been developed, those with disc brushes operating in the vertical plane on a horizontal axis, and those with circular brushes operating in the horizontal plane on a vertical axis (Kouwenhoven, 1997). In the former, brush position on the drive shaft and brush width can be adjusted to different row widths, and crop rows are protected by a tunnel. In the latter, the brushes can be angled and the direction of rotation altered to move soil away from plants or to earth up the crop row and bury any weeds that the brushes cannot reach (Melander, 1997; Steele, 1997). The above ground parts of crop plants can suffer mechanical damage from contact with the brushes. To prevent injury protectors may be fitted in the form of discs, plates or protective hoods that go along both side of the row (Bowman, 1997; Mattsson *et al.,* 1990). An outer ring of softer bristles has prevented crop damage but weed control was less satisfactory (Kouwenhoven, 1997).

In tests with the brush hoe on a horizontal axis, Weber (1994) found that working depth was the most important factor in ensuring good weed control. Tractor speed, brush velocity and soil conditions interact to determine the working depth (Weber & Meyer, 1993). The brush weeder works by uprooting the weeds (Pedersen, 1990), and being able to adjust the depth precisely is a requirement with this type of brush hoe. Vester & Rasmussen (1990), compared the row brush hoe with a conventional hoe in horticultural crops and found the brush hoe to be more efficient because of its ability to work very close to the crop row. However, the brush hoe was less effective against couch (*Elymus repens*), a perennial grass weed. In very dry conditions, the conventional hoe had a better effect against weeds than the brush hoe (Pedersen, 1990). With the brush hoe, work intensity (the ratio between tractor speed and the rate of brush rotation) determined the level of weed reduction. At later weed growth stages a greater work intensity was needed to get a satisfactory effect, increasing brush speed relative to tractor speed. Tractor speed is limited by the operator's ability to steer the brushes close to the crop row at faster speeds. A single inter-row cultivation at any time gave excellent weed control in transplanted broccoli, a crop that rapidly develops a dense leaf canopy (Colquhoun & Bellinder, 1996). Control was poorer in crops of sweet corn *(Zea mays*) where early growth was slow, and in green bean (*Phaseolus vulgaris*) which has a long growing season. In addition to its effect on the weeds, inter-row cultivation may have a damaging effect on the crop. In spring barley, inter-row brush weeding caused more damage than did spring tines (Richards, 1991). Ascard (1993), found that in the absence of weeds inter-row cultivation in carrot (*Daucus carota*) with a horizontal axis brush hoe or a conventional hoe tended to reduce crop yield.

In experiments with a vertical axis brush hoe in carrot (*D. carota*), onion (*Allium cepa*) and sugar beet (*Beta vulgaris*), Fogelberg & Johansson (1993), did not observe any significant reduction in crop yield. The uprooting action rather than soil covering was responsible for achieving in-row weeding in carrots (Fogelberg & Dock Gustavsson, 1999). A greater force was required to up root the carrots compared with weeds at the 2-4 true leaf stage so some selectivity was possible. Brush peripheral speed and tractor driving speed had little effect on weed control and crop yield onions (Melander, 1997). However, the distance between pairs of brushes and brush working depth are important when uprooting weeds. The degree of soil covering increased with brush working depth but this could affect both the crop and weed unless the weeds were small relative to the crop.

Brush weeding in the tree rows of orchards required rotating blades to be fitted ahead of the brushes. Nevertheless, brushing controlled only half the weeds even when the soil was loosened (Kouwenhoven, 1997). In nursery trees, duckfeet hoe blades were fitted ahead of the brushes to loosen the topsoil.

Mowers, cutters and strimmers

Where weeds are much taller than the crop it may be possible to 'top' the weed and at least prevent further seeding. A machine based on a rape swather has been used as an alternative to hand roguing of wild oats in cereals (Steele, 1997). The cutter bar is set just above crop height and after cutting the weed is pushed into a collecting tray for disposal. The machine has the potential to deal with tall weeds in other crops too. Similarly, a rotary cutter has been developed to remove the flower heads of bolted weed beet growing in sugar beet crops (Anon, 2000).

Flail, rotary and reciprocating knife mowers have been used to control perennial broad-leaved weeds but the timing and frequency of cutting was critical. Cutting treatments reduced thistle (*Cirsium arvense*, *C. vulgare*) and perennial sowthistle (*Sonchus arvensis*) numbers over a three year period but were less effective on docks (*Rumex* spp.)(Aquilina, 1992; Aquilina & Clarke, 1994).

Hand held and wheeled strimmers offer the potential to cut down seedling and larger weeds pre-crop emergence overall, or post-emergence between the crop rows without disturbing the soil surface. In the US, a prototype string strimmer has been developed that can be used on four rows at a time (Cooke, 1997). Other alternative techniques based on the principals of cutting, beating and defoliating without soil disturbance have been tested on broad-leaved and grass weeds (Nawroth & Estler, 1996).

Pneumatic weed control

An implement has been developed that injects compressed air into the soil to loosen and uproot small weeds on either side of the crop row (Vale, 1998). It has been used successfully in carrot, maize and sugar beet. These machines works best in dry soils. In a German prototype, air supplied to the hoe blade leg is blasted out through holes the sides of the hoe blade (Vale, 2003). An operating depth of 15 mm and speed of 5-6 km/hr are suggested.

Thermal weed control

Stubble burning is now banned because of the smoke and other hazards, but this traditional form of thermal weed control was used to reduce the number of viable weed seeds returned to the soil after cereal harvest. Soil surface temperatures under the burning straw reached in excess of 200 ^{o}C for 10 -30 seconds and reduced the viability of freshly shed wild oat (*Avena fatua*) and blackgrass (*Alopecurus myosuroides*) seed by up to 30% and 80% respectively (Chancellor *et al.*, 1984). Current methods of thermal weed control use a variety of energy sources to generate the heat needed to kill weed seeds and seedlings.

Flame weeding

Early systems of flame weeding were relatively crude and possibly even dangerous, but the machinery has developed to a high level of sophistication and flame weeding is probably the most popular method of direct weed control after mechanical weeding. Flaming equipment has been developed in several countries including Germany, Holland, Sweden and Denmark (Hølmoy & Netland, 1994), and a range of burners is available in the UK (Caspell, 2002). The main fuel used in the burners is liquefied petroleum gas (LPG) usually propane (Ascard, 1995). Some concern has been expressed about using a finite resource like fossil fuel but renewable alternatives such as hydrogen have been evaluated (Andersen, 1997). Flame weeding can be cheaper than hand-weeding but there is a high machine cost (Ascard, 1990; Nemming, 1994). Nemming (1994), concluded that treating an area of 6-20 hectares would bring costs down to a reasonable level but treating smaller areas could also be profitable depending upon the crop. Hand-held flame weeders are available but these are generally used for weeding in amenity and industrial situations.

Flame weeding kills by an intense wave of heat that ruptures the plant cells. It is necessarily a foliar contact treatment and any long-term effect depends on whether the injured plants recover and on the extent of subsequent weed emergence. For best effect, flaming requires a level soil surface. Flame weeders can be used for total vegetation control or for selective removal of unwanted plants. Selectivity may be achieved by timing the application to kill weed seedlings before the crop emerges (pre-emergence flaming). A sheet of glass laid along a short length of crop row can give advance notice of imminent crop emergence. Once the crop has emerged angling or shielding the burners may allow selective inter-row weeding, or the dose may be adjusted to a level that the crop will tolerate (post-emergence flaming) (Morelle, 1993). Flame weeding is not suitable for crops with shallow or sensitive root systems (Mattsson *et al.,* 1990). The flaming of weed seedlings prior to crop emergence is delayed for as long as possible to ensure that the maximum number of emerging weeds are exposed to treatment. Flaming does not appear to reduce subsequent weed emergence and may even increase the germination of some species (Ascard, 1995). However, unlike mechanical methods of weed control there is no soil disturbance to stimulate a further flush of seedling emergence. In addition, flame weeders have the advantage that they can be used when the soil is too wet for mechanical weeders. The equipment may also be used to desiccate the foliage of potato and onion to aid harvesting, and in strawberries to reduce the incidence of *Botrytis cinerea* by destroying the inoculum at appropriate crop stages (Lampkin, 1990).

The response of non-target organisms to flaming has not been fully investigated, but there was no effect on the activity, density or variety of ground beetles (*Carabidae*) (Dierauer & Pfiffner, 1993). The microbial biomass in the 0-5 mm depth was reduced by 19% when soils were flamed with open flame burners using a flaming intensity of 4600 MJ ha^{-1}. Flaming had little effect on microbial biomass deeper in the soil. The soil temperature at 5 mm was raised by 4.0 °C and at 10 mm by 1.2 °C. Rahkonen *et al*. (1999) concluded that the threat that flaming poses to micro-organisms is small.

There have been many studies to determine the optimum design of flame weeders (Douzals *et al.,* 1993; Parish, 1993). Bertram (1994), has worked out the thermodynamic principles of flame weeding in a model that can be used to calculate the heat transfer rates of defined thermal weeders. This offers one way of optimising the construction and use of these implements. Holmøy & Storeheier (1993), and Storeheier (1994), also studied factors important in the design of optimal flamers. The results suggest that shielding design is critical to keep combustion gases close to the ground for as long as possible. The angle of the burners is also important, an angle to the horizontal of 22.5^{o} to 45^{o} is best. Improving the selectivity of post-emergence inter-row flaming depends in part on directing the heat towards the weeds while avoiding damage to the crop. Andersen (1997), has developed a model that describes the heat dispersion from the base of a plant in the directions outwards, upwards and along the plant row. The model can be used to select and evaluate suitable burners. Ascard (1997), studied the effect of fuel pressure and burner arrangement in field experiments with brassicas as test species. Raising the fuel pressure allowed the ground speed to be increased but using tandem instead of single burners did not.

Models have also been developed to describe the response of plants to flame weeding. Three models were evaluated to describe the dose-response relationship of flame weeding bioassays with white mustard (*Sinapis alba*) in the field (Ascard, 1992 & 1994). Plant size at treatment had a major influence on the dose required, whereas plant density was less important. Ascard (1995) found that a modified logistic model could be used to describe weed responses to flaming. The author suggests that the treatment dose could be adjusted to the weed flora present. Parish (1990a & 1990c) investigated the flame treatment of Italian ryegrass (*Lolium multiflorum*) and white mustard (*S. alba*) seedlings using a test rig under controlled conditions. In a subsequent experiment the effect on a range of grass and broad-leaf weeds was tested. In both experiments, grasses were shown to be more resistant to flaming. Rahkonen & Vanhala (1993), studied the response of a mixed stand of fat-hen (*Chenopodium album*), scentless mayweed (*Matricaria inodora*) and Timothy grass (*Phleum pratense*) to different doses of flaming. All three species were more susceptible at early growth stages. The mayweed suffered less injury by flaming than the other two species. At low doses it recovered, took advantage of the space left by the susceptible species and produced more biomass than untreated plants. Ascard (1995), compared the dose response of different weed species to flaming at various growth stages. Chickweed (*S. media*), fat-hen (*C. album*) and annual nettle (*Urtica urens*) were relatively susceptible to flaming. Shepherd's purse (*C. bursa-pastoris*) and rayless mayweed (*Chamomilla suaveolens*) were intermediate and likely to regrow after flaming. Annual meadow grass (*P. annua*) with its protected basal growing point was damaged but not killed. Regrowth was rapid and survivors were again able to take advantage of the reduced competition from the dying weeds. All the species tested were more susceptible at the earlier growth stages. Perennial grass weeds such as couch (*Elymus repens*) are likely to regrow rapidly after treatment (Ivens, 1965).

Treated plants are exposed to heat for just a brief period and only the exposed tissues may be disrupted initially. A second flaming that reaches the underlying tissues may be more effective than a single treatment. In field trials, however, split applications of two half-dose treatments one week apart did not reduce weed numbers as effectively as a single late treatment with the same total dose (Ascard, 1995). It was suggested that a second flaming at full dose ought to be made soon after regrowth in order to starve the weeds.

The wide range of production methods used in horticultural crops offers more opportunities for using flame weeding than the arable crops. Vegetables are also relatively high value crops where the cost of investing in flame weeding is justified. Flame weeding has been evaluated pre and post-emergence in onions, which have some tolerance to flaming (Ascard, 1990). In onions grown from sets, flaming treatments did not affect crop yield and reduced the labour needed for hand-weeding. In the drilled crop, flaming checked growth temporarily but did not reduce yield. Nemming (1993), used pre and post emergence flaming treatments in drilled onions and reduced weed numbers by between 38 and 90% without affecting crop yield. But, Casini *et al.,* (1993) found that onion numbers were reduced by 20% following flaming. Rifai *et al.,* (1996) noted that the onions over 5 cm tall were more resistant to flaming than the weeds, however, the treatment needed to be repeated to lessen weed density. Reducing tractor speeds during flaming improved weed control. Desvaux & Ott (1988), also found that onions were somewhat more heat resistant once they had reached the four-leaf stage. A number of workers have evaluated the effect of flame weeding in carrot (Parish, 1993; Rifai *et al.,* 1996). In France, pre-emergence flaming reduced weed numbers in carrots by up to 80% and subsequent hand-weeding was minimal (Desvaux & Ott, 1988). Flame weeding has also been tested in the umbelliferous herbs coriander, dill and parsley (Taupier-Letage *et al.,* 1993).

In lettuce, pre-plant flaming alone was insufficient for good weed control but combined with hoeing it was very effective (Balsari *et al.,* 1994). The combination of flame weeding and mechanical hoeing was also successful in white cabbage (Netland *et al.,*1994). Transplanted cabbage has a relatively high tolerance to heat, enabling band flaming to be used along the crop row. Damage can occur when treatment is applied too early but the crop usually recovers (Holmøy & Storeheier, 1993). In sweet corn, flame weeding gave short term weed control but could not maintain control of germinating weeds through the season (Rifai *et al.,* 1996). Flame weeding in transplanted peppers reduced plant numbers and increased the proportion of damaged fruits (Casini *et al.,*1993).

Preliminary trials were carried out to evaluate the effectiveness of flame weeding in a young pear orchard and an established apple orchard (Ferrero *et al.,* 1993). In the young orchard where treatments started on a clean soil after cultivation, flaming kept weed growth in check. In the established orchard there was insufficient control of perennial weeds.

Arable crops are grown on a larger scale than vegetables but are relatively low value and the cost of flame weeding may not be justified. In fodder beet, a crop that germinates relatively quickly, pre-emergence flaming reduced weed numbers by 34 to 44 % (Nemming, 1993).

Infrared radiation

A fundamentally different type of flame weeder fuelled by propane/butane uses infrared radiation (IR) to kill the weeds. The burners heat ceramic and metal surfaces that radiate the heat towards the target plants. Ascard (1998) has compared flame and infrared weeders in field experiments with white mustard (*S. alba*) as the test species. In general, flame weeders were considered to be more effective because they provide higher temperatures. But temperature is not the only consideration, burner height and plant stages were important too. The burners cover a more closely defined area than those of the standard flame weeder (Lampkin, 1990). Infrared weeders have the disadvantages of needing time to heat up, the IR panels are sensitive to mechanical damage, and they are more expensive than flame weeders.

