POSTER SESSION 9C

ORGANIC FARMING: NEW SOLUTIONS TO OLD PROBLEMS

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Organic weed control – back to the future

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ABSTRACT

Some of the current and potential future options in cultural and direct weed control for organic growers are outlined. It is recognised that no single non-chemical technique is as effective as the application of the best selective herbicide. However, the aim is not total eradication but a balance between the weeds and the crop. Cultural measures are needed to maintain weeds at a manageable level for the direct non-chemical control methods to succeed in preventing yield loss. As yet untapped knowledge of weed biology could help to manipulate the equilibrium in favour of the crop.

INTRODUCTION

Weed populations often increase rapidly during the early stages of conversion to organic growing (Albrecht & Sommer, 1998), although, there is evidence that the population stabilises eventually (Davies *et al.,* 1997). Weed control in organic farming systems was reviewed by Rasmussen & Ascard (1995) and by Bond & Grundy (1998). Weed management strategies involve the whole cropping system with cultural measures providing a form of residual control. An integrated approach is needed because at high weed densities even the most effective non-chemical techniques are likely to leave sufficient weeds to reduce crop yield (Rasmussen, 1993). The aim is to maintain weeds at a manageable level by cultural means to ensure direct control measures can succeed in preventing crop losses. The different elements of organic weed control could be improved through better use of the accumulated knowledge of weed biology.

CULTURAL WEED CONTROL

Soil cultivation has long been utilised to control weeds. The method, depth, timing and frequency of cultivation can provide a way of manipulating weed populations, although there may be conflicting requirements. Large clods of soil produce fewer weed seedlings but the rough surface protects weeds against direct weeding methods. Fine seedbeds produce more weed seedlings but the flatter surface improves subsequent weed control measures. The primary choice is whether to plough or not. It is often said that ploughing is needed only to bury weeds. Under reduced tillage there is less risk of soil erosion, greater conservation of moisture and more efficient energy use (Coolman & Hoyt, 1993). Weed problems may increase though, and there has been much research comparing the merits of ploughing with reduced tillage systems for weed management (Forcella & Burnside, 1994).

It is known that careful timing of the cultivations involved in seedbed preparation can help to reduce subsequent weed emergence. Traditional methods of weed control include the preparation of a stale seedbed to flush out germinable weed seeds prior to crop establishment, and reduce later weed emergence. If temperatures are favourable, the main factor determining the timing of a weed flush is adequate soil moisture (Bond & Baker, 1990). Once the flush of emergence has passed, the weeds can be controlled by flaming or shallow cultivation. It is important not to cultivate below the top 1-2 cm soil otherwise a further flush of weeds may emerge (Blake, 1990). A stale seedbed can be effective but growers may be unable to prepare one under unfavourable conditions and reluctant to delay cropping if growing conditions are good.

Another way of reducing weed emergence is to prepare seedbeds in the dark to avoid stimulating seed germination. It is well known that exposure of buried weed seeds to light promotes seedling emergence, but it has only been considered to be of practical use recently (Hartmann & Nezadal, 1990). Shielding implements to prevent light reaching the soil at the point of cultivation avoids the need to work in darkness (Börjesdotter, 1994). Alternatively, guidance systems may facilitate operations performed at night (Zuydam *et al.*, 1995). The technique has been shown to reduce weed emergence by up to 70% but it is often much less effective because the seeds of some species are not sensitive to light or lose their light requirement with age (Börjesdotter, 1994). Seeds at or near the soil surface will receive sufficient light to germinate anyway.

Crop rotation is a requirement of organic farming practice, to aid pest and disease control and provide optimum soil fertility. It also offers opportunities for including the different approaches to weed control in terms of timing, frequency, machinery etc. that are needed to prevent any one weed species becoming dominant. In the past, weed control was achieved primarily by a combination of crop rotation and cultural measures, but it is not simply a question of returning to those earlier ways. Fallowing was used to reduce perennial weeds within the rotation, however, taking land out of production for a full fallow is not favoured in the organic system (Lampkin, 1990). A fallow over part of the growing season may be just as effective and can be fitted into most rotations (Blake, 1990). Crop choice or a ley period in the rotation may permit the reduction of weed populations through crop competition. A description of the suppression of weeds by crops is given elsewhere (Grundy *et al.*, 1999).

Efficient harvesting is critical to prevent weed seed dispersal. Crop propagules lost during harvesting can become weeds too, for example oilseed rape seed and potato tubers. In cereals, the reintroduction and spread of seeds depends on the type of combine harvester (Cousens & Mortimer, 1995). Modification of combine harvesters to avoid returning weed seeds to soil was recommended in a report by Patterson & Bufton (1986). The timing of post-harvest cultivations may help to limit the persistence of freshly shed weed and crop seed. Cultivation soon after seed shedding can instil a light requirement in oilseed rape seed, inducing dormancy and persistence (Pekrun *et al.*, 1995). Unfortunately not all species respond in the same way, and sterile brome (*Bromus sterilis*) seed remaining on the soil surface will persist longer than seed buried soon after shedding (Peters *et al.*, 1993).

