A review of tillage and weed control

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Soil cultivation or tillage in its various forms has long been implemented to control weeds. The mouldboard plough is the traditional implement for burying weeds and crop residues as ground preparation for establishing a new crop (Lampkin, 1998). However, it is not just the cultivations associated with the post-harvest incorporation of crop and weed residue that have weed control benefits.

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). Annual grass weeds are more numerous on uncultivated and shallow cultivated land (Froud-Williams *et al.*, 1983). Perennial and windborne species are also more frequent on uncultivated plots as are certain biennial weeds. Annual dicotyledonous species are often more frequent on ploughed land and few persist in the absence of cultivation. The soil seedbank buffers the effect of different tillage practices on the weed flora at least in the short-term (Légère *et al.*, 2005).

The annual loss of seeds from a natural soil weed seedbank with no addition of fresh seed and no cultivation was 22% (Roberts & Dawkins, 1967). When the soil was cultivated twice a year the annual loss was 30%, and when cultivated four times it was 36%. However, like any other system there may be conflicts. Finer seedbeds produce more weed seedlings but a smooth surface makes direct weed control easier (Bleasdale & Roberts, 1960). Larger clods of soil produce fewer weed seedlings but the rough surface gives emerged weeds protection against direct weeding operations. Excessive cultivation though can also harm soil structure leading to capping of the soil surface and in the longer term to loss from erosion. The effect of ploughing on soil structure is largely dependent on the soil structure before ploughing (Coulomb, 1992). Running machinery on the land will compact the soil and destroy larger pores in the surface soil (Russell, 1966). The more frequently this happens and the wetter the soil, the greater the loss of pores. It also leaves an uneven surface that allows puddles to form in any depressions. Ploughing also creates clods that then require further cultivation to break down. A plough pan may be built up and need dealing with. Under reduced tillage there is better control of soil erosion, conservation of soil moisture and more efficient use of fossil fuel (Coolman & Hoyt, 1993). However, not all soils are suitable for reduced tillage. Less nitrogen may be made available to crops where cultivation is reduced to a minimum (Russell, 1966).

Modelling studies of soil physical structure on seedling emergence can help to optimise tillage and other soil management strategies (Guérif *et al.*, 2001). The effect of physical factors on crop residue decomposition can also be modelled. Residue particle size, position in the soil profile, soil moisture content, temperature and oxygen content are all important and need to be considered in defining model parameters.

Tillage can also affect the fauna in the soil. Some species of earthworm can withstand conventional tillage but deep burrowing and mineral soil dwelling species are favoured by conservation tillage (Rothwell *et al.*, 2005). Intense tillage can reduce earthworm populations due to reductions in food supply, damage to soil burrows and direct injury.

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 (reduced or minimal cultivation, conservation tillage, no-till, direct-drilling etc) systems of soil management. Machinery is now available that will work a stubble down to a seedbed in a single pass. 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. Nevertheless, ploughing has been used in the UK since before the Romans to deal with weeds and trash from the previous crop (Elliot *et al.*, 1977). It remains the basic tool of soil cultivation although changes to the design have made it more efficient. The introduction of the reversible plough in the 19th century was a major development. The substitution of the tractor for the horse in the 20th century allowed an increased number of furrows to be turned at each pass and the speed and depth of operations were also increased. But in recent years reduced cultivation systems that avoid the use of the plough have found favour with farmers.

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).

Working soil to a depth of 10 cm is expected to carry 20 to 40% of seeds to between 5 and 10 cm below the soil surface (Cussans, 1966). 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 mouldboard ploughing had taken place there was a uniform distribution of weed seeds in the top 19 cm of soil (Yenish *et al.*, 1992). In a comparison of cultivation regimes in corn and corn-soybean rotations over a 3 year period, the weed seeds in the top 10 cm of soil following non-tillage, chisel ploughing and moldboard ploughing represented 74, 59 and 43% of the total seeds respectively (Mulugeta & Stoltenberg, 1997). After a 7 year period under different tillage systems, the vertical distribution of weed seeds in the soil showed characteristic differences (Clements *et al.*, 1996). With the moldboard plough and ridge till systems there were 37% and 33% of seeds present in the surface 5 cm of soil. With the chisel plough and no-till system there were 61% and 74% of seeds present in the surface 5 cm layer. In other comparative studies, the moldboard plough moved surface seeds down into the soil as far as 32 cm (Staricka *et al.*, 1990). Around 10% remained within 4 cm of the soil surface. The chisel plough moved seeds down to a depth of 12 cm with around 50% remaining within the upper 4 cm of soil. Seedling emergence of fresh seeds was greater with the chisel plough. Emergence from previously buried seeds was greater after the moldboard plough.