A hand-held infrared weeder is available that can be used for killing the rosettes of perennial broad-leaved weeds in grass. A ceramic disc heated by gas from a small butane cylinder generates infrared radiation when incandescent. The 'hot spear' as it is called also has projecting metal spike which heats up and this is pressed into the centre of the plant to be destroyed and held there for a few seconds. It has yet to be determined how effective the tool is against deep rooted weeds.

Freezing

Plant tissue can be destroyed by low temperatures as well as high ones. A comparison of weed control by flaming with weed control by freezing was made by Fergedal (1993). The flaming treatments were applied with a commercial flamer used liquid petroleum gas (LPG). Two different media were used for the freezing treatments: liquid nitrogen and carbon dioxide snow (dry ice). These were applied to the emerged weeds with a simple, tractor mounted experimental set-up. The dose response curves showed that liquid nitrogen was more effective than solid carbon dioxide for killing weeds but neither was as good as flaming. Freezing would only be advantageous where there was an obvious fire risk from flaming.

Steaming

Steaming is used in glasshouses to sterilise the soil and control both weeds and diseases prior to crop establishment. There has been renewed interest in methods of steam sterilisation in the wake of concern over the use of methyl bromide (Trotter, 1991). Mobile steaming equipment is now available to control weeds and pathogens in polytunnels and in the field. Steam is applied under pressure beneath metal pans forced down onto freshly formed beds for periods of 3-8 minutes. The steam raises the soil temperature to 70-100 °C killing most weed seeds to a depth of at least 10 cm (White *et al.*, 2000a; 2000b). Only clover (*Trifolium* spp.) and other hard seeded legumes appear resistant to this treatment. Weed seeds in the soil below the treated layer are unaffected and will germinate if the soil is disturbed to that depth. However, if there is no further cultivation following treatment, weed control can remain effective for two seasons. The machinery is slow moving and work rates of 40-100 hours per ha of treated bed are likely. At present, field steam sterilisation is not allowed under the UK organic guidelines. Treating only the band of soil where the crop seed will be drilled may be seen as having a less drastic effect on the soil fauna and flora.

Low temperature soil steaming for a short duration has been investigated as a more acceptable method of pest, disease and weed control (van Loenen *et al.*, 2002). Steaming of soil samples at 50-80 °C for three minutes has been shown to kill seed of fat hen (*Chenopodium album*) and couch grass (*Elymus repens*) as well as certain crop pathogens and nematodes. The present system is intended for glasshouse disinfestation of soil.

It is also possible to use jets of steam to kill emerged weeds and machinery has been developed for use in amenity areas (Lilburne, 1997). Field studies using steam to control emerged weeds gave better than 90% control of fat-hen (*C. album*) and pigweed (*Amaranthus retroflexus*) seedlings up to the 4-6 leaf stage but not of mature plants (Kolberg & Wiles, 2002). Water at 175 °C was applied through standard spray nozzles enclosed under a steel housing to prevent rapid escape of steam. Steam was also applied in conjunction with tillage with fixed sweeps to break up the soil at the point where the steam was applied. The treatment did not reduce subsequent seedling emergence and there were indications that emergence of black nightshade (*Solanum nigrum*) was increased.

The application of hot water for weed control in orchards has been investigated in field trials in Germany (Kurfess & Kleisinger, 2000). Water at 85-95 °C applied at a working speed of 6 km/h resulted in good control of leafy weeds without affecting the apple trees. In the UK, there are ongoing trials of weeders that apply hot foam. The foam is intended to remain on the weeds allowing the heat to have a longer effect.

Direct heat

Equipment is available commercially for killing weed seeds in field soil using dry heat (Williams, 1999a: 1999b). The soil is cultivated and set in ridges. The worked ridge of soil is lifted, passed through a chamber heated to 68-70 °C by a diesel-fired burner, and then deposited back onto the ground in a reformed ridge that provides a band of weed free soil. The depth of treatment required depends on the crop. It ranges from 10 cm for shallow rooted crops to 25 cm for potatoes. The dry heat system is slow but allows faster coverage of an area than field steaming. The work rate with a 15 cm depth of soil is 1-2 ha per day, depending on the soil type.

Electrocution

The energy aspects of controlling weeds by electrocution were reviewed by Vigneault *et al.*, (1990). The concept of using electrical energy to control weeds was developed in the late 19th century but more recently tractor mounted machinery has been developed in the US for controlling tall weeds that project above the crops. In Canada, an adaptation of the system to deal with small weeds between crop rows and close to the soil surface failed to operate successfully when seedlings were at a high density. Vigneault *et al.*, (1990), outlined the theoretical concepts behind weed electrocution and concluded that it would not be suitable for primary weed control where weed populations of 200 seedlings m^{-2} were the norm. The method has the advantage of not disturbing the soil, but even with a population of 15 weeds m^{-2} a lot of energy is required to kill the weeds.

In the UK, Diprose *et al.*, (1978b), studied the effect of an electric current on a range of crop and weed plants. In the field, selective electrothermal control of weed beet and bolting sugar beet was examined (Diprose *et al.*, 1980), and compared with herbicide wipers and mechanical cutting (Diprose *et al.*, 1985). All the methods reduced seed return but cutting killed none of the bolting beet, the chemical applicator killed 61% of the bolters and the electrothermal machine killed 38-41%. Good contact between the weeds and the electrode was essential for success in field crops but the method required a great deal of power. It is likely that the safety aspects of using high voltage electricity would necessitate operation of the machinery by a specialist contractor. Development work in the UK has been curtailed.

Microwave radiation

Microwave radiation utilises ultra high frequency (UHF) electromagnetic energy with wavelengths much greater than those of light. One of the frequencies allocated to microwave devices for industrial and domestic use is 2450 Mhz, which corresponds to a wavelength of

12.25 cm. Most weed control studies with microwaves have used this frequency (Diprose *et al.*, 1984).

Many factors determine the reaction of seeds to microwaves, and species may vary in tolerance. In the UK, Diprose *et al.,* (1978a), demonstrated the possibility of selectively controlling wild oat seed (*A. fatua*) mixed in with cereal grains by irradiation with 1 Kw 2450 Mhz energy. Germination of the wild oat was reduced while wheat and oat were almost unaffected. Moist seeds were more susceptible than dry seeds, hence seeds in wet soils were more easily killed than in dry (Rice & Putnam, 1977). The damage to seeds is likely to be thermal but this is not certain (Davis *et al.*, 1973). The effects of microwaves have been observed on seeds in soil in the US. Wayland *et al.,* (1975), using microwave generators drawn over field plots obtained reliable kill of seeds at energy levels above 70 J cm^{-2}. There was no consistent selectivity between broad-leaved and grass weeds. Menges & Wayland (1974), applied UHF energies of 45 to 730 J cm-^{2}, 2450 Mhz, to irrigated and non-irrigated soils before planting cantaloupe melon and onion. The treatments killed several weed species without any effect on the crop. Microwave heating of soil has also been evaluated as an alternative to chemical sterilisation (Barker & Craker, 1991). The time required to reach seed killing temperatures in soil was a limiting factor in the application of this technique.

Growing plants can also be killed by microwaves (Davis *et al.*, 1971). Wayland *et al.,* (1975), using microwave generators drawn over plots of emerged weeds found that broad-leaved weeds were more susceptible than the single grass species tested. Established plants were more susceptible than seedlings of the same species. While it has been demonstrated by many workers that microwaves kill weeds, the method is very slow and expensive. The amount of energy required determines the speed, and treatment times of between 92.6 and 1037 hours per ha have been quoted. There are also the safety implications for operators and passers-by of exposure to microwaves (Diprose *et al.*, 1984).

Electrostatic fields

Static electricity is generated naturally when severe weather conditions upset the natural electrical balance of the atmosphere. An electrostatic field can also be generated in the air gap between electrodes connected to a voltage source. Both beneficial and lethal effects have been observed in plants subjected to natural and artificial electric fields. However, weed control systems are unlikely to be developed because of the dangers involved in using high voltage electricity outside the laboratory (Diprose *et al.*, 1984).

Irradiation

Radioactivity has been employed to sterilise soil but at high doses the soil fauna and micro-organisms are also damaged. The dose of γ-irradiation needed to kill weed seeds in soil was determined by Suss & Bacthaler (1968), with the aim of using it to obtain weed-free soil. Seeds of wild oat (*A. fatua*), blackgrass (*Alopecurus myosuroides*), charlock (*Sinapis arvensis*) and silky bent (*Apera spica venti*) were irradiated and then tested for viability and germination. In these preliminary tests, wild oat was the most sensitive species and charlock the least. Because of technical difficulties, and possible mutagenic effects, weed control methods based on γ-radiation are unlikely to be developed (Sandwald & Koch, 1978). In addition, irradiation of food is not allowed under the standards for organic food and farming in the UK.

Lasers

Light in the form of lasers has been shown to inhibit the growth of water hyacinth (*Eichornia crassipes*) in the US (Couch & Gangstad, 1974). The treatment did not generally kill the weed but treated plants were smaller, propagated fewer daughter plants and covered less water surface than the untreated. More recently, the possibility of using a CO_2 laser as a device for cutting down weeds has been demonstrated (Heisel *et al.*, 2001; Heisel *et al.*, 2002).

Ultraviolet light

The use of ultraviolet light for weed control has been patented but remains at an experimental stage (Andreasen *et al.*, 1999).

Solarization

Solarization is a method of heating moist soil by covering it for around 6 weeks with plastic sheeting to trap solar radiation. (Horowitz *et al.*, 1983). Unlike steam sterilisation, solarization does not sterilise the soil and create a biological vacuum, but there is some control of soil pathogens (Bell *et al.*, 1988). For solarization to be effective it requires a climate with long periods of clear skies and sunshine to heat up the soil under the sheeting and maintain a sufficiently high temperature (> 65 ^{o}C) for long enough to kill the weed seeds (Standifer *et al.*, 1984). Countries that have high ambient temperatures but hazy skies may be unable to take advantage of solarization. In the cooler climate that prevails in the UK, studies of vegetable cropping under polyethylene sheeting indicate that weed development may be enhanced rather than impeded by the covers (Bond & Burch, 1989); but covers laid in midsummer could prove to have some weed control benefits. Even under ideal conditions the effective depth of control may be limited and seeds further down the soil profile are unlikely to be killed (Horowitz *et al.*, 1983). However, if there is no soil disturbance following treatment, weed control may remain effective for two seasons (Sauerborn *et al.*, 1989).

Not all weed species are susceptible to high soil temperatures (Egley, 1990). Hard seeded annual weeds and perennials with buried vegetative organs are not easily controlled by solarization (Bell *et al.*, 1988; Horowitz *et al.*, 1983; Rubin & Benjamin, 1984). Elmore *et al.*, (1993), found that perennial grass weeds were killed by solarization but field bindweed (*Convolvulus arvensis*) regrew after treatment.

Research on this form of weed control has been confined mainly to countries having suitable climates for solarization to work reliably (Abu-Irmaileh, 1991; Al-Masoom *et al.*, 1993; Bell *et al.*, 1988; Horowitz *et al.*, 1983; Sauerborn *et al.*, 1989). Even here, studies have often been restricted to horticultural crops like lettuce and garlic (Al-Masoom *et al.*, 1993), squash and tomato (Abu-Irmaileh, 1991), and others where the relatively high costs of using plastic covers can be justified (Bell *et al.*, 1988). In northern Syria, which has a Mediterranean climate, 46 out of 57 weed species tested were reduced in number after 50 days solarization. Only nine species were controlled completely but charlock (*S. arvensis*) was controlled after only 20 days treatment (Linke, 1994). The control of perennial and biennial species with vegetative organs in the soil, was much less effective, and the emergence of *Muscaria racemosum* noticeably increased following solarization.

There have been few investigations of solarization in Europe. In Portugal, Silveira *et al.*, (1993), evaluated its the potential for weed control in lettuce, carrot and onion. In France, Arufat (1993), found solarizing soil for 45 days reduced weed growth by 80%. In Italy, Garibaldi (1987) evaluated the control of soil borne diseases by solarization, and found that soil temperatures under plastic in the open were insufficient to control even disease incidence.

Soil temperatures under covers depend on the thermal characteristics of the material as well as the level of incoming radiation. Transparent plastic is more efficient than black in heating soil using solar radiation. Types of transparent plastics differ in their transmittance characteristics and the resulting soil heating ability (Horowitz *et al.*, 1983; Majek & Neary, 1991). Adjusting the light transmitting quality of the sheeting could provide greater retention or conversion of the light radiation as heat, and warm the soil sufficiently to kill weed seeds at relatively low levels of light. Such covers could provide a better chance of weed control from solarization in the UK and other countries than ordinary plastic films.

There are some disadvantages to using solarization for weed control. There is a loss of crop production for 6-8 weeks in summer. The purchase and laying of the sheeting is relatively expensive which limits its use to high value crops. After use, plastic sheeting requires lifting and disposal. Machinery has been developed for both laying and lifting different forms of sheeting in the field. It is possible to reuse or recycle plastic film but contamination with soil causes problems with the recycling of sheeting that has been laid in the field.

In addition to soil solarization, one novel way to use sunlight for direct weed control has been reported. It involves using a curved freshnel lens to concentrate sunlight into a narrow band at the soil surface, which can reach 290 °C in a few seconds (Forcella & Burnside, 1994; Hoekstra, 1992). The wheeled device is pulled slowly along between crop rows to wither and burn off the inter-row weeds.

Mulching

Covering or mulching the soil surface can reduce weed problems by preventing weed seed germination or by suppressing the growth of emerging seedlings. Mulches are generally ineffective against established perennial weeds. A mulch may take many forms: a living plant ground cover, loose particles of organic or inorganic matter spread over soil, and sheets of artificial or natural materials laid on the soil surface. Spray-on mulches have been developed that form a thin latex-based film on the soil surface (Stout, 1985). Others for hydro seeding motorway embankments consist of fibres that protect the grass seed during germination and form a carrier for water and nutrients. Once sprayed, the fibres mesh together around the seeds, forming a water holding layer on the soil that resists wind, rain and erosion (Anon, 2003). Residues from preceding crops may be used to form a mulch but this is discussed in more detail in the use of cover crops to suppress weeds. With mulches consisting of organic materials, crop stand and vigour, particularly of direct-seeded small-seeded crops, may be reduced by chemicals released from the decomposing residues (Ozores-Hampton, 1998; Wallace & Bellinder, 1992).

It is more practical to use mulches in well-spaced crops, particularly transplants. Plastic sheeting and straw mulches have long been used in soft fruit such as strawberries (Lieten, 1991). In perennial crops and some other situations mulches may be intended to remain effective for many years (Wofford & Orzolek, 1993). In strawberries, Mypex, a black, woven, polypropylene mulch, is expected to last for up to three crops (9-10 years) (Tolhurst, 1994). These mulches may be expensive but labour costs are reduced in the long term (Feldman *et al*.,2000).