Regardless of how well weeds are managed within a field, many mechanisms offer the means of introducing additional weed seeds and potential new species (Cousens & Mortimer, 1995). Contaminated crop seed has been a major source of weed seeds and the decline of formerly common weeds such as corncockle (*Agrostemma githago*) can be attributed directly to improved seed cleaning (Salisbury, 1961). But crop seed continues to be an important agency for the spread of weeds (Don, 1997). Organic seed crops are likely to have greater potential for weed seed contamination than those grown conventionally. Also, despite the possible risks, there are significant attractions for organic growers in using home-saved seed including cost savings, availability and adaptation to local conditions (Wibberley, 1989). Seed raised in other countries, provides a route for the introduction of weeds from a different genetic background and of alien species that may multiply to become a future weed problem (Williamson & Fitter, 1996). Soil improvers, manures and mulches are other potential sources of weed seed contamination in organic systems.

DIRECT WEED CONTROL

Weeds differ from many pests and diseases in that controlling them by direct physical means is a practical option. For example, Jones *et al.*,(1996) found the most effective mechanical treatment for controlling seedling weeds was burial to 1 cm depth or cutting at the soil surface. Research and development have followed both traditional and novel directions based in particular on mechanical and thermal methods of control, and the use of mulches.

Mechanical weed control

Whatever the farming system, there may be times when simple hand-roguing of the odd plant or patch of weed can prevent weed build-up. Hand-weeding after mechanical inter-row weeding can also deal with weeds remaining in the crop row (Ionescu *et al.*,1996), but labour is often limited. The ergonomics and efficiency of hand weeding tools have been evaluated mainly for use in developing countries (Chatizwa, 1997).

Developments in mechanical weed control were reviewed by Rasmussen (1996). Chain harrows bury the weeds but do not uproot them and are most effective against seedlings of annual weeds. Blind harrowing may be carried out after drilling but before crop emergence to kill the first flush of weeds (Lampkin, 1990). Tine weeders, with rigid or spring-loaded tines, are considered less damaging to the crop than chain weeders, burying weed seedlings under loose soil without pulling up cereal plants that are beyond the 3-leaf stage. Finger weeders have flexible tines that act selectively at the late tillering stage of cereals when the crop foliage forces the tines into the inter-row (Rasmussen, 1994). The ground driven rolling cultivator used inter-row, usually has two ground driven 'star' or 'spider tine' rotors covering each row (Pullen & Cowell, 1997). The angle of the rotors can be set to move soil away from the crop, or to ridge up the crop and bury small inter-row weeds. The timing and frequency of harrowing can affect the weeds and the crop (Rasmussen & Svenningsen, 1995). A model to describe crop yield response to harrowing has been developed for cereals (Rasmussen, 1991). Variables take into account crop damage, weed density and weed reduction. 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 using a model that describes the relationship between soil covering and weed control (Rasmussen, 1992).

Hoeing is particularly effective against mature weeds. Tractor steerage hoes cut through the soil at 2-4 cm depth. Increasing the working depth did little to improve weed kill, but higher forward speed increased soil covering of weeds (Pullen & Cowell, 1997). Implements may incorporate ridging bodies to bury weeds along the row with a band of loose soil (Baumann & Slembrouck, 1994), giving a measure of intra-row weed control. The powered rotary hoe is fitted with rotating blades on a horizontal axle and can be adjusted to different row spacings for inter-row weeding (Pullen & Cowell, 1997).

The brush weeder has nylon brushes that rotate and brush the weeds out and onto the soil surface. Two main types have been developed, those with disc brushes operating in the vertical plane, and those with circular brushes operating in the horizontal plane. In the former, brush width and position on the drive shaft can be adjusted to different row spacings. In the latter, the brushes can be angled and the direction of rotation altered to move soil away from or earth up the crop row (Steele, 1997). Tractor speed, brush velocity and soil conditions interact to determine the working depth which is important for ensuring good weed control (Weber & Meyer, 1993). The brush hoe worked closer to the crop row than a conventional hoe and operated in moister soils, but the steerage hoe worked better in dry conditions (Pedersen, 1990).