Weed species favoured by minimum tillage include groundsel (*Senecio vulgaris*), shepherd's purse (*Capsella bursa-pastoris*), common chickweed (*Stellaria media*) and the mayweeds (*Matricaria* spp.). The mayweeds require light for germination. 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 (*Poa annua*), wild-oat (*Avena fatua*) and blackgrass (*Alopecurus myosuroides*) were all favoured by non-ploughing techniques. However, wild-oat is at a disadvantage if left on the soil surface and will persist longer if buried (Cussans, 1966). In experiments over 9 years using different primary cultivations in a vegetable crop rotation there was a pronounced effect on seed numbers of annual meadow grass (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). Barren brome (*Anisantha sterilis*) is said to be controlled almost completely by ploughing (Chancellor *et al.*, 1984). Perennial weeds are seriously affected by ploughing but often thrive under reduced tillage (Cussans, 1966). The perennial grasses common couch (*Elytrigia repens*) and black bent (*Agrostis gigantea*) show some growth modifications under minimum tillage. The rhizomes grow closer to the soil surface. Where a litter layer has built up the rhizomes may grow over the soil surface. The rhizome spread is generally slower in the compacted soil and patches remain more localized.

In a German long term study of different tillage systems in a 7-phase rotation, mouldboard ploughing resulted in less weed than when only chisel ploughing was carried out (Kainz *et al.*, 2005). The rotation was ley, potato, wheat, sunflowers, ley, wheat and rye. Weeds, especially grasses, caused severe competition with the crops especially following the ley. A system where ploughing followed a ley and chisel ploughing followed potatoes and sunflowers was a sustainable compromise that reduced the expenditure on tillage and improved profit margins. Earthworm activity and abundance was greater in the absence of ploughing. 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, common couch (*Elytrigia 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 or planting. Typically it involves disking or harrowing to a depth of 10 cm. The cutting and mixing action of the disk harrow depends on the diameter, weight and concavity of the blades (Bowman, 1997). Rotovators and power harrows are also used and are able to prepare seedbeds even when ploughing has not been carried out. Implements are available that can combine shallow seedbed preparations with some deeper cultivations in a single pass (Lampkin, 1998). Others can loosen the soil below the surface while leaving the preceding crop debris on the soil surface.

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 (*A. 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). In spring-sown cereals, sowing date affects the composition of the weed flora (Milberg *et al.,* 2001).

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. It 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). The false seedbed technique involves a second shallow cultivation to kill the weeds after they emerge. The second cultivation often creates the true seedbed. The stale seedbed technique involves killing the weeds by methods such as flame weeding that do not disturb the soil surface. Punch planting makes use of the stale seedbed technique but minimises soil disturbance further by dropping the seed into holes made by a dibber (Rasmussen, 2003). Delaying sowing extends the stale seedbed effect.

When soil 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 over time. 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. In a study of the behaviour of weed seeds in soil clods of different sizes, less germination in large clods was followed by lower emergence of weed seedlings (Terpstra, 1986). Leaving a rough seedbed will therefore result in fewer weeds emerging in the crop. Lack of light and depth of incorporation in the clods are the main factors that affect germination and emergence. The effect is more noticeable with species having small seeds.

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 the 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 was considered only recently to be of practical importance (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 (1996) found that night time cultivation could reduce weed numbers by 25% compared with daytime cultivation. However, no difference was found between one-time harrowed plots and twice-harrowed plots. 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. Daytime cultivation with a moldboard plough stimulated weed seedling emergence 200% greater than night-time ploughing (Botto *et al.*, 1998). However, when a chisel plough was used weed emergence was much greater overall and there was no difference between night and daytime cultivations. Covering soil with opaque material immediately after cultivation or leaving it exposed to light made no difference to weed emergence suggesting that it is the exposure to light during cultivation that is important.