Mulches may be used as an alternative to cultivation to clear vegetation before cropping. Lennartsson, (1990), showed that a range of light excluding materials left in place for 12 to 18 months could be used to clear an established grass pasture prior to planting onions. However, there are practical problems with covering large areas for long periods. In freshly prepared seedbeds, short term mulching can be used to manipulate or reduce weed seedling emergence. Black polyethylene is generally left down for the duration of a crop but studies have been made where the sheeting has been laid on the seedbed for much shorter periods (Davies *et al.*, 1993; Davies, 1995) and then lifted before planting brassicas. The short term covering of the soil with black polyethylene reduces subsequent weed emergence (Grundy *et al.*, 1996) giving the crop an advantage over the weeds.

The high cost of mulching makes it economic only for high value horticultural crops (Runham & Town, 1995) unless there is another reason for its use. In addition to weed control, mulches may be used: to prevent soil erosion (Russo *et al.*, 1997), reduce pest problems (Costello & Altieri, 1994; Bottenberg *et al.*, 1997), to aid moisture retention (Wofford & Orzolek, 1993), and to prevent nitrate loss (Benoit & Ceustermans, 1992/3).

Living mulches

A living mulch consists of a dense stand of low growing species established prior to or after the crop. The undersowing of cereals with clover and grass could be seen as forming a living mulch. It has been argued that annual weeds would provide a natural ground cover if managed properly (Anaya *et al.*, 1988). Váradi *et al.*, (1989), suggested using crabgrass (*Digitaria digitalis*) as ground cover in vineyards because it inhibited the growth of other weeds. A living mulch of *Portulaca oleracea* L. (common purslane) from seed broadcast before transplanting broccoli (*Brassica oleracea* L. var. *botrytis* L.) suppressed weeds without affecting crop yield (Ellis *et al.*, 2000). Living mulches are sometimes referred to as cover crops, but they grow at least part of the time simultaneously with the crop. Cover crops are generally killed off prior to crop establishment.

Often, the primary purpose of a living mulch is that of improving soil structure, aiding nutrition or avoiding pest attack (Costello & Altieri, 1994), and weed suppression may be just an added benefit. In cereals, an understorey of clover has been shown to improve soil fertility, and reduce pest and disease problems in addition to suppressing weeds (George *et al.*, 1997; Clements *et al.*, 1997). The clover can be left to recover after cereal harvest and is then cut or grazed before direct drilling of another cereal crop (Clements, 1995). Maintaining vegetation cover is important for preventing soil erosion, nitrate leaching and weed emergence in slowly developing crops like maize. Werner (1988), investigated the influence of different mulch species on weed density and diversity. Weed numbers were reduced and maize yield was not affected where growth of the mulch was reduced by cutting or flaming treatments. When the growth of a living mulch is not restricted, or when soil moisture is inadequate, even a relatively vigorous crop like potato may suffer competition and loss of yield (Rajalahti & Bellinder, 1996).

Studies have been made of the use of living mulches to suppress weed emergence in horticultural crops but there are many different factors to take into account (Müller-Schärer & Potts, 1991). In the US, Bottenberg *et al.,* (1997), investigating the impact of rye (*Secale cereale*) residue and seeded red clover (*Trifolium pratense*) as a weed suppressing mulch in transplanted cabbage found that supplemental weed control was needed. Yield loss in transplanted cabbage due to competition with the living mulch for light or moisture was recorded by Bottenberg *et al.,* (1997). Timely mowing of a clover (*Trifolium spp*.) living mulch prevented such competition in transplanted broccoli (Costello & Altieri, 1994). Ilnicki & Enache (1992), also found that mowing of a subterranean clover (*Trifolium subterraneum*) mulch was necessary to reduce early competition when sweet corn, tomato and cabbage crops were planted into it. Competition was not a problem when dwarf beans were planted into a clover mulch as it began senescing. Subterranean clover is self-seeding, an advantage when its use as a living mulch is ongoing, but a disadvantage in other situations.

Living mulches are well suited to use in perennial crops such as fruit where self-reseeding is an advantage (Ingels *et al.,* 1994). However, even in established apple and apricot orchards a living mulch growing along the planted row may depress crop growth (Domange, 1993). In the UK, Marks (1993), found that a grass sward within the tree row restricted crop growth and severely reduced the marketable yield of apples. Reduced growth of the crop may be due to competition for water or some other limited resource, or the mulch may be having an allelopathic effect. It is important to make the correct choice of living mulch (Ingels *et al.,* 1994). In raspberries, a white clover (*Trifolium repens*) living mulch did not affect the crop but perennial ryegrass (*Lolium perenne*) reduced berry yield (Freyman, 1989). Newenhouse & Dana (1989), evaluated different grass living mulches for strawberries, and found perennial ryegrass was best because it covered the ground quickly but did not spread into the crop rows.

Particle mulches

Loose materials like straw, bark and composted municipal green waste provide effective weed control but the depth of mulch needed to suppress weed emergence is likely to make transport costs prohibitive unless the material is produced on the farm (Merwin *et al.,* 1995). Ligneau & Watt (1995), showed that a 3 cm layer of compost was needed to prevent the emergence of annual weeds. Weed control usually improves as the thickness of the organic mulch increases (Ozores-Hampton, 1998). Weed seeds in the mulch itself can be a problem if the composting process has not been fully effective or there is contamination by wind blown seeds. In straw mulches, volunteer cereal seedlings are a particular problem due to shed cereal grains and even whole ears remaining in the straw after crop harvest. There may be a risk of crop damage from herbicide or growth regulator residues remaining on straw from conventionally-grown cereals. With particle mulches like straw that consist of light materials there is the possibility of them being blown around by the wind.

In rhubarb (*Rheum rhabarbarum*), a straw mulch 15 cm thick controlled weeds better and was more cost effective than herbicide or hand-weeding treatments (Creager, 1989). The straw-mulched plots produced larger plants and higher yields in field trials over 6 years. In the US, Munn (1992), found shredded newspaper at 2-3.4 tons/acre to be equally effective, if not superior to wheat straw in suppressing most annual and some perennial weeds in sweet corn (*Zea mays*), soybean (*Glycine max*) and tomato (*Lycopersicon esculentum*). A grass and alfalfa straw mulch applied shortly before planting maize (*Zea mays*), reduced weed germination and emergence (Yih, 1989). Initially the mulch suppressed crop growth too but this was only temporary. A cut ryegrass mulch spread between planted rows of tomatoes and peppers, was more expensive than herbicide or cultivation treatments but the higher financial returns from the mulched crops made it the most profitable system (Edwards *et al.,* 1995). A mulch of chipped green kenaf (*Hibiscus cannabinus*) compared favourably with black polyethylene for weed control, but reduced the yield of transplanted cabbage (Russo *et al.,* 1997). The yield of transplanted onion was not affected and it was suggested that kenaf may have an allelopathic effect on cabbage.

Weibel & Niggli (1990), showed that fresh bark of conifers and of oak, as well as rape straw, gave good control of weeds when laid as mulches under the trees in apple orchards. Composted bark, leaf compost and rotted apple husks were less effective. In the UK, Marks (1993), found that a straw and a bark mulch applied along the tree row controlled weeds effectively in the first year of use. However, there was a slight increase in weed numbers in year two. Also in the second year, there was a reduction in soil mineral nitrogen (SMN) concentrations under both mulches associated with decomposition of the organic matter. Soil structure is likely to benefit from the use of organic mulches (Feldman *et al.,* 2000).

Sheeted mulches

Black polyethylene mulches are widely used for weed control in organic and conventional systems in the UK and elsewhere. Clear mulches are better than black for warming the soil but do not control the weeds. Plastic mulches have been developed that selectively filter out the photosynthetically active radiation (PAR) but let through infra red light to warm the soil. Infra red transmitting (IRT) mulches have been shown to be effective in controlling weeds (Majek & Neary, 1991). Various colours of woven and solid film plastics have been tested in the field (Horowitz, 1993). White and green coverings had little effect on the weeds, brown, black, blue, and white on black (double colour) films prevented weeds emerging. There are indications that mulching films, like white on black, with a higher rate of light reflectance are beneficial to the crop (Benoit & Ceustermans, 1992/3). Light reflectance may also affect the behaviour of certain insects (Lamont, 1993), and plastic mulches in a greater array of colours are likely to become available.

In the US, Ricotta & Masiunas (1991), compared a number of chemical and non-chemical weed control strategies including black polyethylene mulch in transplanted herbs. Mulching increased the yield of basil (*Ocimum basilicum*) and rosemary (*Rosmarinus officinalis*) but not parsley (*Petroselinum crispum*) compared with some other treatments. In the UK, black polyethylene mulch gave good weed control and increased the yield of transplanted sprouts and calabrese over treatments without mulch (Cox, 1991a).

In apples in the UK, black polypropylene woven mulch (Mypex) laid along the crop row gave almost complete weed control and higher crop yield than other mulching and chemical treatments (Marks, 1993). In the US, the increased crop value from mulched apple orchards justified the greater costs of mulching with various films and fabrics (Merwin *et al.,* 1995).

However, there were problems in laying the mulches, due to the wind lifting and tearing the sheeting.

After cropping, lifting and disposal may be a problem with plastic and other durable mulches. Sheeting made from paper, non-woven natural fibres and degradable plastics have the advantage of breaking down naturally, and can be incorporated into the soil after use (Runham & Town, 1995). Paper mulches have compared favourably with black polyethylene in trials with transplanted lettuce, Chinese cabbage and calabrese in the UK (Runham, 1997; Runham & Town, 1995). Tearing and wind blowing can be a problem but correct laying of the paper and rapid crop establishment are the key to success (Runham, 1998). There can be additional environmental benefits if the paper mulch is made from recycled materials such as cardboard cartons (Cooke, 1996). In Holland, brown and black paper mulches have been tested with salad and flower crops. Both gave good weed control but stretching and contracting following wetting and drying caused the brown paper mulch to tear. The black mulch was creped to allow for this and did not tear (Wilson, 1990a).

Biological weed control

Biological control would appear to be the perfect solution for pest, disease and weed control in organic and conventional agriculture (Cooke, 1988). In its widest sense it has been taken to include such basic practices as crop rotation but the term biological control is now usually restricted to the deliberate application of some natural control agent. There is considerable potential for encouraging the use of native biocontrol agents against weeds (Liebman & Davis, 2000). However, the application of biological weed control in agricultural systems in Europe has proved difficult (Müller-Schärer *et al.*, 2000).

Wapshere *et al.,* (1989), reviewed the different approaches to the control of weeds by biological methods and the steps normally followed when introducing a biocontrol agent. Classical (or inoculative) control describes the introduction of host-specific, exotic natural enemies to control alien weeds. Inundative (or augmentative) control involves the mass production and release of native (usually) natural enemies against native (usually) weeds. Conservative control is an indirect method whereby the natural level of the pests that attack the native insects that feed on the particular native weeds are reduced and maintained at a low level. This is a long term strategy that requires a detailed knowledge of the ecology of the target weeds. Broad spectrum control (or total vegetation control) as the name implies, does not always involve a single weed and often refers to modification of a whole habitat.

It is essential that biocontrol agents are thoroughly tested for host specificity so that they do not pose a threat to other plant species. An example of the systems needed for the importation, testing and release of biological control agents is outlined by Shepherd (1993). The potential harmful effects of introducing non-indigenous species for biological control purposes are reviewed by Simberloff & Stiling (1996). The protected crop situation is ideal for introduced biocontrol agents, which remain contained because they will not survive outdoors in the UK. It is more difficult to control the likely spread of agents that are intended to be released into the open.

The prediction of how biological control may affect the interaction between species, and influence the life cycle of non-target species is extremely complicated. The example that is often quoted is the decline of the large blue butterfly (*Maculina arion*) following the attempt to control rabbits by introducing the *Myxoma* virus into the UK. Reduction of the rabbit population, lessened the grazing of natural grassland, and colonies of the ant (*Myrmica sabuleti*) that 'nursed' the caterpillars of the butterfly did not thrive in the altered habitat. There is the additional concern that the control agents may continue to evolve, and that changes in host specificity could occur by natural selection or mutation. The assessment of the extent of the potential risks involved in biological control remains a contentious issue (Simberloff & Stiling, 1996). Even if there were no risk to non-target species, there could still be a conflict of interests because some may perceive a particular plant as a weed while others see it as a desirable wild flower, or even a potential crop.

Classical biological control

Classical biological control with insects and with micro-organisms (Evans & Ellison, 1990) has been successfully applied in South Africa (Morris, 1991), Australia (McLaren, 1993), the US and elsewhere. It continues to be an important area of study, particularly in non-European countries. In 1992, classical biological weed control was evaluated by 56 countries in over 700 trials involving 144 weed species and using 370 control agents (Igrc & Maceljski, 1993); but only one trial was listed for the UK in that year.

Many of the annual weed species in the UK have been introduced at some time in the past and could be considered candidates for classical biological control. However, since their arrival most have become an established part of the flora and as such their wholesale destruction by exotic pests or diseases would not be welcomed. It has been suggested that some of the introduced, invasive perennial weeds such as giant hogweed (*Heracleum mantegazzium*), Himalayan balsam (*Impatiens glandulifera*) and the Japanese knotweeds (*Reynoutria* spp.). would be ideal candidates for classical biological control (Child *et al*., 1993; Evans & Ellison, 1990; Fowler *et al.,* 1991). However, the giant Japanese knotweed (*Reynoutria sachalinensis*) has been shown to be a source of a natural fungicide (Maché, 1991/92), and it is possible that the other weeds may have some, as yet undiscovered, desirable feature. If so, an introduced biocontrol agent could itself need to be controlled in the future. It would be like introducing Colorado beetle (*Leptinotarsa decemlineata*) to control volunteer potatoes and then discovering that potatoes were good to eat!

In the UK, the only candidate for classical biological control has been the perennial weed bracken (*Pteridium aquilinum*) (Fowler *et al.*, 1989 & 1991). Attempts to use the caterpillars of two species of South African moth as potential biocontrol agents have not however been successful. The introduction of a classical biocontrol agent may not be deliberate. The rust *Puccinia lagenophorae* is of Australian origin where it attacks a range of *Senecio* spp. It was unknown in Europe before 1960 but since then it has been recorded in France and the UK on groundsel (*Senecio vulgaris*) (Evans & Ellison, 1990). The rust does not kill the weed but makes it less competitive. Higher yields have been recorded in lettuce experiments with rusted groundsel compared with rust-free plants (Paul & Ayres, 1986).

Examples of biological control by endemic phytophagus insects occur but in other situations the insects may be pests of desirable plants. Gliessman (1984) reported that in the US, flea beetles had attacked wild radish (*Raphanus raphanistrum*) and wild mustard (*Brassica campestris*) in preference to collards. In the UK, flea beetles have also been seen to reduce the number of wild radish seedlings (*Raphanus raphanistrum*) that emerged in a crop of drilled onions (Personal experience). However, it is unlikely that growers would want to encourage an increase in flea beetle numbers.