Flail, rotary and reciprocating knife mowers have been used to control perennial broad-leaved weeds but the timing and frequency of cutting is critical (Aquilina & Clarke, 1994). Weeds that are taller than the crop may be 'topped' to prevent them seeding. A rape swather, with the cutter bar set above crop height, has been used as an alternative to hand roguing of wild oat (*Avena fatua*) in cereals (Steele, 1997). Strimmers have the potential to trim off weeds overall before crop emergence, or from the inter-rows after crop emergence without soil disturbance. A prototype string strimmer has been developed that can be used on four rows at a time (Cooke, 1997). Alternatives methods of cutting, beating and defoliating weeds have been tested (Nawroth & Estler, 1996).

To protect crop plants from mechanical damage during inter-row weeding shields can be fitted, but poor machine guidance can still remove a significant number of crop plants. A self-steering mechanism, or a second operator can be employed to improve guidance. More complex systems under development use image analysis to find and follow the crop rows (Marchant, 1996). A prototype driverless system has been developed that can operate completely automatically (Williams, 1996), but the costs involved in precision weeding suggest it may only be economic in high value crops.

Thermal weed control

Current methods of thermal weeding use a variety of energy sources to generate the heat needed to kill weed seeds and seedlings. While some flame weeders remain relatively crude, other machinery has been developed to a high level of sophistication. The main fuel is propane but renewable alternatives such as hydrogen have also been evaluated (Andersen, 1997). A brief wave of intense heat ruptures exposed plant cells but a second flaming may be needed to kill the underlying tissues. For best results, flaming requires a level soil surface. Flame weeders can be used to kill weed seedlings before the crop emerges. Once the crop has emerged, angling or shielding the burners may allow inter-row weeding, or the dose may be adjusted to a level that the crop will tolerate (Morelle, 1993). Certain crops, like onions, are tolerant of post-emergence flaming (Ascard, 1990). Models have been developed that describe the response of different plants to flame weeding (Ascard, 1995).

There have been many studies to determine the optimum design of flame weeders (Bertram, 1994; Storeheier, 1994). The results suggest that shielding design is critical to keep combustion gases close to the ground for as long as possible. Thermal weeders have been developed with burners that heat ceramic and metal surfaces to produce infrared radiation (IR) that is directed at weeds in a closely defined area (Lampkin, 1990). The IR panels need time to heat up, are more sensitive to mechanical damage and may not generate such high temperatures as standard flame weeders (Ascard, 1998).

Thermal methods are also used to partially sterilise soil and kill any weed seeds or seedlings present. Mobile steaming equipment is available that allows steam sterilisation in the field. Under present organic guidelines, steam sterilisation is only allowed in greenhouse situations but field steaming of the surface layer of soil may prove acceptable and effective. Weeds may be killed directly using steam, and the machinery is available for amenity use (Lilburne, 1997).

Solarization relies on solar energy to heat field soil under clear plastic sheeting to temperatures high enough to kill weed seeds (> 65 °C) (Horowitz *et al.*, 1983). It takes around six weeks and requires a climate with long periods of clear skies and sunshine. In the UK, weed development may be enhanced rather than impeded under clear plastic covers (Bond & Burch, 1989). The temperature under the covers depends on the light transmittance characteristics of the plastic (Horowitz *et al.*, 1983; Majek & Neary, 1991). Adjustment of the light transmitting quality could allow greater conversion of the solar radiation to heat at low light levels.

Mulching

Mulching the soil surface with a living ground cover, loose particles of organic or inorganic matter, and sheets of woven or non-woven material can physically suppress weed seedling emergence. Residues from preceding crops can be used as a mulch, but phytotoxins may be released from the decomposing plant materials. The high cost makes mulching economic only for high value or long-term crops (Runham & Town, 1995) unless it has another purpose such as to reduce pest problems (Costello & Altieri, 1994; Bottenberg *et al.*, 1997). Sheeted mulches may be laid for many months to clear unwanted vegetation (Lennartsson, 1990), or for just a few weeks to reduce weed emergence before crop planting (Davies, 1995).

Living mulches are well suited to use in perennial crops such as fruit, however, even in established orchards a living mulch along the tree row may depress crop growth (Domange, 1993). It is important to make the correct choice of living mulch (Ingels *et al.*, 1994). In vegetable crops, many factors limit the use of living mulches to suppress weeds (Müller-Schärer & Potts, 1991). Yield loss in transplanted cabbage due to competition with the living mulch was recorded by Bottenberg *et al.*, (1997) but timely mowing can avoid competition (Costello & Altieri, 1994). Annual weeds would themselves form a natural ground cover if managed properly (Anaya *et al.*, 1988). Loose materials can provide effective weed control but the depth of mulch needed to suppress weed emergence may make transport costs prohibitive. Seeds present in the mulch itself can be a problem, particularly in crop materials like straw where cereal grains are common.

Black polyethylene sheeting is widely used for weed control in organic and conventional systems. Various colours in woven and non-woven materials 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 films prevented weed emergence. Plastic films that filter out photosynthetically active radiation but let through infra red light to warm the soil have been shown to control weeds (Majek & Neary, 1991). Disposal may be a problem with plastic and other durable mulches. 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).