There are several reasons why cultivation in the dark does not give consistent results. There is some evidence that exposure of imbibed seeds to periods of chilling and warming can affect their light sensitivity (Hartmann & Mollwo, 2000). 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 (*Stellaria media*) and fat-hen (*Chenopodium album*) was reduced by cultivating in darkness but that of blackgrass (*A. myosuroides*) was unaffected. In addition, some light sensitive species like the mayweeds (*Matricaria* spp.) 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.

Light penetration into the soil surface depends on soil density, particle size and moisture content (Baumgartner, 1953). Reflection depends on the darkness of the soil and this is influenced by moisture. The soil may filter the light and alter the spectrum. Generally light does not penetrate through soil particles only through the pores by reflection off the particles. The bigger the particles, the bigger the pores and the deeper the light will penetrate. Only about 1% of light penetrates up to 6-8 times the particle diameter. The least light penetration is in clay soil. The results of experiments comparing the effect of cultivation in the light and in the dark on seedling emergence are dependent on cultivation intensity and the choice of implement (Jensen, 1995). Prolonged exposure to moonlight or even starlight may be sufficient to stimulate the germination of light sensitive seeds (Hartmann *et al*., 1998). In this case the effectiveness of night time tillage will depend on the sensitivity of seeds in the soil seedbank.

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 (Ascard, 1993; 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 elsewhere in the 'organicweeds' website under mechanical weed control.

Other tillage opportunities

Ridge tillage, first investigated in the 1950's, does not require primary tillage (Regnier & Janke, 1990). At planting, the soil, crop residue, weeds and freshly shed seeds are scraped off the top of ridges formed the previous season and moved into the furrows. The soil exposed on the decapitated ridges provides a weed and residue free seedbed. Inter-row cultivation and re-ridging control the weeds in the developing crop. Permanent ridges are used in north America for widely-spaced crops on medium to heavy soils where non-inversion tillage is practiced (Cloutier *et al.*, 2007). In general, the regular soil movement stimulates seed losses through germination (Forcella & Lindstrom, 1988). However, more seeds were present in the soil seedbank after 7-8 years of continuous corn grown under ridge tillage than in conventional tillage (Forcella & Lindstrom, 1988b). This was due to late-emerging weeds, stimulated by summer cultivations, setting seeds before crop harvest.

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 movement and 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 induce dormancy and cause problems in later cropping sequences (Rauber, 1986). Post-harvest cultivation made 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, barren brome (*A. sterilis*) 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.

Early, shallow stubble cultivation a few days after cereal harvest has been shown to reduce weed seed numbers in the soil but has little effect on the emerged annual weed population in the crop that follows (Pekrun & Claupein, 2006). However, when followed by deep ploughing in the autumn there is a reduction in perennial weed populations compared with leaving the stubble untouched. Early stubble cultivation is not beneficial in reducing volunteer crop seeds.

While stubble cleaning may not be appropriate for dealing with the shed seeds of some weed species it can be an effective way of controlling certain important weeds including charlock (*Sinapis arvensis*), common chickweed (*S. media*), groundsel (*Senecio vulgaris*), wild radish (*Raphanus raphanistrum*), shepherd's purse (*Capsella bursa*-pastoris) and some speedwells (*Veronica* spp.). The surface soil should be cultivated to a depth of not more than 2 inches and this operation repeated at 14 day intervals. Some farmers take this a stage further and prepare a seedbed at this time but leave it unsown until spring. The land is cultivated at regular intervals to deal with seedling weeds and then ploughed after Christmas in preparation for spring cropping. Weeds controlled by 'autumn cleaning' include blackgrass (*A. myosuroides*) and charlock (*S. arvensis*). Nutrient leaching is likely to be a problem in soil left bare over winter.