Inundative biological control

The inundative method of biological control involves the culture and release of large numbers of a biocontrol agent into the region or field where the target weed needs to be controlled. It has the advantage that native organisms can be used but there is the same requirement for host specificity (Weidemann & Tebeest, 1990). Some agents, particularly plant pathogens (mycoherbicides), can be applied as sprays in the same way as conventional herbicides.

The history of development and the future prospects of bioherbicides are reviewed by Wall (1995). The mycoherbicides in particular offered much promise but there have been many technical difficulties to overcome in the culture, storage and application of a biological material. In the UK the potential for bracken control with mycoherbicidal formulations has been investigated by Munyaradzi *et al.*, (1990). Their results indicate that to improve inoculum retention and ensure effective disease development an adjuvant was needed. Bioherbicides have the dual hurdles of the regulations that apply to biological control agents as well as those that apply to a conventional pesticide. Success also depends on collaboration between individuals from several disciplines, and between the public and private sectors (Templeton, 1988). Commercial products have been developed based on mycoherbicides but success has been limited (Bannon, 1988; Greaves & Maqueen, 1990). The attitude of plant protection companies to bioherbicides is discussed by Wilson (1990b). Even if production problems are solved, to be successful, bioherbicides need to match chemicals in efficacy and ease of application if they are to be commercially viable; market size is also an important factor.

The specificity of a bioherbicide is increased where the susceptibility of the target organism can be enhanced. This may allow a selected area of a weed to be controlled without affecting nearby plants of the same species. Isolates of *Xanthomonas campestris* pv. *poae*, have some activity against annual meadow grass (*P. annua*), a lawn weed (Imaizumi *et al.*, 1997). The inoculum is taken up more readily through cut surfaces so mowing makes the weed more susceptible than *P. annua* plants outside the mown area that are undamaged. There can also be synergetic effects between two pathogens. In groundsel (*Senecio vulgaris*), plants naturally infected with the rust *Puccinia lagenophorae*, were killed by inoculation with the pathogen *Botrytis cinerea*, while healthy plants were not (Hallett *et al.*, 1990). It has been suggested that improvements could be made in the activity and host specificity of mycoherbicides through techniques of genetic manipulation (Bailey, 1990; Sands *et al.*, 1990). Such an approach is unlikely to be approved of by organic farmers.

A further development of the concept of bioherbicides is the isolation and application of just the toxin responsible for killing the weeds as a 'natural herbicide' rather than applying the living organism (Hatzios, 1987). The chemical would be easier to store, formulate and apply than a mycoherbicide, and without the risk of proliferation in the environment; production and development costs may still be prohibitive (Froud-Williams, 1991). The isolated phytotoxins may exhibit similar host and non-host specificity to the pathogen. AAL-toxin, a natural metabolite of the pathogen *Alternaria alternata* f. sp. *lycopersici* has been tested on a range of

crop and weed species, and has been patented as a herbicide (Abbas *et al.*, 1995).
There is increasing interest in studying the mechanisms and sites of action of natural phytotoxins to aid the search for new herbicides (Duke *et al.*, 1997). The acceptability of ‘natural’ herbicides to the organic standards authorities is unclear (Stopes & Millington, 1991).

Although much of the work on biocontrol agents has concentrated on the growing weed plant, there is considerable potential for using micro-organisms to manipulate or deplete the soil weed seedbank (Kremer, 1993). The persistence of weed seeds in the soil is the key to their success in continuing to emerge despite repeated control measures over many years. Greater predation or an increase in natural decay would reduce the soil seedbank and hence future weed populations.

Conservative biological control

Conservative biological control requires a detailed ecological knowledge of the weeds and control agents involved. It has received little attention and remains largely a theoretical concept based on a reduction in the native parasites, predators and diseases that attack the native biocontrol agents of the target weed (Wapshere *et al.*, 1989).

Broad spectrum biological control

The oldest example of broad-spectrum biological control is the use of grazing animals and birds (cattle, sheep, horses, goats, ducks, geese etc.) to maintain pasture. In aquatic situations, the use of grass carp (*Ctenopharyngodon idella*) and other phytophagous fish has been investigated. In Australia, goats have been used to control blackberry (*Rubus fruticosus* agg.) (Dellow *et al.*, 1988). In cereals, sheep grazing in spring is a traditional practice of many organic growers to aid weed control. In the UK, the effect of weeding and sheep grazing on grain yield and quality of organic wheat has been investigated by Cosser *et al.*, (1997a). Weeding increased grain yield but grazing reduced ear number. In Malaysia, weed control by sheep in permanent tree crops reduced weeding costs by up to 26% and provided additional profit from the sale of mutton (Stöber, 1993). It is known that different breeds of livestock vary in their grazing or browsing preferences and abilities and should may be taken into account for improved weed control (Soil Association, 2002).

Allelopathy

Within the broadening perceptions of biological control, allelopathy can be legitimately regarded as a component of biological control (Lovett, 1991). Allelopathy refers to the direct or indirect chemical effects of one plant on the germination, growth, or development of neighbouring plants. The effect is exerted through the release of allelochemicals by the growing plant or its residues. Micro-organisms may also play a role in the production of these chemical inhibitors. Allelopathy has been considered a defence mechanism in plants (Lovett, 1982). It makes a significant contribution to the process of plant succession (Numata, 1982). The broad ecological role of allelopathy is discussed at length by Rice (1984). Widdowson

(1987) considers the allelopathic interactions that are important in progressing towards holistic agriculture.

Allelochemicals may be present in the mucilage around a germinating seed (Kosemura *et al.*, 1993), in leachates from the aerial parts of plants (Tukey, 1966), in exudates from plant roots (Weston *et al.*, 1997), in volatile emissions from the growing plant (Charron *et al.*, 1995), and among decomposing plant residues (Bewick *et al.*, 1994). There has been much study of the biochemical aspects of allelopathy and investigation of the effect of plant extracts and leachates on seed germination and seedling growth in the laboratory (Waller, 1989). In the field, the evidence for allelopathy has largely come from studies of the use of organic mulches and cover crops to suppress weed emergence (Putnam *et al.*, 1983; Putnam & Defrank, 1983).

The effectiveness of living mulches, intercrops or smother crops may in part depend on their allelopathic ability. The decomposition products of organic mulches and cover crops residues may continue to prove toxic to weeds in subsequent crops. Unfortunately, such phytotoxins are also know to reduce the germination and development of drilled small seeded crops. Even the growth of transplanted crops may be checked (Russo *et al.*, 1997). Newman (1982), and Saxena *et al.*, (1996) have reviewed the relevance of allelopathy to agriculture where the toxicity of plant residues is particularly important because of the adverse effects it can have in rotational crops. While allelopathic crops or their residues inhibit the growth of certain weeds (Steinsiek *et al.*, 1982), weeds such as fat-hen (*Chenopodium album*) that have allelopathic ability, may also influence the growth of some crops (Goel *et al.*, 1994; Qasem & Hill, 1989). Weeds can also inhibit the growth of other weeds (Anaya *et al.*, 1988).

The potential use of allelopathy for weed management has been reviewed by Altieri & Doll (1978), Numata (1982), Putman (1985), and Putnam *et al.*, (1983). Allelopathy could be used to manipulate the crop-weed balance by increasing the toxicity of the crop plants to the weeds. Where a crop has only a limited allelopathic effect it may still be sufficient to reduce the emergence of difficult to control weeds in the crop row, leaving only the inter-row weeds to be controlled mechanically. Studies have been made to evaluate the allelopathic ability of different cultivars in a limited range of crops e.g. peppers (Gonzalez *et al.*, 1993), oats (Fay & Duke, 1977), and cucumber (Putnam & Duke, 1974). The use of techniques that might allow genetic transfer of allelopathic ability into crop plants (Putnam, 1985), is unlikely to be an acceptable to organic practice. Other studies have evaluated crop cultivars for their tolerance to the allelochemicals produced by weeds (Ray & Hastings, 1992). Another approach has been to determine the crops that contain those chemicals or their precursors with the potential to suppress weeds. The glucosinolates for example, precursors of several toxic metabolites including isothiocynates, are found principally among members of the Cruciferae (Duncan & Milne, 1989). Grossman (1993), discusses the potential use of brassicas as alternatives to herbicides and soil fumigants for weed, pathogen and nematode control. There have been suggestions that the allelochemicals themselves (Chung & Miller, 1995), or synthetic derivatives (Macias *et al.*, 1997) could form the basis of ‘natural’ herbicides (Newman, 1982; Duke *et al.*, 2000). Corn gluten meal is said to provide natural pre-emergence weed control. It has been shown to reduce germination and root growth in a range of weed species (Gough & Carlstrom, 1999; McDade & Christians, 2000).

Biodynamics

Although not strictly part of biological control, biodynamics and related methods are included here because they rely on the use of natural materials for their effect. The control of perennial weeds by treating them with the potenced ashes of those particular weed or their seeds is one area of particular interest to organic farmers. There is little scientific information on how these so called weed peppers work. The principle is similar to the use of homeopathic medicines. Scherrer (2000) has begun testing the impact of weed peppers on *Solidago alissima* and S. *gigantea* but the treatments are expected to take several years of repeated applications to show an effect. Biodynamically prepared compost applied to field crops reduced weed numbers but no more than non-biodynamic compost (Carpenter-Boggs, 2000).

Integrated weed control

The concept of integrated weed control can mean many different things to different people (Cussans, 1995). In its simplest form, integrated weed control is used to describe the use of two or more direct weeding methods in combination or sequence to improve the standard of control of one or a range of weed species. Often this is taken to mean a mixture of chemical and non-chemical methods but it can be applied equally well to combinations of physical and biological methods. In addition to improved weed control there may be economic and environmental benefits from such integration.

While mechanical cultivation or intercropping alone did not give adequate weed control in transplanted broccoli, a strategy of combining cultivations and intercropping was effective in controlling the weeds without adversely affecting crop yields (Tessier & Leroux, 1993). In transplanted cabbage, Bellinder *et al.*, (1996) used a sequence of tine cultivations followed by interseeding with ground covering crops to suppress weeds. The cover crop remains after cabbage harvest to meet the requirements of the law in the US to provide a minimum of 30% ground cover year round on soils liable to erosion.

In lettuce, pre-planting flaming alone was insufficient for good weed control but combined with hoeing it was very effective (Balsari *et al.*, 1994). The combination of flame weeding along the crop row and inter-row mechanical hoeing was also successful in transplanted white cabbage, which has a relatively high tolerance to heat (Netland *et al.*, 1994). Pre-emergence flaming and harrowing followed by post emergence inter-row hoeing gave the best weed control in drilled leeks and onions (Melander & Rasmussen, 2001). To reduce the high cost of overall thermal applications, Casini *et al.*, (1993) developed a prototype machine that combined on-row flaming with inter-row hoeing in a single operation. The method decreased weed numbers significantly in both vegetable and arable crops but yields were often reduced due to thermal damage to the crop plants.

The term integrated weed management (IWM) can also be applied to the more holistic approach to weed control as part of an integrated pest management system (IPMS) within an integrated farming system (IFS) (Shaw, 1982). The aim of IWM is to reduce the need for control and this may involve both direct and indirect methods for dealing with weeds, and all stages of crop production (Regehr, 1993). Manipulation of the crop-weed relationship to favour the crop at the expense of the weeds is the basis of integrated weed management (Walker & Buchanan, 1982). In Canada, research in IWM takes into consideration all aspects of the cropping system (Swanton & Weise, 1991). It encompasses knowledge of the critical period of weed interference, alternative methods of weed control, enhancement of crop competitiveness, modelling of crop-weed interference, influence of tillage systems, crop rotation and seedbank dynamics. The importance of the transfer of knowledge and technology is emphasised.

There may be long term and short term objectives to chosen weed control strategies. Models are useful because they allow different elements to be considered and the levels of different factors varied at will to test and refine optimum weed control strategies. Even the most elegant systems will not run without adequate data (Cussans, 1995). Such models need inputs of basic biological information about crops and weeds to provide realistic simulations and predictions (Schreiber, 1982). The predictions can then be used to form the basis for decision support systems from which might be derived information on weed thresholds, optimum weeding times, or weed control treatments for specific crop situations.

In organic and other low-external-input (LEI) farming practices, the approach to weed management involves the whole cropping system (Liebman & Davis, 2000). The aim is to maintain a balance between crop plants and weeds, with the grower adjusting the balance in favour of the crop whenever possible. In integrated farming systems (IFS) the intention is to reduce synthetic inputs (Jordan *et al.*, 1997). In the Netherlands, IFS is seen as a prelude to national conversion to sustainable agriculture (Proost & Matteson, 1997). In the UK, the aim of the LINK Integrated Farming Systems (IFS) project has been to develop a practical integrated arable system. The emphasis is on the whole system and weed control is not the sole objective (Ogilvy *et al.*, 1994), crop rotation is a key component (Jordan & Hutcheon, 1996). The scheme is one of reduced inputs and although cultural practices aimed at reducing weeds are included, judicious use of selective herbicides remains an important part of the system (Coutts & Prew, 1996). Nevertheless, the study provides valuable information on experiences with mechanical weed control in different crops, and the long term effects of cultural practice on weed populations under UK conditions. Other low input research projects on the long term environmental and economic effects of integrated arable cropping systems include the LIFE (Low Input Farming and Environment) (Jordan & Hutcheon, 1995), the SCARAB (Seeking Confirmation of Results at Boxworth), the TALISMAN (Towards A Lower Input System Minimising Agrochemicals And Nitrogen) (Hancock *et al.*, 1995), and the RISC (Reduced Input Systems of Cropping) (Easson & Picton, 1994) projects. The impact of these low input strategies on the weed population and weed competition has been monitored (Cooke *et al.*, 1996; Easson *et al.*, 1996; Ogilvy *et al.*, 1993; Wilson *et al.*, 1994) but the use of even low levels of herbicides prevent the direct application of the results to non-chemical weed control systems. There is a similar problem with the LISA (Low Input Sustainable Agriculture) program in the US which shares many production practices with organic farming but allows limited use of pesticides and synthetic inputs (Grubinger, 1992).

It may be possible to develop models that can separate out and remove the pesticide effects from the data and allow the effects of non-chemical factors to be elucidated. The COIRE (Crop Optimisation by Integrated Risk Evaluation) project aims to assist in understanding the complexity of the interactions between inputs, husbandry, pests, weeds and diseases, and environmental factors in arable farming systems (Davies *et al.*, 1997b).

To develop and promote integrated crop management in the farming community, LEAF (Linking Environment And Farming) was set-up. It assists farmers with environmental issues, and increases the awareness of non-farmers to ICM benefits. In the UK there are 14 LEAF demonstration farms. LEAF encourages farmers to carry out an annual environmental audit to assess the impact on the environment of all aspects of farming practices including weed control (Drummond, 1994).