WEED BIOLOGY

There is a view that only research conducted within a wholly organic system is of significance to organic farmers (Marland, 1989), but knowledge of weed biology can benefit all growers. Despite the wealth of information, Norris (1992) concluded that weed biology had done little to improve weed management over the last 50 years. In surveys of weed scientists in the UK (Moss, 1994) and US (Norris, 1997), however, the contribution of weed biology to weed management was rated as substantial to high.

There have been many studies of weed competition in arable and horticultural crops world wide since Tull (1762), described placing sticks in cereal crops to show that it was more than just the physical presence of weeds that reduced crop yield. But there has been criticism that little practical use has been made of the majority of the information (Cousens, 1992). One aim has been to identify the threshold level when control measures become economic (Orson, 1990). Thresholds are normally associated with herbicide application, but the same principle could be applied to non-chemical treatments. It has often been reported that mechanical weeding treatments in arable crops have reduced weeds but there has been no increase in crop yield (Rasmussen & Svenningsen, 1995). However, the threshold concept may not provide a basis for the rational use of weed control measures in the organic system. A low weed population may not merit control for a limited yield gain but in terms of likely seed return and future weed problems, weed control is usually justified in organic crops. With some crops, the timing of weed removal is more important (Turner *et al.*,1999) but this depends on the pattern of weed emergence.

Attempts have been made to exploit knowledge of the weed seedbank and predict weed seedling emergence (Forcella, 1992). In arable soil, the weed seedbank may vary in density from zero to more than one million seeds m^{-2} within the ploughed layer. There may be many species represented but generally a few dominant species comprise 70-90% of the total seedbank. Recent studies on the seedbanks of organic systems have been reported by Albrecht & Sommer, (1998). Studies of weed seeds put in different soil layers have provided data for modelling the emergence of a range of weed species (Grundy *et al.*, 1996; Grundy & Mead, 1998). Horizontal movement of soil is important for the dispersal and spread of weeds (Rew & Cussans, 1997), but the depth to which the implements move seeds in the soil controls seedling emergence. Few studies have quantified the vertical distribution of seeds during cultivation, yet this is an important factor in determining weediness (Cousens & Moss, 1990). Data on the vertical movement of plastic beads during soil cultivation, has been used to model the movement of seeds in soil profile (Mead *et al.*, 1998). Models of seed movement and seedling emergence linked with models of crop-weed competition could form the basis of a weed management decision support system for organic growers.

CONCLUSIONS

In organic systems, current direct weeding methods alone are insufficient to control weeds effectively. It is important that growers make full use of cultural methods to keep weeds at a manageable level to avoid the increase in weed numbers that can follow conversion to organic growing. Although, the range and efficiency of non-chemical weeding techniques is improving, it would be unwise to rely upon even the most effective non-chemical technique alone. The result could be a change in the weed population in the same way that repeated use of a particular herbicide would favour tolerant weed species. Weed scientists need to assist growers in applying and building upon the knowledge of weed biology to formulate more effective weed control strategies for long term weed management. Economics and labour availability may be over-riding factors in the choice of weeding system, but crop, weed flora and soil type are important too (Lampkin, 1990). Relatively expensive control methods should not be dismissed because they are uneconomic in large acreage arable crops. Different techniques are appropriate for different crops, and success depends on matching up the weed control and cropping strategies.

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Options for organic weed control – what farmers do

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ABSTRACT

Weed management is a crucially important component of organic cropping systems. A postal survey was conducted to ascertain what techniques farmers currently use for weed management,. The questionnaire was sent to selected registered organic farmers in south-east England, north-east Scotland and south-west Wales. All farmers used a range of measures for weed management but none used biological control. The specific techniques used were related to the crop being grown and the weed species present. Most farmers rated their weed management as generally effective, none thought it was poor, but few thought it to be very effective. This highlights the need to develop more effective weed management techniques if this perceived barrier to conversion to organic systems of production is to be removed.

INTRODUCTION

The inability to use chemical control methods is perceived by many farmers using conventional production systems as a barrier to conversion to organic systems (e.g. Peacock, 1990; Yarham & Turner, 1992). Additionally, Davies *et al.*, (1997) showed that weeds and the weed seed bank increased during the conversion from conventional to organic farming. Nevertheless increasing numbers of farmers are accepting the challenge of converting to organic status. In a recent survey of organic farmers in USA, the respondents identified weed management as their top research priority (OFRF, 1998). This indicates both the importance of weeds in reducing crop yield (and quality) and the interest in developing new weed management techniques.