Where there is a 2-4 week period in the autumn between the harvesting of one crop and drilling of the next, there is an opportunity for early tillage operations to stimulate weed emergence and for those weeds to be controlled mechanically before final seedbed preparation (Jensen, 1996). Success is dependant on climatic conditions. In dry conditions the burial of shed cereal grains can induce dormancy in them causing volunteer weed problems in later cropping sequences.

Cultivation as soon as practicable after harvest is also recommended for the control of rhizomatous grass weeds such as common couch (*E. repens*) and black bent (*Agrostis gigantea*). 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.

Post-harvest operations that lead up to establishment of a following crop can influence the movement of freshly seeds and other propagules on or in the soil, as well as those already there. Experiments using plastic beads or dyed cereal grains have shown that blench harrowing moves seeds horizontally 1.1 to 2.38 m, a tine cultivation 1.26 to 1.84 m, ploughing 0.23 to 1.02 m and drilling a mean of 0.27 m (Marshall & Brain, 1999). There was more lateral spread of the seeds with the tines than the other implements.

Fallowing

Fallowing has been shown to reduce perennial weeds within a rotation (Hintzsche & Wittmann, 1992). The aim is to kill the vegetative organs of the weeds by mechanical damage and desiccation. For a full or bare fallow, heavy land is ploughed in April to give the weeds time to start into growth. It is cultivated or cross ploughed 10-14 days later to produce a cloddy tilth. The soil is cultivated or ploughed at frequent intervals to move the clods around and dry them out. By August the clods should have broken down and the soil is left to allow the weed seeds to germinate. In September/October the weeds are ploughed in and the land prepared for autumn cropping. If a cereal is to follow the fallow, wheat bulb fly may be a problem because it lays eggs on bare ground in July. This can be overcome by sowing a green manure such as mustard to cover the land during this period. Although there is the benefit of a reduction in weed the control requirements in subsequent crops after an effective fallow, the economics of taking land out of production for a full year together with undesirable effects on the soil and the environment, make the use of a bare fallow unlikely for weed control in the organic system (Lampkin, 1990). There is no financial return during the fallow period while labour costs accumulate during the fallowing operations. As an alternative to fallowing, cleaning crops such as potatoes and turnips allow repeated hoeing for weed control but are not suited to heavy land.

Tillage for a season in the absence of a crop is sometimes referred to as a black fallow (Nalewaja, 1999). Fallowing the land for part of the growing season as a bastard or summer fallow can be as effective as a full fallow, is more suitable for lighter land 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 conditions are essential. Ploughing begins in June/July allowing time for an early crop to precede it. A bastard fallow is often used after a ley to reduce perennial weeds before sowing a winter cereal. There is also an opportunity for birds to feed on wireworms exposed during soil disturbance.

A similar effect to that of fallowing can be achieved with rapidly developing crops like radish (*Raphanus sativus*) 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).

Non-ploughing systems

The cost of ploughing on heavier land can be a significant part of establishment costs (Gibbard *et al.,* 1989). Shallow cultivations are less expensive and faster to carry out. However, the adoption of minimum tillage in the 1970’s relied on herbicides to maintain weed control. The ultimate in reduced cultivations is no-till or zero tillage usually relies on the use of broad-spectrum contact herbicides to deal with the weeds (Frye & Lindwall, 1986). Organic growers may therefore appear unable to practice energy-saving, non-inversion tillage (Rasmussen & Ascard, 1995). However, in the UK there have been promising results in terms of soil improvements from organic zero-tillage (Zarb, 2002). With zero tillage there is a build-up of plant residues on the soil surface that may have benefits for soil and moisture conservation. There may be an effect on soil temperature that could delay crop germination and early growth. The residues will also have affect weed emergence through the effect on soil temperature, moisture and light penetration (Légère *et al.*, 2007). The crop residues may have an allelopathic effect and may reduce soil fertility, at least initially. The use of allelopathic cover crops in reduced tillage systems may provide additional weed control benefits. Winter rye grown to increase soil organic matter and protect the soil leaves a residue able to reduce weed biomass by over 60% (Barnes & Putnam, 1983). The effect of the build-up of crop residues on pests and diseases is not known but there are thought to be benefits.