Improving direct weed control

Machine guidance and automated weed detection systems

Guidance and weed detection systems have been developed mainly to make more effective use of pesticides, either for band spraying along a crop row or detecting individual weed or crop plants for treatment (Marchant *et al*., 1997; Miller *et al*., 1997; Thompson *et al*., 1991; Kouwenhoven, 1997; Tillett *et al*., 1998).

Laser transmitters and receivers have been used to guide tractor mounted machinery in a straight line across a field (Naber *et al*., 1992; van Zuydam *et al*., 1995). With this system, seedbed preparation, mechanical or chemical weed control, or fertiliser operations could be carried out day or night. More complex guidance systems rely on finding and following the crop rows by identifying features of the row structure. A method of tracking row structures using image analysis allowed a machine to follow the crop row in cauliflower, wheat and sugar beet with reasonable accuracy (Marchant, 1996). Sophisticated guidance and weed detection systems have now been applied to mechanical weeding implements (Tillett *et al*., 1999; Tillett & Hague, 1999). These have lead to the development of tractor-mounted hoes with automatic guidance systems (Williams, 2001a; 2001b; 2003). Modified CCTV cameras take pictures ahead of the tractor and computer analysis of these maintains the position of the hoe in relation to the crop rows. The greater accuracy of the vision guidance system means it requires a only a 26.1 mm gap either side of the tine to avoid crop damage 99.7% of the time at a forward speed of 6.5 kph (Home *et al*., 2001).

Plant detection systems have included image analysis (Miller *et al*., 1997) based on leaf shape (Woebbecke, 1995a), or colour (Woebbecke, 1995b). Other systems use spectral sensing or light reflectance as a way of discriminating between crop and weeds (Hahn & Muir, 1994). Such techniques could also be used to detect weeds in non-chemical weed control systems. They could improve selectivity and allow faster operating speeds. An automatic guidance system is unlikely to be cheap but there could be reduced labour costs. In flaming systems in particular automatic guidance would give greater operator safety. The costs involved in precision weeding suggest that this method of control may only be economic in high value crops (Leake, 1996).

A Danish 'Advanced Tool Control' system has been developed comprising a vision system, guidance frame and a wheel sensor linked by computer (Moore, 2000). This automatic guidance system has been designed for mounted inter-row cultivators and band sprayers. In the UK a prototype driverless system that uses image analysis for guidance has been developed that can operate completely automatically (Williams, 1996). The Dutch too have developed a vehicle that uses DGPS signals to hoe accurately between crop rows. It is said to be capable of working to an accuracy of 1 cm at speeds of 7 kph (Vale, 2002). A French mechanical intra-row hoe has been developed that uses an infra red sensor to detect crop plants (Vale, 2003).

The signal is transmitted to a computer that triggers an air cylinder to push the hoe blade out of position before it reaches the crop plant. The blade then returns to the working position.

INDIRECT WEED CONTROL

Weed management is probably a better term to use than weed control. In organic growing systems and now increasingly in conventional ones, the approach to weed management involves the whole cropping system. There is a balance between crop plants and weeds with the grower manipulating the balance in favour of the crop. Indirect weed management is unlikely to be sufficient on its own but direct control of weeds should be seen as the last resort.

Cultural weed control

Tillage

Soil cultivation or tillage in its various forms has long been implemented to control weeds. However, there are other additional cultivations that may be associated with crop harvesting, as well as the post-harvest incorporation of crop and weed residue for disease control, and to prevent seed shedding by the weeds. The method, depth, timing and frequency of cultivation may influence the composition, density and long term persistence of the weed population (Mohler & Galford, 1997). It can provide an effective way of manipulating or managing weeds (Håkansson, 2003). However, like any other system there may be conflicts. Finer seedbeds produce more weed seedlings but a smooth surface makes direct weed control easier. Larger clods of soil produce fewer weed seedlings but the rough surface gives emerged weeds protection against direct weeding methods. Excessive cultivation though can also harm soil structure leading to capping of the soil surface and in the longer term to loss from erosion. Under reduced tillage there is better control of soil erosion, conservation of soil moisture and more efficient use of fossil fuel (Coolman & Hoyt, 1993a). However, not all soils are suitable for reduced tillage.

Tillage is often divided into three forms primary, secondary and tertiary (Forcella & Burnside, 1994), but there are other cultivations that do not fall into these categories.

Primary tillage

Primary tillage is the principal method chosen for cultivation prior to crop establishment. The main choice is between ploughing or non-ploughing (No-till) systems of soil management. Daly & Stevenson (1990) posed the question “to what degree can surface cultivation be used to establish a relatively sterile surface layer and how often should this be alternated with ploughing”. Ploughing is seen as a method by which weed seeds can be buried below the depth from which they are capable of germinating, and it is sometimes said that ploughing is needed only to bury the weed problem. But this short term solution to poor weed control in a previous crop often leads to long term problem due to the persistence of the buried weed seeds in the soil seedbank.

Primary tillage has been the subject of considerable research in comparing the merits of ploughing with reduced tillage systems for weed management (Forcella & Burnside, 1994). The concept of direct drilling crops without resorting to ploughing became popular after the development of the non-residual herbicides paraquat and diquat. Recently, there has been renewed interest primarily out of concern for soil conservation, and in particular to prevent erosion (Buhler, 1995). However, as with the herbicide-based system, wind disseminated and perennial weed species can increase (McLaughlin & Mineau, 1995), and volunteer weeds are also likely to be a problem (Buhler, 1995). Nevertheless, non-inversion tillage keeps fresh weed seeds near the soil surface where shallow cultivations can be directed to depleting seed numbers (Melander & Rasmussen, 2000). In a no-tillage system, 60% of the weed seeds in the top 19 cm of soil were in the surface 1 cm of soil. Where the soil had been chisel ploughed 30% of seeds were in the top 1 cm of soil and seed concentration then declined linearly with depth. Where moldboard ploughing had taken place there was a uniform distribution of weed seeds in the top 19 cm of soil (Yenish *et al*., 1992).

In the UK, Cussans *et al*., (1979) found that annual broad-leaved weeds were less influenced by tillage than annual grass weeds. Annual meadow grass (*P. annua*), wild oat (*A. fatua*) and blackgrass (*Alopecurus myosuroides*) were all favoured by non-ploughing techniques. In experiments over 9 years using different primary cultivations in a vegetable crop rotation there was a pronounced effect on seed numbers of *P. annua* (Roberts, 1965). At the end of the experiment, seed numbers were 7, 11 and 23 million per acre respectively for deep ploughed (14-16 ins), shallow ploughed (6-7 ins) and rotary cultivations (6-7 ins).

In a Norwegian study of tillage for preventive weed control, Teslo (1994) concluded that plough-based methods were better than harrow-based methods in grain crops. In another Norwegian study, although annual weeds were not a serious problem, shallow cultivation resulted in more weeds than deeper cultivation (Børresen & Njøs, 1994). Infestations of the perennial grass weed couch (*Elymus repens*) were also greater following shallow tillage. Perennial weeds are thought to increase in organic farming systems and, depending on the weeds involved, it may be necessary to plough periodically to keep them at a manageable level.

Secondary tillage

Secondary tillage is used to prepare seedbeds and leave a level surface for drilling. Typically it involves disking or harrowing to a depth of 10 cm. The timing of seedbed preparation affects weed populations considerably and is an opportunity to reduce weed numbers that emerge in the growing crop. One traditional method of weed control is the stale or false seedbed technique. A novel method of reducing seedling emergence is to carry out the seedbed preparations in the dark to avoid stimulating weed seed germination.

Timing

It is well known that sowing autumn cereals as late as possible allows blackgrass (*Alopecurus myosuroides*) to germinate and be controlled before the cereal crop is established. Like blackgrass, many other weed species emerge only at particular times of year. Delaying drilling until mid October may reduce disease problems as well as weeds but germination and growth of the crops can be slow making them vulnerable to slug attack (Leake, 1996).

Stale seedbed

A stale or false seedbed, may be defined as a seedbed prepared several days, weeks or even months before planting or transplanting a crop (Johnson & Mullinix, 1995). The technique is recognised as a strategy suitable for organic farming and has been widely used for many years. The stale seedbed is based on the principle of flushing out germinable weed seeds prior to the planting of the crop, depleting the seedbank in the surface layer of soil and reducing subsequent weed seedling emergence. It can be an effective method of decreasing the density of annual weeds, as has been demonstrated in many studies including weed control in maize production systems (Leblanc & Cloutier, 1996).

When temperatures are not limiting, the most important factor determining the timing of a flush of weed emergence is adequate soil moisture (Roberts & Potter, 1980). Consequently, in dry years the stale seedbed method does not serve as a good method of weed control without the intervention of irrigation. The dependence of the strategy on soil moisture availability is clearly demonstrated by Bond & Baker (1990). When conditions were moist, 50% of the weed seedlings (expressed as a percentage of the total seedling emergence in a 16 week period) emerged within 6 weeks of cultivation. In contrast, in drier years 50% emergence was related to rainfall events, sometimes as much as 13 weeks after the initial cultivation event. Bond & Baker (1990), also observed that the use of irrigation generally gave more consistent patterns of weed emergence and reduced the spread of emergence. Jensen (1996), also noted that soil moisture level following ploughing 2-3 weeks in advance of drilling, significantly affected the control of both volunteer winter barley and broad-leaved weeds in winter oilseed rape.

Although adequate moisture is vital in determining the efficacy of the stale seedbed technique, soil factors such as the fineness of the seedbed (Bleasdale & Roberts, 1960), and prevention of capping (Roberts *et al.*, 1981) are also important for maximising weed seedling emergence. Following studies on the effect of tillage on volunteer sunflowers, Robinson (1978) concluded that whilst shallow tillage may stimulate emergence, soil pulverisation is preferable as it destroys clods and improves weed seed contact with the soil, so providing conditions conducive to seed germination.

Covering soil with polyethylene sheeting is known to increase weed emergence (Bond & Burch, 1989). The potential for using pre-planting polyethylene mulches to improve weed germination and hence depletion of the seedbank has been examined as a way of improving upon the stale seedbed technique (Davies *et al.*, 1993). Covering soil with clear polyethylene increased weed seed germination, but germination continued after the first flush of weeds had emerged and the covers were lifted. In contrast, following the removal of the black polyethylene the ground was clear due to seedling death or a lack of emergence. There was little subsequent weed germination, and the reduction in weed emergence was reflected in the yield of the brassica crops planted after removing the sheeting.

There are a number of problems that are associated with using the stale seedbed technique in organic systems. To ensure success, removal of emerged weeds needs to be delayed until the main flush of emergence has passed (Bond & Baker, 1990). Growers may be reluctant to delay planting or drilling if soil conditions are good and there is a risk of heavy rain preventing future operations. If there is no rain during this period there can be increased soil erosion and soil drying (Johnson & Mullinix, 1995). The resulting dry seedbed conditions and delayed crop establishment can reduce crop yield (Rasmussen & Ascard, 1995). Once the weeds have emerged they must be killed or removed by an acceptable method. Emerged weeds can be controlled by flaming or light cultivation/undercutting (Caldwell & Mohler, 2001). It is important not to cultivate below the top 1-2 cm soil otherwise a further flush of weeds may emerge (Blake, 1990). To gain the most advantage from the technique, the seedbed needs to be weed-free at the time of crop planting or drilling.

Rasmussen & Ascard (1995) emphasise the importance of understanding the germination and development requirements of the different weed species in order to increase the reliability and efficacy of the stale seedbed method. The date and the prevailing conditions prior to and after soil cultivation have a strong effect on seedling numbers and timing of emergence. For example, in spring the mean seedbed temperature in the week after cultivation and the number of seedlings in the flush of emergence are highly correlated (Vleeshouwers, 1997).

Cultivation in darkness

It is known that light can break weed seed dormancy and stimulate germination. Although it was known in the past that a brief exposure to light of weed seeds buried in soil promoted a flush of seedling emergence, it has only been considered to be of practical importance recently (Hartmann & Nezadal, 1990). Cultivation in the dark has been shown to reduce weed emergence by up to 70% but it is often much less effective (Ascard, 1994; Börjesdotter, 1994; Scopel *et al*., 1994), and it still leaves enough weeds to reduce crop yield. Fogelberg (1999) found only a small, and not always significant, reduction in weed numbers following seedbed preparation and carrot drilling in darkness. After intra-row brushweeding, there was little difference between carrot crops drilled in the dark and others drilled in the light.

There are several reasons why cultivation in the dark does not give consistent results. Not all weed species have light sensitive seeds (Leake, 1999). whilst the seed of others can lose their light requirement with age. Welsh *et al.,* (1999) found that the emergence of common chickweed (*S. media*) and fat-hen (*C. album*) was reduced by cultivating in darkness but that of blackgrass (*Alopecurus myosuroides*) was unaffected. In addition, some light sensitive species like the mayweeds are small-seeded and will only emerge from shallow layers of soil. Therefore, seeds left near the soil surface following dark cultivation may still receive sufficient light in order to germinate. The results of experiments comparing cultivation in the light and in the dark are also dependent on the cultivation intensity and choice of implement (Jensen, 1995).

Following the generally disappointing results from studies in the UK, a number of potential areas of improvement in the method have been highlighted (Samuel, 1992). One suggestion has been to roll the soil following cultivation to consolidate the seedbed and prevent light penetration into the top few mm of soil. It is not necessary to work the soil in total darkness, covering the cultivating implement with sheeting to prevent light reaching the soil at the point of cultivation may be sufficient (Börjesdotter, 1994; Scopel *et al*., 1994). The covering of tractor lights, with green filters, has also been reported (Samuel, 1992). Alternatively, guidance systems may allow a range of operations to be performed in complete darkness (van Zuydam *et al.,* 1995).

Tertiary tillage

Tertiary tillage is the soil cultivation that is used directly as a means of physical weed control. It is dealt with in some detail in the direct weed control section under mechanical weed control.

Other tillage opportunities

An additional consideration when using tillage to aid weed control is the timing of any form of post-harvest soil cultivation in relation to its effect on the persistence of weed and crop seed shed during or after crop harvest. The burial of recently shed seeds can induce dormancy when conditions are not appropriate for germination. For example the burial of winter barley seeds in dry soil can actually induce dormancy and cause problems in later cropping sequences (Rauber, 1986). Post-harvest cultivation too soon after seed shedding and in sub-optimal conditions for germination, can instil a light requirement and as a consequence induce dormancy and persistence in oilseed rape seed shed during crop harvest (Pekrun *et al.*, 1997). Not all seeds have the same response; *Bromus sterilis* L. (barren brome) seeds left on the soil surface persist longer than those buried soon after shedding (Peters *et al.*, 1993). In this instance, early cultivation would be more appropriate to ensure control.