The long-term nature of weed infestations is due to the longevity of individual weed seeds in the soil seed bank. Techniques to reduce the size of the weed seed bank include stale seedbed preparation and repeated cultivation. It is important that any weeds that do grow in the crop must be prevented from producing seed which replenishes the weed seed bank in the soil. In organic systems, this long-term view is at least as important as that of reducing yield losses from current weed competition. The use of clean seed becomes crucially important to avoid sowing new seeds along with the crop into the good seedbed which has been created. This postal survey sought information from organic farmers in three regions of UK on the range of techniques and measures they incorporated into their weed management programmes.

MATERIALS AND METHODS

A questionnaire was designed for a postal survey of organic farmers. It sought information on the farm background (including total and organic area, soil type and crops grown) together with a more detailed section eliciting responses on the farmers' main perceived weed problems and the organic control techniques implemented on the unit.

The questionnaire was posted to registered organic farmers in three areas of the UK: south-east England, north-east Scotland and south-west Wales. A copy of the questionnaire was sent to thirty farms in each area which were chosen randomly from the Soil Association Regional Lists with no restriction to crop types. If there was no response within two months then a further copy was sent.

The completed questionnaires were statistically analysed, mainly using the chi-squared test to compare the frequency of observations which fell into specific categories and the association between particular responses. Because the chi-squared test only produces reliable estimates when any observed value is greater than about 5, classes were amalgamated where necessary to achieve this.

RESULTS

Of the 90 questionnaires posted, a total of 52 returns were received, 14, 25 and 13 from south-east England north-east Scotland and south-west Wales respectively. This represents an overall response rate of 57% which is higher than that usually received from postal surveys of about 25% (Dillman, 1978). The profile of total farm sizes in each of the survey regions was similar (χ^2 = 13.2, d.f. = 10, P = 0.22) as was the actual registered organic area on each farm (χ^2 = 4.7, d.f. = 10, P = 0.91) (Table 1).

Table 1. Number of farms in particular size categories according to the total farm area and their registered organic area

Area (ha)	South-east England		North-east Scotland		South-west Wales	
	Farm area	Organic area	Farm area	Organic area	Farm area	Organic area
0-25	1	3	3	4	7	6
26-50	3	2	1	1	2	3
51-75	2	2	1	3	6	6
76-100	1	2	4	2	4	2
101-150	2	1	2	1	5	3
150 +	5	4	2	2	1	1

The questionnaire asked for information on the main organic crops grown. Not surprisingly the cropping patterns of each area differed significantly (χ^2 = 20.2, d.f. = 8, P = 0.01) with no organic wheat recorded in north-east Scotland and a higher proportion in south-east England. Organic grass was lowest in south-east England and highest in north-east Scotland.

Farmers were asked to identify their most problematic weeds. It appeared that many weed species were common to all three areas, including docks (*Rumex* spp), charlock (*Sinapis arvensis*), wild oats (*Avena fatua*) and thistles (*Cirsium* spp). In addition, each region had weeds specific to that area e.g. mayweed (*Chamomilla* spp), blackgrass (*Alopecurus myosuroides*) in wheat and poppy (*Papaver* spp) were only identified as major problems in south-east England. Hempnettle (*Galeopsis* spp) was the only weed identified as particularly problematic in north-east Scotland, mainly in oat crops, but chickweed (*Stellaria media*) and couch grass (*Elytrigia repens*) were also important. In south-west Wales, redshank (*Polygonum persicaria*) and rushes (*Juncus* spp) were the main concerns of organic farmers.

Farmers were asked to indicate which weed control method they used in each of their crops. Responses were specifically sought on 'pre-cropping decisions' (crop rotation, selection of competitive varieties), 'establishment practices' (high seed rate, stale seed bed) and 'in-crop weed management measures' (scarification/harrowing, flameweeding, hand roguing/weeding, biological control). Despite a specific question no farmers used biological control. There were significant differences ($\chi^2 = 53.0$, d.f. = 12, $P < 0.01$) between regions. Farmers in north-east Scotland appeared to use less weed management than other areas but there was a concentration on topping/mowing/grazing which was associated with the greater preponderance of organic grass in this region. Rotation was identified as the most popular weed management technique in all areas. The use of a stale seed bed, scarification and hand weeding were all used about equally in south-east England and south-west Wales. Farmers in south-east England chose competitive varieties and used higher seed rates as weed management measures more than other areas. The high seed rate was used mainly in wheat crops.