Non-ploughing systems range from shallow cultivations with discs or tines to direct-drilling into the stubble or mulched remains of the preceding crop. Heavy-duty tines may be needed to break up stubble and avoid ploughing before drilling the next arable crop. Speed and depth of cultivation will have a major effect. The results also depend on soil and weather conditions (Measures, 2004). Many find it impossible to dispense with the plough routinely. In addition to the effect on weeds and weed control, the use of reduced cultivations may have implications for disease and pest control, and for nutrient cycling (Lampkin, 1998). Even where there is no tillage, drilling and natural weathering will cause some soil disturbance (Cussans, 1966). There will also be soil and weed seed movement due to earthworms. It is important to maintain a flexible approach based on crop, soil and weeds.

Minimum cultivation techniques have been developed based on permanent raised beds (Zarb, 2002). Narrow beds are used that are the same width as the machinery to limit soil compaction.

Ploughing is not suitable for semi-arid prairie soils in North America due to the risk of wind erosion (Cloutier *et al.*, 2007). The aim of non-inversion tillage is to prepare a rough seedbed and maintain crop residues in the upper layers of soil. Wide blade (1.5–2.0 m) cultivators that operate at 7 cm deep were developed for these conditions in the 1930's but required a powerful tractor and did not control weeds in wet conditions. Many growers now use field cultivators and rod weeders. A tine harrow weeder is used for post-emergence weed control

The punch planting technique minimises soil disturbance prior to crop sowing (Rasmussen, 2003). After autumn ploughing the land is harrowed in April and may or may not be worked down again to a finer tilth. The crop seed is dropped into holes made with a mechanical dibber. The area is flame weeded just prior to crop emergence in much the same way as for a stale seedbed.

A 2-year cultivation strategy has been developed in combination with non-inversion tillage (Melander, 1999; Melander & Rasmussen, 2000). In year 1, the inter-rows of a cereal crop are kept weed free with repeated use of a tractor-hoe that also stimulates seed germination and reduces the weed seedbank. In year 2, row crops are sown where the previous inter-rows had been while the previously cropped strips become the new inter-rows and are cultivated accordingly.

Specialised drilling equipment is needed to cut through the crop residues and precision drilling may be impossible. Crop harvesting may also be more difficult. In the USA a subsurface tiller-transplanter has been developed that makes transplanting vegetables directly into plant residues possible (Giacchetti, 1997). It cuts through the surface residue and opens the soil allowing transplants to be dropped in. It can also be used where a cover crop has been grown and cut down.

In the past it was thought that ploughing left a layer of slowly decaying vegetation at plough depth while discing incorporated vegetation in a way that maintained soil structure (Faulkner, 1945). The organic matter helps to absorb rainfall, retains that soil moisture for plant use and prevents run off and leaching. It also aids capillary action to bring moisture to the upper soil layers in dry conditions. A dense mat of vegetation at ploughing depth may hinder capillary action.

Effect on the weed flora

In comparisons between ploughed and reduced cultivation treatments, there were consistently 3 to 6 times more broad-leaved weeds in the ploughed plots (Cussans, 1966). Reduced cultivations in cereals do not necessarily reduce overall weed biomass but can alter the relative importance of individual weed species (Froud-Williams *et al*., 1981). Certain broad-leaved weeds increase in importance including groundsel (*S. vulgaris*), shepherd's purse (*C. bursa-pastoris*), parsley piert (*Aphanes arvensis*) and the mayweeds (*Matricaria* spp.). Knotgrass (*Polygonum aviculare*) and fat-hen (*C. album*) may become the dominant species according to some authors but others have found that fat-hen and annual *Polygonum* spp. decrease in the absence of cultivation (Tuesca *et al.,* 2001). Many species show no response to changes in cultivation regimes including common poppy (*Papaver rhoeas*), common field-speedwell (*Veronica persica*) and scarlet pimpernel (*Anagallis arvensis*). In 2 cycles of a maize/soyabean rotation in Canada, unsprayed no-till treatments had a much greater total weed density than unsprayed moldboard, chisel plough or ridge tillage treatments (Benoit *et al.,* 1991). More perennial weed species were observed in the no-till treatment.