Cultivation as soon as practicable after harvest is also recommended for the control of rhizomatous grass weeds such as common couch (*Elytrigia repens* (L.) Desv.) and black bent (*Agrostis gigantea* Roth). An intensive rotary cultivation is needed to work the soil to the full depth of the shallow rhizome system. The aim is to fragment the rhizomes as small as possible and this works best in previously undisturbed soil. After the initial cultivation, further passes at this time only serve to move the broken rhizomes pieces around. Fragmentation stimulates regrowth of a dormant bud on each rhizome fragment. Cultivations to control regrowth may be repeated every 2-3 weeks or when the grass has leaves 5-10 cm long, until no further regeneration occurs. Alternatively, the land may be deep ploughed to bury any regrowth below the depth it will emerge from.

Crop rotation

Crop rotation is a requirement of organic farming practice, to aid pest and disease control and to provide optimum soil fertility. Until well into this century, weed control was achieved largely by a combination of crop rotation and other cultural measures (Lee, 1995). Aspects of a rotation may favour some weed species more or less than others but the chances of any one species becoming dominant are minimised as crops and associated cultural practices vary. It is possible to actively discourage the growth and reproduction of a particular weed species by introducing unfavourable conditions and practices into a rotation (Karlen *et al.*, 1994). In the past, ‘cleaning’ crops such as potatoes were used to reduce weed problems in the year before sowing a less competitive crop. The benefit to succeeding has to be balanced against any yield loss in the cleaning crop due to frequent cultivations (Moursi, 1955). However, maintaining a particular rotation just for suppressing weeds is difficult when other factors, including economic and market forces determine the cropping sequence. Nevertheless a competitive grass/clover ley mixture sown primarily to improve soil fertility, will also help to reduce the weed seedbank through seed deaths that occur during the ley period combined with the suppression of further weed seed production.

The decline in the use of rotations has been blamed for many of the current weed problems (Cussans, 1976). When crops are sown repeatedly, strong crop and weed associations are known to develop (Hill *et al.,* 1989). In Denmark, following the change to monocultures of cereals, crop type was identified as the most important factor in governing the structure of weed communities (Streibig *et al.,* 1993). Even though the use of herbicides reduced the frequency of some weed species, the effect was secondary to that of the crop.

The success of rotation systems for weed suppression appears to be based on the use of crop sequences that create varying patterns of resource competition, allelopathic interference, soil disturbance and mechanical damage to provide an unstable environment and prevent the proliferation and dominance of any particular weed (Liebman & Dyck, 1993; Liebman & Davis, 2000). Hill *et al.,* (1989), found that when no additional weed control measures were taken, weed cover and seedbank numbers increased in the first cycle of a four year rotation but no single species predominated. Studies of changes in weed population due to crop rotation have been made in conventional systems but herbicide use and/or nitrogen application modify or lessen the effects (Andersson & Milberg, 1996).

Within organic systems the aim is not the total eradication of weeds but a balance between the yield penalties of high weed populations and the benefits of biodiversity. Control is achieved by the combination of cropping sequence and the cultivations associated with each particular crop. The ley period in particular permits the reduction of weed populations through suppression by competitive grass/clover mixtures (Millington *et al.,* 1990), and seed death during the 3-5 year ley period (Stopes & Millington, 1991). In UK studies comparing different ley/arable crop rotations in an organic farming system it was observed that weed seedbank populations were greater in plots that followed a high proportion of arable crops in the previous four years (Younie *et al.,* 1996).

Comparisons in the size and composition of weed populations have been made between organic and conventional cropping systems. However, not all such studies are realistic. Bàrberi *et al.,* (1998), found higher weed seed numbers in the soil following 5 years continuous maize cropping in an 'organic' system than a conventional one. The difference was attributed to the efficacy of weed control methods in the maize crop, but there was no crop rotation to support the direct weeding methods.

Despite the use of rotations, some weeds have been identified as particular problems in organic farming systems. They may occur in all cropping situations or may only be problems in particular crops, certain parts of the rotation, in local areas, or only in horticultural or in arable systems. Couch grass (*Elymus repens*) and other creeping perennial grasses, and creeping thistle (*Cirsium arvensis*) are often cited as the main problem weeds in all organic systems (Lampkin, 1990; Peacock, 1990). Blackgrass (*Alopecurus myosuroides*), an annual grass weed can become more frequent when cereals form a significant part of the rotation. Docks (*Rumex* spp.), are a particular problem in grassland, and bracken (*Pteridium aquilinum*), has become a severe problem in upland areas of pasture. In perennial crops and permanent grassland, there is no opportunity for rotation following crop establishment. Land preparation is therefore vital to avoid or minimise perennial weed problems at the outset. On some soils, improved drainage may help to eliminate weeds that favour wet conditions.

Cultivar

It is not simply the choice of crop that influences weed development within a rotation, the characteristics of the cultivar such as morphology and growth rate can have a significant effect on both crop and weed development. Currently, organic growers rely heavily on cultivars developed for conventional growing systems as part of conventional breeding programs (Lammerts van Bueren *et al.,* 2002). Many of the desired traits that will benefit the cultivars when grown organically are not given sufficient priority in current breeding programmes. In addition the selection process needs to be carried out under organic growing conditions for optimal results (Wolfe, 2002). The aim should be to move from the current use of organic seed of conventional cultivars to the growing of cultivars specifically bred for organic systems. Weed control is one of the main challenges in the production of organic seed crops (Marshal & Humphreys, 2002). The breeding of organic cultivars that contribute to improved weed control will assist both the organic growers and the seed producers.

Recent work in cereals has shown that both cultivar choice and crop seed rate can be effective in suppressing weeds and hence minimising weed control inputs (Christensen & Rasmussen, 1994). Restriction of light through crop shading, may be one such method of harnessing varietal attributes to manipulate the weed population (Verschwele & Niemann, 1993). Regulation of a growth limiting factor such as photosynthetically active radiation (PAR) could be exploited as an alternative weed control measure as part of both organic and integrated systems. It has been shown previously that light interception is correlated with crop height (Wicks *et al.*, 1986), and Easson & Courtney (1989) considered the taller development of the spring barley cv. Atem, relative to cv. Triumph, to be a major influence in its greater weed suppression. Similarly, in a study comparing the two winter wheat cultivars, Mercia and the traditional longer strawed cultivar Maris Huntsman, both total above-ground weed dry weight and the number of weed species found on the plots were significantly reduced in the presence of Maris Huntsman (Grundy *et al.*, 1993). Work in Germany in winter wheat has also shown that tall cultivars tend to yield better than shorter ones in organic systems, but it is not known whether this is due to greater weed suppression or an innately better nutrient uptake from the soil (Richards, 1989). However, it should be noted that whilst the short stature of some varieties can give an advantage to taller weeds such as *Avena fatua*, tall varieties may themselves favour certain weed species (Gooding *et al.*, 1993).

Although shading is accepted as a major contributory factor to weed suppression in cereals, there are number of other equally important morphological traits that confer a cultivar with greater competitive ability over weeds (Christensen, 1995; Lemerle *et al.*, 1996). For example, earliness of crop ground cover is thought to be vital in weed suppression (Richards, 1989; Richards & Whytock, 1993), and research has indicated that larger initial crop seed size can significantly improve early crop establishment and hence increase the competitive ability of winter wheat cultivars (de Lucas Bueno & Froud-Williams, 1996). However, there is a dearth of information regarding the competitive ability of individual crop varieties to weeds. Some work has been published with respect to small grain cereal varieties for weed suppression (Balyan *et al.,* 1991; Dhaliwal *et al.*, 1993; Blackshaw, 1994; Seavers & Wright, 1995 & 1997; Froud-Williams, 1997; Sodhi & Dhaliwal, 1998), and a few studies have specifically concentrated on varieties suitable for organic systems (Richards & Heppel, 1990; Cosser *et al.,* 1997b).

Only a limited number of studies have examined the relative competitive ability of vegetable cultivars, for example carrots, calabrese and spring beans (William & Warren, 1975; Cox, 1991b; Taylor, 1993, respectively). Balsari *et al.*, (1994) noted that a vigorous cabbage cultivar suppressed weed numbers more effectively than some other varieties.

Competitive ability has not been a trait selected for in breeding programmes, or tested in official trials. Most progress has been associated with factors such as improving grain yield, above-ground biomass, harvest index, total N uptake and general root and shoot morphology as reviewed by Feil (1992). Some earlier studies have even dismissed the idea of improving varietal tolerance to weeds as being "too complicated", or unnecessary as long as the crop has enough inputs (Callaway, 1992). Identifying and quantifying the traits associated with competitive ability against weeds is indeed complicated by the fact that, although different cultivars have unique characteristics, many of these traits can change over development stage (Verschwele & Niemann, 1993; Christensen, 1995). The distinction should also be made between varieties that tolerate weeds compared to those that actively suppress them, the latter being preferable (Froud-Williams, 1997). Plant breeders are unlikely to select for certain attributes, such as taller varieties because of problems associated with lodging. However, many other varietal attributes, including differential rooting patterns, early vigour, leaf size and allelochemical properties may influence the ability of a cultivar to suppress weeds and be successfully selected in breeding programmes (Lemerle *et al.*, 1996). Correct choice of cultivar may not only be essential in exploiting the crop's ability to compete with potential weed problems, but also in maintaining crop quality. The relative merits of traditional organic cultivars and modern cereal varieties in grain quality are discussed by Samuel and East (1990).

Intercropping

Intercropping and undersowing offer scope for weeds suppression in the rotation (Baumann *et al.*, 2000). Improved weed control alone is unlikely to justify their use and there must be other obvious benefits if the change in cropping practice is to prove economic (Theunissen, 1997).

Increased yield, not improved weed control, is probably the main benefit expected from intercropping but there is concern that plant competition could reduce the yield of one or both of the intercrops. Fukai & Trenbath (1993) have reviewed the processes determining intercrop productivity and the yields of component crops. A competition model has been developed and validated that can predict the growth of plants in mixed cropping situations (Aikman *et al.*, 1995, Benjamin & Aikman, 1995a). Further development would allow it to be used to simulate crop growth in a wider range of intercrops.

Intercropping is a practice that applies particularly to agriculture in less developed countries but it can have an important role in sustainable systems anywhere (Coolman & Hoyt, 1993b). Phaseolus bean grown as an intercrop with maize (*Zea mays*) reduced the weeds and increased the yield of maize in Kenya but bean yield was low (Maina & Drennan, 1996). In the UK, the intercropping of field beans (*Vicia faba*) and wheat grown organically, reduced the growth of weeds and gave a substantial yield advantage over sole cropping, (Bulson *et al.*, 1990; Welsh *et al.*, 1999). In the US, an oat (*Avena sativa*) companion crop helped to suppress the weeds during establishment of an alfalfa crop (*Medicago sativa*), and contributed to the increased yield of forage in the first cut (Lanini *et al.*, 1992).

Plant spacing is an important factor in determining both crop yield and weed suppression in intercrops. In Africa, intercropping melon (*Colocynthis citrullus*) and plantain, suppressed weed growth for 7 months and enhanced plantain yield, but getting the correct melon planting density was critical (Obiefuna, 1989). Sharaiha & Gliessman (1992), evaluated different crop combinations and row arrangements in intercrops of lettuce (*Lactuca sativa*), favabean (*Vicia faba*) and pea (*Pisum sativum*). Intercropping reduced weed biomass compared with sole crops except where lettuce and pea were grown together. The effect of the remaining weed on crop yield depended on specific row arrangements.

The choice of companion crop is also important. Robinson & Dunham (1954), found that soybean (*Glycine max*) yields were increased and weeds suppressed when wheat or rye was the intercrop. But, alfalfa (*Medicago sativa*), vetch (*Vicia* spp.), red clover (*Trifolium* spp.), bromegrass (*Bromus* spp.) and timothy grass (*Phleum pratense*) did not give satisfactory weed control, and pea (*Pisum sativum*) caused lodging of the soybean crop.

Cover crops

The inclusion of cover crops in the rotation, at a time when land might otherwise lie uncropped, will suppress weed development while maintaining soil fertility and prevent erosion (Liebman & Davis, 2000). Cover crops have different characteristics, and selection depends on the purpose they are intended for (Fielder & Peel, 1992). The primary object of most autumn sown cover crops is to absorb nitrates from the soil to prevent them leaching and then make them available to subsequent crops (Henley, 1990). For weed control, rapid development and dense ground covering are the characters to select for (Nelson *et al.,* 1991). Some cover crops may be suitable for both purposes (Dyck *et al.,* 1995). Allelopathic ability may play a part in reducing weed development but it is the weed suppression due to competition for growth factors that is the main effect of a cover crop (Grundy *et al*., 1999). It has been suggested that weeds themselves may provide a natural cover crop that will suppress the growth of other weeds (Anaya *et al.,* 1988). In Mexico, *Ipomoea tricolor* and related species have been traditionally grown by peasant farmers as a cover crop to suppress weeds (Anaya *et al.,* 1990). Disadvantages of using cover crops are that they may affect the seedbed preparation for following crops, and could act as a source of infection to those crops (Shepherd, 1992).

In horticultural systems cover crops can be managed in several ways (Putnam, 1986). Cover crops may be sown in the autumn and killed off before vegetable crops are seeded in spring. Destruction through incorporation greatly reduces any weed control benefits. Using frost sensitive cover crops eliminates the need for destruction in spring but earlier establishment is needed to obtain good ground cover before the first frosts. In the US, forage soybean (*Glycine max*) was sown in April, killed off in August by mowing or rolling, and then broccoli seedlings planted into the cut mulch (Heathcox, 1998). The mulch suppressed weed emergence and enriched the soil with nitrogen.

Cover crop residues left on the soil surface can suppress weed emergence and growth. Although allelopathy may be involved, other factors such as light transmittance, soil temperature and soil moisture under the residue is also important (Teasdale, 1993; Teasdale & Mohler, 1993). The plant residues provide a protective habitat for seed predators and this may also help to reduce weed numbers (Reader, 1991). In addition, the decomposing cover crop residues may release allelochemicals that inhibit the germination and development of weed seeds (Putnam, 1986; Liebman & Davis, 2000). Unfortunately, drilled, small-seeded crops may also be adversely affected. Stirzaker & Bunn (1996), found that residues of ryegrass (*Lolium rigidum*) and subterranean clover (*Trifolium subterraneum*) covercrops reduced seedling growth of lettuce (*Lactuca sativa*), broccoli (*Brassica oleracea* var. *italica*), and tomato (*Lycopersicon esculentum*). The phytotoxic effect of ryegrass lasted longer than that of clover.

A reliable method of mechanically killing the cover crop, before establishing a following crop, is necessary in organic systems as contact herbicides cannot be used. There may be disadvantages in using a flail mower that scatters the mulch. Creamer *et al.,* (1995) have investigated the use of an undercutter to provide a thick, evenly distributed layer of weed suppressing mulch. Other non-chemical methods of killing or suppressing cover crops include mowing, rolling, roll chopping and partial rotitilling (Creamer & Dabney, 2002). Regrowth may be a problem depending on growth stage, grasses are more likely to regrow than broad-leaved cover crops. A strimmer would appear to be the ideal implement for cutting down cover crops but there has been little work on this. Planting into freshly killed residues may require equipment to move the residues from the planting row (Creamer & Dabney, 2002).