There were significant differences ($\chi^2 = 105.1$, d.f. = 24, $P < 0.01$) in the preferred weed management technique for particular crops. Not surprisingly, topping/mowing/grazing was the preferred technique in organic grass. When the weed management techniques were combined into three broad categories – 'land preparation' (rotation, stale seed beds), 'plant competition' (competitive varieties, high seed rate) and 'in-crop measures' (hand-roguing/weeding, scarification/harrowing, topping/mowing/ grazing) and compared in the five main crop types reported, there was a significant ($\chi^2 = 28.9$, d.f. = 8, $P < 0.01$) difference in usage (Fig 1). High

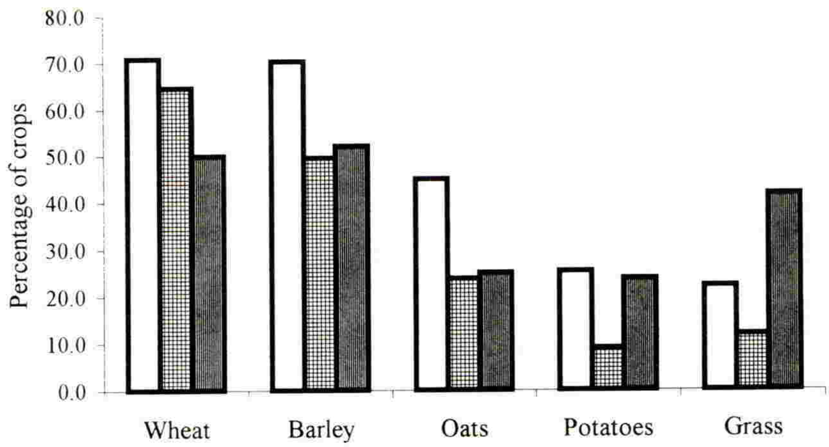

Fig 1. Main weed management categories used in organic crops:
Land preparation, Plant competition, In-crop control.

seed rate was avoided in potatoes because seed rate also determines the size of the tubers harvested and so land preparation and in-crop measures had a higher priority. There was a significant difference ($\chi^2 = 12.2$, d.f. = 6, $P < 0.05$) in the weed management categories used against the regional weed floras: in particular, plant competition was used greatly to control those weeds identified as specific problems in south-east England.

Growers were asked to state their own perceptions of the ease and effectiveness of their weed management programmes. In south-east England farmers considered that they achieved moderately effective control while in north-east Scotland and south-west Wales they achieved moderately effective to effective control (Fig. 2). Few growers thought their weed management was poor. About 20% of growers in north-east Scotland thought their weed control was very effective.

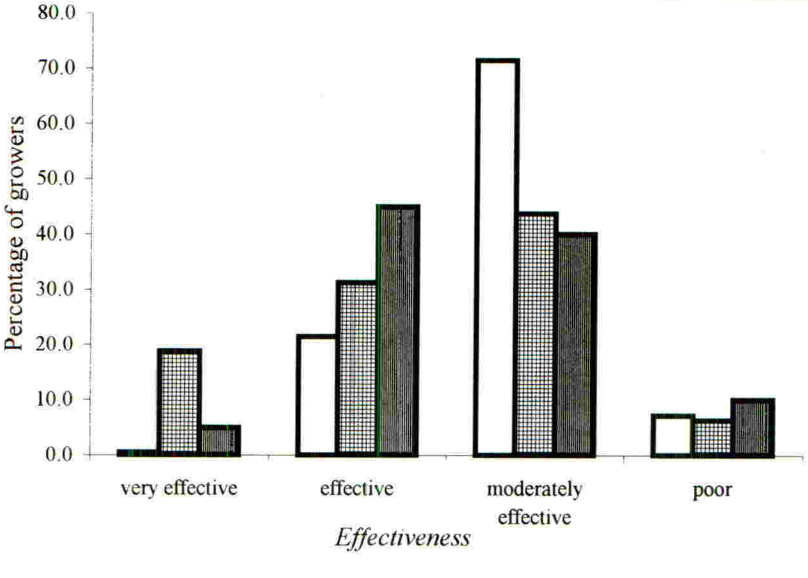

Figure 2. Growers' perceptions of weed management in organic systems in □ s.e. England, ▦ n.e. Scotland, ■ s.w. Wales.

In converting to organic status, only 14% of growers converted via set-aside, the remainder converted directly. Two-thirds of growers who converted to organic status used no special weed management technique to prepare for this. For those who did, the most common weed control measure prior to conversion was the use of glyphosate to control perennial weeds such as couch, nettles and thistles.

The sample of farmers from south-east England all obtained their seed from merchants, but in north-east Scotland and south-west Wales 20-30 % obtained seeds from co-operatives or used farm-saved seeds. The use of organic quality seed will be compulsory for organic farmers from 31 December 2000. Many farmers voiced concern that organic seed supplies would be limited and therefore of high price, and particularly that varietal choice would be limited. Variety availability was an issue raised, especially on farms growing many different varieties.