There is usually an increase in annual grass weeds and the decline of some broad-leaved annual weed with reduced cultivations (Froud-Williams *et al*., 1981; Tuesca *et al.,* 2001). This is exacerbated where a monoculture of cereals is practiced (Cussans, 1976). The early sowing of winter cereals associated with minimal cultivations and the use of tine cultivations has favoured blackgrass (*A. myosuroides*). Fat-hen (*C. album*) though tends to be less of a problem in minimum cultivations possibly because there is a greater loss of seeds on the soil surface due to predation and post-germination losses. It has been suggested that wild oat would be less persistent under no-till where seeds were left on the soil surface open to predation and post-germination mortality (Miller & Nalewaja, 1990).

The long-term decline of seed reserves in soil will be less in the absence of cultivations (Froud-Williams *et al*., 1981). The response of the weed flora to reduced cultivations may depend on the balance between the buried seed reserves and freshly shed seed. Changes in the soil structure may also influence the species composition by affecting seed germination and seedling establishment. The importance of seed-soil contact is well known. Differences in cultivations may affect moisture retention and temperature fluctuations in soil as well as altering the microtipography. This may have a differential effect on species with seeds of different shapes, sizes and seed-coat characteristics. Seeds with rough or mucilaginous seed coats may be better able to germinate in drier conditions. Seeds with a light requirement may also benefit from reduced cultivations.

Tillage systems that cause the least soil disturbance have been shown to build-up a larger and more diverse weed seedbank (Feldman *et al.,* 1997). In a 3-year study in continuous wheat, conventional tillage with a mouldboard plough gave the lowest seed density and there was no difference between the 0-5 cm and 5-10 cm layers of soil. No-tillage gave a denser seed bank especially in the upper layer of soil. Chisel plough and double-disk harrow systems gave intermediate results. The changes in the seedbank occurred over a relatively short period of cropping. The build-up of stubble debris at the soil surface under chisel plough and no-till systems gave shed seeds some protection from predation. In a 6-year study of cultural practices on weed seed numbers and distribution in the soil seedbank, there was a greater number of seeds in the upper 5 cm layer of soil in no-till treatments and fewer under conventional tillage (Hoffman *et al.,* 1998). In this study, total weed seed number in soil was not influenced by tillage due to the increased demise of seeds on the soil surface and the greater persistence of seeds buried by ploughing. However, this was influenced by the greater seedling emergence under no-till that could potentially result in greater seed deposition. It is therefore important to prevent seeding in no-till crop management.

Species that increase vegetatively will also benefit, and there is evidence that perennial species increase in the absence of cultivations (Froud-Williams *et al*., 1981; Cussans, 1976). Common couch (*E. repens*) is one of the main species to benefit. Others include onion couch (*Arrhenatherum elatius*), creeping thistle (*Cirsium arvense*), field bindweed (*Convolvulus arvensis*) and the docks (*Rumex* spp.). Biennial species that are normally not adapted to cultivated land may increased if cultivation is less vigorous. Wind-borne seeds are opportunistic colonisers of reduced cultivation situations and these also include some perennials for example perennial sow-thistle (*Sonchus arvensis*), mugwort (*Artemisia vulgaris*), coltsfoot (*Tussilago farfara*), willow herbs (*Epilobium* spp.), ragwort (*Senecio jacobaea*) and dandelion (*Taraxacum* spp.). Annual species such as Canadian fleabane (*Conyza canadensis*), wild lettuce (*Lactuca* spp.) and smooth sowthistle (*Sonchus oleraceus*) can become a problem (Tuesca *et al.,* 2001). Stubbles left after harvest will attract seed and fruit eating birds that will increase seed predation but could also increase seed dispersal in bird droppings. Seedlings of black nightshade and elder for example may become more common. In reduced cultivation systems, seed shedding by crops at harvest may result in an increase in volunteer weeds. Many of the current annual weeds were introduced originally as seed contaminants and are not adapted to dispersal other than by the action of man, and it is these species that may decline under reduced cultivations.

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