Fallowing

Fallowing has been shown to reduce perennial weeds within a rotation (Hintze & Wittmann, 1992). However, the economics of taking land out of production for a growing season together with undesirable effects on the soil and the environment, make the use of a full fallow unlikely for weed control in the organic system (Lampkin, 1990). Fallowing the land for part of the growing season, as a bastard fallow, may be just as effective and can be fitted into most rotations (Blake, 1990). The aim is to cultivate the soil progressively deeper over time, exposing underground plant parts to desiccation at the soil surface; dry weather conditions are essential. It is often used after a ley to reduce perennial weeds before sowing a winter cereal.

A similar effect to that of fallowing can be achieved with rapidly developing crops like radish (*Raphanus sativus* L.) that are harvested before the onset of weed competition. The short interval between crop establishment and harvesting in this crop encourages weed seed germination but does not allow the weeds time to set seed or reproduce vegetatively (Bond *et al.*, 2000).

Conversion

The conversion period may be seen as an opportunity to experience and learn to cope with the difficulties involved in controlling weeds in the absence of herbicides in much the same way that growers learn the problems associated with any change in crop production (Hanson *et al.*, 1997). There have been general (Buchner, 1984; Patriquin *et al.,* 1986) and specific studies (Davies *et al.,* 1997a; Landa, 1993) that provide information on the effect of the transition to organic husbandry on weeds.

Many studies state that an increase in perennial weeds is a major problem during conversion. Patriquin *et al.,* (1986), noted an increase in the size and frequency of thistle patches (*Cirsium arvense*), and in the number of dandelions (*Taraxacum officinale*). The increase was probably associated with reduced soil tillage. A combination of partial summer fallowing and cultivation at 21-day intervals was introduced to bring the thistle under control. Landa (1993), found that weed diversity almost doubled in the second year of conversion but this varied with the crop. The lowest range of species was found in a crop grown for green manure and the highest in winter wheat. In the UK, although weed populations appear to increase rapidly during the early stages of conversion, there is some evidence that growth stabilises eventually (Davies *et al.*, 1997a). It was noted that periods of grass ley longer than two seasons greatly reduced weed population growth during conversion.

Following conversion, Albrecht & Sommer (1998), analysed the relative frequency of 49 weed species. Three years after the change, total seed numbers in soil had increased from 4050 to 17320 m^{-2}. Of the species present, 17 remained constant and 32 were found more often. Naturally, the increasing species included the ones that were most difficult to control. The percentage of cereals in the crop rotation had a considerable influence on weed species composition and increased frequency. Conversion may be seen as a time to limit future weed problems but species composition largely depends on the previous cropping history of the land.

Set-Aside

There have been many studies of the weed control implications of set-aside (Davies *et al.*, 1992). Such studies are of interest to organic growers because within the rules of the five year set-aside scheme there has been an opportunity for farmers to consider conversion to organic production (Ramsay, 1992).

Under set-aside, grasses seem to increase in abundance (Brodie *et al.*, 1992). On heavy land, management of naturally-regenerated vegetation by cutting resulted in a sward dominated by couch grass (*Elymus repens*) which could pose a serious problem in future organic crops (Shield & Godwin, 1992). However, cutting removed the flower heads of the grasses and reduced the populations of those that reproduced by seed alone.

Fallowing in set-aside is likely to result in weeds seeding and increasing the weed seedbank leading to greater weed problems in following crops. The inclusion of competitive cover crops reduced but did not eliminate seeding completely in comparison with natural regeneration (Zwerger *et al.*, 1993). Once a seedbank has been built up it takes a long time to reduce it again.

Crop establishment

Plants that emerge first in the field have a competitive advantage and for a crop this improves selectivity during subsequent weeding operations. Crop seed vigour is particularly important in early establishment (Rasmussen & Rasmussen, 2000). The way a crop is grown can also give the crop an early advantage that has subsequent benefits for weed control. The gain may take the form of greater selectivity between crop and weeds during harrowing or it may widen the 'weeding window' and increase flexibility in optimum timing of weed removal. In field vegetables, the use of seed priming, fluid-drilling of germinated seed and the planting of bare-root or module raised plants can help organic growers reduce the weed problem. Although not compared directly, there was greater flexibility in the timing of weed removal from module raised bulb onions than from drilled salad onions in both organic and conventional growing systems (Bond *et al*., 1998a). However, Melander & Rasmussen (2001) found little advantage in terms of weed control from seed priming onions and leeks but yield was improved.

Crop density and plant spacing

The suppression of weeds by increasing sowing density in cereals has been noted in a number of studies (Welsh *et al.*, 2002). Andersson (1986), demonstrated a reduction in weed weight with increasing seed rate in the presence of both winter wheat and spring barley. Moss (1985), also found that with dense infestations of blackgrass (*Alopercurus myosuroides*), higher crop seed rates gave the crop a competitive advantage and resulted in higher yields than at lower seed rates. Similarly, increased seed rates of wheat have been shown to suppress ryegrass (*Lolium rigidum*) (Medd *et al.*, 1985), and reduced total above-ground weed dry weight in experiments with winter wheat (Grundy *et al*, 1993; Korres & Froud-Williams, 1997).

Evidence for the suppressive effect of crop seed rates above the standard has also been confirmed in organic systems (Samuel & Guest, 1990). Weed biomass was significantly reduced where the densities of wheat and bean intercrops were increased (Bulson *et al.*, 1997), and where seed rates of spring oats were increased in Scottish trials (Taylor *et al.*, 1996). Younie & Taylor (1995), found that sowing the crop at narrow spacing increased the rate of crop growth and ground cover, and thereby reduced subsequent weed development. However, the increased seed rate provided greater weed suppression than the narrow crop spacing.

While there may be some opportunities to adjust crop plant spacing to suppress weeds more effectively, in field vegetables there are limitations due to the requirement for crops to be grown to market specifications. In the absence of herbicides it may be necessary to allow wider row spacings for mechanical weeders to operate efficiently. Some compromise may be needed to devise the most appropriate spacing to meet all the different requirements.

Even with cereals, some concerns remain regarding negative effects that increasing crop seed rate may have on subsequent crop quality. However, Samuel and East (1990) confirmed that there was little effect of seed rate on specific weight and Hagberg Falling numbers in their organic trials. Work by Cromack and Clark (1987) in spring barley has also shown that increasing sowing density does not impair grain quality, with the possible exception of conditions that may limit grain fill, for example prolonged drought during this critical period.

Limiting the introduction and dispersal of weeds

Regardless of how well weeds are managed within a farming system, weed seeds may still enter from external sources providing additional weed problems. No field is a sealed system and several mechanisms including animals, wind, fibres and farm machinery offer means of introducing weed seeds and potential new species to a field (Cousens & Mortimer, 1995). Weed seeds may even be dispersed in irrigation water taken from open waterways (Forcella & Burnside, 1994).

Contaminated crop seed has been the major source of new weed seeds as reviewed by Salisbury (1961) and Froud-Williams (1988), and continues to be an important agency for the spread of weeds (Don, 1997; Streiberg, 1988). There have been considerable developments in seed cleaning which have reduced the return of these weed seeds to the soil. The decline of several formerly common weed species such as corncockle (*Agrostemma githago*) can be directly attributed to improvements in the seed cleaning process (Salisbury, 1961). However, some weed seeds still get through and appear in the crop row. Presently, most vegetable seed is produced outside the UK, providing a route for the introduction of alien species or of common weeds from a different genetic background. If the alien weeds are still within the limit of their geographical range, they may germinate, grow and multiply to become a future weed problem (Williamson & Fitter, 1996; Perring, 1996). Repeated introduction can also ensure the survival of species that are at their geographical limit (Froud-Williams, 1988).

It has become a requirement of organic farming that all crop seed is grown organically. Based on the assumption that organic growers tolerate rather than eradicate weeds, organically grown seed crops will have even greater potential for weed seed contamination than their conventionally grown counterparts. There are also significant attractions for growers in using home-saved seed including cost savings, availability and adaptation to local conditions (Wibberley, 1989). Weed seed contamination is generally greater in home-saved than merchant's seed with more than 18% of farm-saved samples containing over one thousand weeds seeds per sample compared to only 4% of merchant's seed having ten or more weed seeds per sample (Wibberley, 1989).

Another source of weed seed contamination in organic systems is through the use of soil improvers, mulches and manures (Buhler *et al.*, 1997). Municipal compost, comprised primarily of green botanical waste from both domestic gardens and civic amenity sites, can be used to improve soil quality or act as a mulch in both horticultural and agricultural situations (Lopez-Real, 1990). Compost mixtures may also be used for the production of transplants that will be put out in the field. If the composting process is carried out correctly no weed seeds should remain viable (Kuhlman, 1990). However, the large spatial differences in the temperature that can occur in a windrow can have implications for the efficacy of the composting process to destroy weed seeds (Salisbury, 1961). When attempting to reduce weed seeds in compost, the identification and elimination of external sources of contamination such as wind blown seeds are also essential (Adams, 1990). An assessment of the level of weed seed contamination in compost is included in the Compost Analysis and Testing Service (CATS) operated by Henry Doubleday Research Association (HDRA). Improved methods of weed seed determination in municipal compost have been developed by Grundy *et al.*, (1998). Organic material that has not been composted may present an even greater risk of introducing weed seeds. Volunteer weed seeds can be a particular problem in harvested plant material. Cereal straw used for mulching often contains shed grain and sometimes whole ears of wheat or barley. If the straw is from a weedy crop, weed seeds may also be present. Manure from sheep was found to add almost 10 million weed seeds ha^{-1} at each application compared with 182,000 seeds ha^{-1} from farmer-saved seed and just 120 seeds ha^{-1} from irrigation water in studies in Iran (Dastgheib, 1989).

Crop harvest is a critical time for the dispersal of crop and weed propagules. In cereals, it has been estimated that on average 40% of weed seeds have been shed by the time of harvest (Fogelfors, 1982). About 5% of seeds remain at below normal stubble height, leaving between 45 and 70% of weed seeds to pass through the combine harvester. The combine can aid both the reintroduction and spread of crop and weed seeds to other parts of a farm. Weeds maturing at the time of crop harvest and at a height intercepted by the combine will have a proportion of their seeds reintroduced into the field. Other seeds may remain lodged on the combine to be deposited at a later time and possibly at great distance from the parent plant. The magnitude and distribution of these seeds is dependent on the type of combine (Cousens & Mortimer, 1995). In a Swedish study, 66% of the weed seeds were found in the grain tank (including secondary filter), 25% in the chaff, and the remainder in the straw and in weed seed spillage (Fogelfors, 1982). In the UK, modification of combine harvesters to separate out weed seeds from grain and straw, to avoid returning seeds to soil, was recommended in a report by Patterson & Bufton (1986). Crop seeds lost during harvesting can also be dispersed to become volunteer weeds in subsequent years, for example oilseed rape (Lutman, 1993). Seed shed during the harvesting of oilseed rape can give rise to over 500 seedlings m^{-2} in following crops (Cussans, 1978). Another example is that of volunteer potatoes resulting from the small daughter tubers that escape the harvesting process. A number of adaptations to the harvesting machinery have been suggested. Tubers may be destroyed either by crushing during harvesting or by increasing their chance of exposure to freezing through appropriate post-harvest tillage (Lumkes, 1979). Identification and elimination of modes of reintroduction and spread of weeds through the harvesting process offers a substantial area of improvement for reducing potential future weed populations without resorting to chemicals.

Field margins have been considered a potential source of weeds that will spread into the crop but the distribution pattern of plants associated with arable field edges indicated that most of the species in the margins did not occur in the crop area (Marshall, 1989). Studies with some grass weeds have shown that 87-99% of seed was disseminated within 1 metre of the source unless carried further by combine harvesting (Rew *et al.,* 1997). Some pernicious weeds like creeping thistle (*Cirsium arvense*), couch grass (*Elymus repens*), and cleavers (*Galium aparine*) pose a real threat of spreading into crops. However, the ingress of aggressive weeds has been reduced but not prevented by sowing grass/wildflower boundary strips around the margins rather than leaving them unsown (West *et al.,* 1997).

WEED BIOLOGY

It has been argued that much of the biological information on weeds is not helpful in weed control and often is not intended to be. Sagar (1968) stressed the need for a much closer liaison between weed biologists and those concerned with the control of weeds. Norris (1992) also concluded that studies of weed biology had not done much to improve weed management over the last 50 years. He was however optimistic enough to state that a greater knowledge of the physiology and biochemistry of weeds may lead to new approaches to weed management, but could not predict what they might be. While Eussen (1982), concluded that the value of ecological approaches to weed management was likely to increase in the future. In surveys of the opinions of weed scientists in the UK (Moss, 1994) and US (Norris, 1997), the contribution of weed biology to weed management was rated as substantial to high.

Some direct evidence of the use of weed biology is shown by Lampkin in his book, Organic Farming (1990), where the chapter on weed management is illustrated with figures describing the seasonal patterns of weed emergence, produced by H A Roberts from weed biology experiments made under the conventional growing system. Mortensen et al. (2000) conclude that although the contributions have been modest the knowledge of weed biology and ecology has helped to shape weed management strategies in some important ways.

The weed seedbank

The soil seedbank has been called the memory of the land. It not only shapes future plant populations but it also reflects the management history of the land, not just in the previous season but over many years (Buhler *et al.*, 1997). In arable soil it is referred to as the weed seedbank and denotes the reserves of viable weed propagules present in the soil and on its surface. Seedbanks may be used to monitor the success of long term weed control programmes, and a knowledge of the species composition of the seedbank may give some guidance on the choice of future weed management strategies (Roberts, 1981). The continuing importance of weed seedbank studies is reflected in the number and range of papers given at a recent UK conference devoted to their determination, dynamics and manipulation (AAB, 1998). However, of the 41 papers presented, only three specifically reported on changes in the seedbanks of organic systems (Albrecht & Sommer, 1998; Bond *et al.*, 1998b; Barberi *et al.*, 1998). Weed seedbanks may vary in density from zero to more than one million seeds m^{-2} down to plough depth. There may be many species represented in a seedbank but generally there are a few dominant species that comprise 70-90% of the total seedbank (Buhler *et al.*, 1997). The seeds enter the seedbank from many sources but the largest contribution to the seedbank each year comes from the plants producing seed within the field. Many weed species have the potential for prolific seed production, and low weed numbers are likely to produce enough to maintain or even increase the seedbank. However, the species composition of the seedbank may alter.

Any weed control strategy, even a non-chemical one is likely to have an effect on the immediate weed flora. Depending upon the cultivations and the crop rotation that follows, this may have a great or a limited effect on the weed population that emerges in the following crop. The weed seedbank acts as a buffer to change but prolonged or repeated use of a particular crop or weed management strategy is likely to cause a major long-term shift in the weed flora. In addition to reducing the effectiveness of a particular weeding strategy, such changes may adversely affect biodiversity with the associated problems that this can bring. However, inclusion of certain longer-term crops, such as a grass/clover ley, in the rotation may help to keep seedbank numbers relatively low (Younie *et al.*, 2002).