Some respondents were involved in organic herb and fruit production using up to 230 varieties, which they suggested would be almost impossible to obtain. Potatoes were a special worry, with organic farmers predicting poor seed potato quality and, particularly, an increased likelihood of seed-borne diseases. Several farms were contemplating the use of farm-saved seed.

DISCUSSION

The accelerated shift towards organic food production has been interpreted as likely to produce a sharp reduction in world agricultural productivity and food production (Pinstrup-Anderson & Pandya-Larch, 1998). However, in industrialised countries, interest in organic farming is increasing and is demand-led as consumers respond to scare stories about the quality of food produced in conventional systems and seek an assurance of 'safe' food.

The main conclusions from this work are that organic farmers are aware of and use a variety of techniques for weed management. Not surprisingly the location, main crops grown and main weed species encountered are all inter-related and interact to determine the weed management techniques used. Although many weed species occur in crops and cause severe local problems, relatively few are common and widespread (Tottman and Wilson 1990). The weed species identified by the respondents to the questionnaire produced lists of weeds common to many farms in one region and several species common to all three regions. Many more weed species occur in organically managed fields compared to conventional systems: indeed several plant species threatened with extinction have been found only on organic land (Lampkin, 1990). Expansion of the organic sector is seen as a measure to enhance biodiversity and the area of organically farmed land is considered an environmental indicator (Parris, 1999).

The perceived difficulty of weed control in organic crops is a major disincentive for some farmers to convert to organic production (OFRF, 1998). Conventional farmers regard techniques such as hand-hoeing as obsolete (Moule, 1995). Nevertheless, in a recent postal survey of 1192 organic farmers in USA (representing a 26% rate of return), hand weeding or hoeing, mechanical weeding and crop rotations were each used by 75% of respondents (OFRF, 1998). Our results from a small survey of UK organic farmers are similar. Crop rotations also contribute to the containment of pests and diseases. Despite clear reports of the value of choosing competitive varieties of crops as a component of weed management strategies (e.g. Richards & Whytock, 1993, Karim, Naylor & Whytock, 1997) this is not given as a factor in choosing a variety in conventional arable cropping (Jellings & Fuller, 1995) but was regularly used by organic farmers. Nevertheless, these results demonstrate that a range of techniques is available for weed management in a range of organic crops and that farmers believe these to be generally effective. However, at the same time few farmers rated their weed management as very effective.

The continued, or increased use of farm-saved seed in organic systems can be predicted as a response to low availability of organic seed. However, farm-saved seed has a risk of containing a higher weed seed contamination compared to samples of certified (conventional or organic) seed which is usually relatively weed free and has a guaranteed legal maximum weed seed content (Don, 1997).

Most respondents appreciated the need for good crop management to prevent the build-up of weeds and of the weed seed bank in the soil. Specific comments included "weed management is simple, monotonous and labour-intensive" and "the need to act early on weeds before they become uncontrollable is vital". Such statements emphasise the farmers' view that current weed control is imperfect. Thus these results identify a research and/or development need for the organic farming industry that is to develop effective weed management techniques suitable for a range of crops and weeds and which are also cost-effective. The awareness of the benefits of using competitive varieties could be increased.

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Weed control strategies for organic cereal crops

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ABSTRACT

Weed control remains one of the most significant agronomic problems associated with organic arable crop production. This paper aims to report the major findings from a series of research projects designed to evaluate a range of weed control approaches. Crop rotation is shown to have a significant effect on weed levels with the most effective control resulting from the alternation of autumn/spring cropping as well as from the inclusion of break crops such as potatoes. Intercropping wheat with field beans offers a competitive advantage over sole cropping, whilst, in isolation, cultivation in darkness was of limited practical use. Spring-tine harrowing in winter wheat was rarely beneficial in terms of improved yield whilst inter-row hoeing demonstrated considerably greater potential.

INTRODUCTION

Weeds remain one of the most significant agronomic problems associated with the production of organic arable crops (Yarham & Turner, 1992). Organic farmers rely on numerous methods to control weeds including crop rotation, cultivations, crop density, varietal selection and mechanical weed control in the growing crop (Stopes & Millington, 1991; Lee, 1995). The challenge for organic farmers, however, is to manage weeds in such a way as to accommodate their beneficial effects whilst still producing an acceptable crop.

Over the past decade, Elm Farm Research Centre (EFRC) has completed a number of research projects that have evaluated a range of approaches to control weeds including crop rotation, intercropping, cultivation in darkness and mechanical methods. It is the aim of this paper to report some of the major findings of this work.

RESULTS AND DISCUSSION

Crop rotation

Rotations are the primary means of maintaining soil fertility and achieving weed, pest and disease control in organic crop production systems. Recently, there has been considerable interest in the development of predominately arable or organic stockless systems. Stockless systems do not include the long ley phase in the rotation, used to build fertility and control arable weeds on more typical organic mixed farming systems (Bulson *et al.*, 1996). Instead, they usually depend on short duration (one or two year) fertility building green manure crops. The motivation amongst farmers to convert to such organic systems is generally economic since the cost of converting a conventional arable farm to a typical mixed organic system is very high in terms of the investment in livestock, buildings and infrastructure.