Freshly shed seed falls directly onto the soil surface or may be transported there by other means. Once there it may germinate at once or it may lie dormant. The persistence of weed seeds in soil is mainly due to their ability to remain dormant until conditions are favourable for germination. Some of the factors responsible for the mechanism and regulation of dormancy and germination have been reviewed by Hilhorst & Toorop (1997). Ungerminated seeds may be eaten by birds or insects, which can have a substantial, and often underestimated effect on weed seed dynamics (Andersson, 1998). Weed seeds may also be eventually moved into the soil profile by natural means or by soil tillage. Consequently the timing and method of soil management, may have an important influence on the persistence and likely germination of the weed seeds. It is well known that ploughing provides a short-term solution to weed problems by burying seed below the depth of germination. However, the seed can persist at this depth leading to long term weed problems. For some freshly shed weed seeds and more particularly volunteer crop seeds, better control may be obtained by delaying cultivation and allowing the seeds to germinate. With oilseed rape, a two-week delay in cultivation at harvest may be sufficient for germination to begin (Pekrun & Lutman, 1998). It is not true for all species however, and exposure at the soil surface is likely to impose dormancy in seed of sterile brome (*Bromus sterilis*) causing it to persist longer than seed buried soon after shedding.

The weed seedbank provides a valuable source of information and a number of models have attempted to exploit this in order to predict weed seedling emergence (Forcella, 1992). Such models, based on the seedbank, have potential application for the identification and development of new weed control strategies in conventional and organic systems alike. Forcella *et al.*, (1993) state that "if the chemical load to the environment is to be reduced, without appreciably affecting crop yields, an intimate understanding of weed ecology is necessary". For example, once a seed is moved into the soil profile, the depth of burial has a profound effect on the ability of that seed to germinate and emerge successfully (Chancellor, 1964). Studies of weed seedling emergence from different soil layers in artificially created seedbanks have provided data for modelling the emergence of a range of weed species (Grundy *et al.*, 1996). The model's predictions have been validated using data from previous unrelated studies, and recent studies have allowed further development of the model (Grundy & Mead, 1998).

Weed seeds can be carried and spread within a field, to a nearby field or over long distance by agricultural implements (Mayer *et al.*, 1998). Although horizontal movement of weed seeds is important for the dispersal of seeds and for the potential spread of weed patches (Rew & Cussans, 1997), it is the depth to which the implements move the seeds in the soil that is critical for controlling seedling emergence. Relatively few studies on the effect of cultivation have quantified or controlled the vertical distribution of seeds, yet this is an important factor in determining the weediness of cultivated and uncultivated plots (Cousens & Moss, 1990; Mohler, 1993). Studies have highlighted this important effect of cultivation on seedbank composition and models have been proposed to relate this to weed emergence (Clements *et al.*, 1996). More recently, data collected from field experiments with different horticultural implements on the movement of plastic beads during soil cultivation, has been used to model the vertical movement of seeds in soil (Mead *et al.*, 1998). In 1997, Forcella stated that seedling emergence from different soil depths and the depth distributions from differing tillage systems could be combined to answer important questions. Such models could provide an insight into weed seed dynamics and eventually form the basis for weed-crop management decision support systems.

WEED COMPETITION

Weed competition studies have a long history. Tull (1722), described planting sticks in cereal crops as simulated weeds to demonstrate that it was more than just the physical presence of weeds that reduced crop yield. Since that time there have been numerous studies worldwide of weed competition in many arable and horticultural crops (Zimdahl, 1980). The studies have taken several forms and there has been much discussion about methodology, e.g. the relative merits of the additive and replacement series experiments (Connolly, 1988). There has also been criticism that little practical use has been made of the vast majority of the information from the bulk of the weed competition studies (Cousens, 1992).

Studies have determined the effect of individual weed species on a particular crop e.g. couch grass (*Elymus repens*) in potato (Baziramakenga & Leroux, 1994), volunteer barley (*Hordeum vulgare*) on oilseed rape (*Brassica napus*) (Lutman & Dixon, 1991), and creeping thistle (*Cirsium arvense*) in spring barley (Kolo & Froud-Williams, 1993). Other studies have compared the relative competitiveness of a range of weed species on a particular crop (Lutman *et al.*, 1995; Van Acker *et al.*, 1995; Wright *et al.*, 1997) or the relative sensitivity of a range of crops to a particular weed (Lutman *et al.*, 1994). In addition, some field studies have determined the competitive effect of the natural weed population on a particular crop (Bond & Burston, 1996).

In cereals, the aim has been to identify the threshold levels at which the weeds do little to reduce crop yield, and hence control measures are uneconomic (Lutman *et al.*, 1994; Onofri & Tei, 1994; Orson, 1990; Woolley & Sherrott, 1993). While thresholds are normally associated with deciding the economics of whether or not to apply herbicide treatments, the same principle could be used to determine the economics of applying a non-chemical weed control treatment to control a particular weed population. It has often been reported that while mechanical weeding treatments in arable crops, particularly cereals, have reduced weed numbers or weed biomass there has been no increase in crop yield (Rasmussen & Svenningsen, 1995; Stiefel & Popay, 1990; Welsh *et al.*, 1997). There may be some merit in defining the amount of weed pressure a particular crop can cope with before yield is lost and using this to determine the economic benefit of applying a control measure. Edwards *et al.*, (1995), evaluated a threshold cultivation treatment aimed at maintaining weed numbers below a threshold level in tomatoes, peppers and cucumbers. Threshold levels were assessed visually and varied with the weed species present and the growth stages of the crop. Debaeke (1993), used a similar idea to thresholds for non-chemical weed control within a decision support system. However, the threshold concept may not provide a basis for the rational use of weed control measures in the long term (Wallinga & van Oijen, 1997), particularly in the organic system. Although a low weed population may not merit control for a limited benefit in yield, in terms of likely seed return and future weed problems, weed control is usually justified in organic crops.

In field vegetables, even low numbers of weeds have been shown to reduce yield (Bond, 1991), and crop quality and marketability are also affected. However, experiments have shown that a crop does not need to be weed-free from sowing until harvest to prevent loss of yield due to weeds (Zimdahl, 1980). The term critical period was defined by Nieto *et al.*, (1968), for the time in the growth cycle when the crop needed to be free of weed competition to avoid loss. Studies to determine the critical weeding periods under conventional growing systems have been made in broad bean (*Vicia faba*) (Hewson *et al.*, 1973), drilled cabbage (Roberts *et al.*, 1976), beetroot (Hewson & Roberts, 1973), sugar beet (Montemurro *et al.*, 1999), drilled lettuce (Roberts *et al.*, 1977), winter wheat (Soroka & Soroka, 1996) and navy bean (*Phaseolus vulgaris*) (Woolley *et al.*, 1993). Studies to determine optimum weeding periods under conventional and organic growing systems have been made in horticultural crops (Turner *et al.*, 1999). In organic systems, studies of critical periods have made in winter wheat (Welsh *et al.*, 1997).

To investigate the practical use of the critical or primary weeding period, the optimum timing of weed removal was defined and tested in drilled and transplanted onions (Bond & Burston, 1996, Bond *et al.,* 1998), carrots (Bevan *et al.,* 1993, 1994), and drilled and transplanted maize (Santos *et al.,* 1993). In studies made with vegetable crops grown both organically and conventionally, the optimum weeding times were equally effective in both systems (Bond, 1997; Bond *et al.,* 1998a; Bevan *et al.,* 1993 & 1994). There was naturally some concern that not keeping the crop weed-free throughout could lead to greater weed problems in subsequent crops. However, studies have shown that limiting weed control to a single carefully timed weeding does not necessarily lead to an increase in the weed seedbank after harvest (Bond *et al.,* 1998b & 1998c).

Plants that emerge first in the field have a competitive advantage over those that emerge later. Seed priming and the fluid-drilling of pre-germinated seed are likely to give crops a head start over the weeds. Transplanting young crop plants ensures and enhances the crop-over-weed advantage (Andres & Clement, 1984). Such advantages may increase the competitive ability of the crop and widen the optimum weeding period 'window', giving growers more flexibility in the timing of weeding operations.

Plants respond differently to a whole range of cultural and environmental factors and this can affect the competitive ability of crops and weeds. Soil fertility, particularly nitrogen is known to have an effect (Angonin *et al.,* 1996). Water stress may also affect the relative competitive ability of crop and weed (Marshall *et al.,* 1996). Some weeds are able to adapt the architecture of their root system in response to drought (Berntson & Woodward, 1992). The prospect of global warming has increased interest in the effect of elevated levels of carbon dioxide on competing plants (Hunt, 1995) and individual weeds species (Berntson & Woodward, 1992; Houghton, 1996; Houghton & Thomas, 1996). There are many implications for the ecology and control of weeds if major environmental changes occur, but their genetic diversity and phenotypic plasticity together with the seed reserves in the soil will buffer weeds against the vagaries of climate (Froud-Williams, 1996).

Modelling competition

There are limits to the number of combinations of cultural factors and their levels that can be tested in different crops, under different production systems and environmental conditions for their effect on weed competition. In addition, for the weeds, there are the spatial and temporal patterns of seedling emergence and the species composition of the weed flora. The modelling of crop-weed interactions allows different factors to be tested at will. Field studies are needed to provide the initial parameters for the model, but these need not be complex. Limited field experimentation is then required to validate particular scenarios.

The simplest models predict growth in spaced monocrops but these may be modified to predict growth in mixed species stands (Benjamin & Aikman, 1995b). Other models simulate the processes involved in the competition between two plant species (Kiniry *et al.,* 1992; Vleeshouwers *et al.,* 1997), or between many species (Smith & Murdoch, 1997).

The nature of the models that have been developed has depended on the objectives of the research. Much of the work relates to plant populations in general and not just to weed competition. Kenkel (1991), reviewed the major spatial approaches to modelling intraspecific interactions in plants. Such models examine the interaction of individual plants and their neighbours. A zone of influence is defined around each plant, and the shape and extent of the zone is modified by neighbouring plants. The zones can apply to both above and below ground organs. Models can take into account competition for resources such as light (Kropff, 1993a), water (Kropff, 1993b) and nitrogen (Kropff, 1993c). The effect of phytotoxins, such as allelochemicals that may modify the competitive ability of plants, can also be modelled (Thijs *et al.,* 1994).

Crop-weed models have practical applications in predicting likely yield losses from particular weed populations, and in simulating critical or optimum weeding periods for given crop-weed combinations (Kropff *et al.,* 1993; Lotz *et al.,* 1994; Singh *et al.,* 1996). Weaver *et al.,* (1992), found good agreement between simulated and observed critical periods of weed competition in sugar beet, and in seeded and transplanted tomato. Following weed removal experiments to assess different aspects of weed competition in seeded onion, Dunan *et al.,* (1996) used a polynomial multiple regression model to describe the effects. This may form the basis of a bioeconomic model to calculate economic period thresholds in onion. Berti *et al.,* (1996), have taken a methodological approach to determining the optimum time to control weeds. Based on a concept of time density equivalent, it integrates weed biology, weed-crop competition and economics, and has been tested for different weed control strategies in maize (*Zea mays*) and in soybean (*Glycine max*).

Some models predict the competitive effects of crop and weed density on both crop yield and on weed biomass, (Wilson *et al.,* 1995). Future weed seed production can then be related to the predicted weed biomass. Similarly, competition models can be linked to population dynamics models to predict future weed populations and weed-crop competition scenarios based on given control levels (Lotz *et al.,* 1994). Models can then predict the dynamics and spread of weed patches. Even the characters that are likely to give the crop a competitive edge over the weeds can be determined using modelling studies (Lotz *et al.,* 1994). Competition models could also be used in intercrops to determine the best crop mixtures and planting arrangements for high yields and for weed suppression. The models also have the potential to simulate the growth of living mulches, and display the effect of different times of establishment, and management practices on crop and mulch development.

For practical use, models that predict yield loss need to be based on a parameter that can be readily measured early enough to be able to take remedial action. One approach has been to use early observations of the relative leaf area of weeds (Kropff *et al.,* 1995). The system has been validated in experiments with sugar beet in Finland, Italy, Netherlands and Spain, and with wheat in Canada, Denmark, Netherlands, Spain and the UK (Lotz *et al.,* 1996). The use of weed density alone was not successful in predicting yield loss in winter wheat (Ingle *et al.,* 1996; 1997) because weed species differ in their competitive ability. A system of crop equivalents based on the relative weights of weed and crop plants has been developed (Wilson, 1986). However, Wilson & Wright (1990) found that a competitive index derived from yield density relationships was more likely to reflect the competitive ability of a species. Relative ground cover assessment takes account of crop and weed vigour, and is easily measured in the field. Studies have shown though, that with such a subjective assessment individuals can differ in their perception of the relative area that the crop and weed occupy (Lutman *et al.,* 1996). Adequate training of recorders or mechanisation of the assessment method was recommended to reduce errors.

Limitations to the application of models in weed control strategies include a lack of basic biological information on the range of combinations of crop and weed species that can occur. For threshold weed management to be of long term value requires improved prediction of population dynamics. This can only be achieved with a better understanding of weed demography and population biology (Jordan, 1992). Another obstacle is the lack of validation in the field of the models and the effects that they predict (Paolini, 1996).

A combination of weed seed production, seed movement, seedling emergence and weed competition models would provide a powerful tool for making and testing decisions on weed management that would allow more effective strategies for control to be developed (Grundy & Turner, 2002). It would also highlight the problem areas, and the gaps in the data where more research was needed.

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APPENDIX

Standards for Organic Food and Farming * Section 3 Revision 9 January 1996

3.8 WEED CONTROL

3.801 Weed control must primarily be approached by adjustments in the management of the system, by giving attention to rotation design, manure management etc.

3.802 Recommended

1) Balanced rotations.
2) Varying weed suppressing with weed susceptible crops.
3) Composting manures and plant wastes.
4) Slurry aeration.
5) Hygiene - in the field and on machinery

3.803 Permitted

1) Pre-sowing cultivations.
2) Stale seed bed techniques.
3) Variety selection for vigour and weed suppression.
4) Pre-germination, propagation & transplanting.
5) High seed rates.
6) Under-sowing.
7) Utilisation of green manures.
8) Raised beds and no dig systems.
9) Mulches.
10) Mixed stocking & tight grazing.
11) Re-cleaned seed.
12) Pre-emergence and post-emergence mechanical operations (e.g. hoeing, harrowing, topping, hand weeding).
13) Pre-emergence and post-emergence flame weeding.
14) Plastic mulches.
15) Steam sterilisation - greenhouse soils only.

3.804 Prohibited

1) The use of any chemical and hormone herbicides, within the crop, at the edge of fields, within or below hedgerows, headlands and pathways on registered holdings.

*Taken from: **Standards for Organic Food and Farming**
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