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The stockless experiment established at EFRC in 1987 comprised three intensive arable rotations (Table 1) with the aim of quantifying the extent to which agronomic problems affected the performance of the rotations. This basic information could then be used to inform the development of agronomically viable stockless rotations on farms. For more complete details see Bulson *et al.* (1996).

Table 1. Rotations in the EFRC stockless experiment

	Course			
	1	2	3	4
Rotation				
A	Red Clover	Winter Wheat	Winter Wheat	Spring Oats
B	Red Clover	Potatoes	Winter Wheat	Winter Oats
C	Red Clover	Winter Wheat	Winter Beans	Winter Wheat

The importance of rotation design for weed control was clearly illustrated by the lower weed biomass which resulted from the inclusion of potatoes and winter oats in rotation B compared with rotations A and C (Figure 1). The wheat (B3) grown after potatoes had the lowest level of weed biomass of all wheat crops, although it was only significantly ($P = 0.05$) lower than the second wheat in rotation A (A3). This was due in part to the inclusion of potatoes (planted in April) breaking the life cycle of autumn and early spring germinating annual weeds, but the potatoes also provided a good opportunity for aggressive in-crop mechanical weeding. Winter (B4) and spring (A4) sown oats tended to have lower levels of weed biomass compared with the wheat crops. Once again, in the case of spring oats, this was partly due to the alternation of autumn/spring cropping, although other factors such as allelopathy may also account for the low levels of weed biomass (Lampkin, 1990). The mean yield of spring oats, however, was very low, which mainly resulted from the unsuitability of the site for spring cropping. Growing successive wheat crops (A2 – A3) resulted in the most serious weed problems and lowest yields (Figure 1).

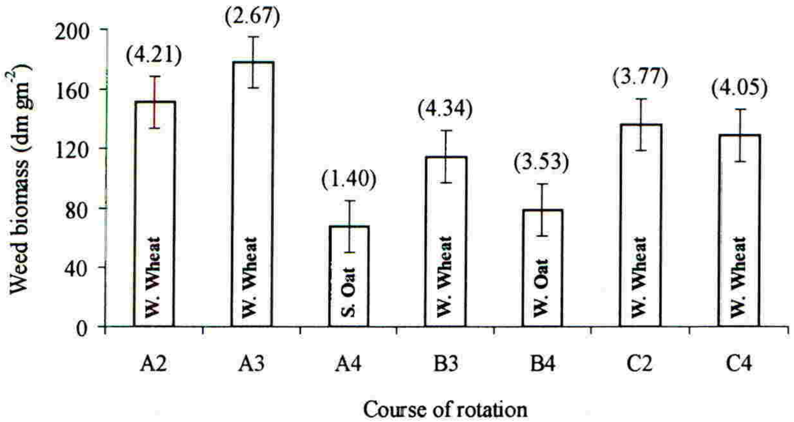

Figure 1. The effect of crop rotation on weed biomass (dm gm^{-2}) at crop maturity and crop yield (t ha^{-1}) (in parenthesis). Data are mean values for the period 1988-1995. Error bars denote ± SED of means.

Cultivation in darkness

Some research has indicated the possibility that reducing the exposure of seeds to light during cultivation might be used in a weed control strategy (Hartmann & Nezadal, 1990; Ascard, 1994). This is of particular interest to non- or reduced herbicide approaches to control weeds in low external input systems such as organic farming.

Two experiments were established to test the hypothesis that cultivating and drilling in darkness can reduce weed seedling emergence and weed biomass. Plots were cultivated and drilled either during the daytime or at night. The first experiment (1994-95) was conducted in the autumn and included the use of a lightproof covering on the combination power harrow/drill to determine whether cultivation and drilling in darkness could be achieved during the daytime. The second experiment (1996) was conducted in the spring (EFRC, 1997; Welsh, 1998).

Reductions of weed seedling emergence as a result of cultivating and drilling in darkness ranged from 0 to 70% compared with plots cultivated in daylight (Figures 2A & 2B). The use of a lightproof cover on the combination drill during the daytime also resulted in a reduction of weed emergence, although this was not statistically significant (Figure 2A). It was also evident that individual weed species responded differently to cultivation in darkness. The emergence of both chickweed (*Stellaria media* (L.) Vill.) and fat hen (*Chenopodium album* L.) (Figures 2A & 2B) was reduced, whilst blackgrass (*Alopecurus myosuroides* Huds.) (Figure 2A) was unaffected.

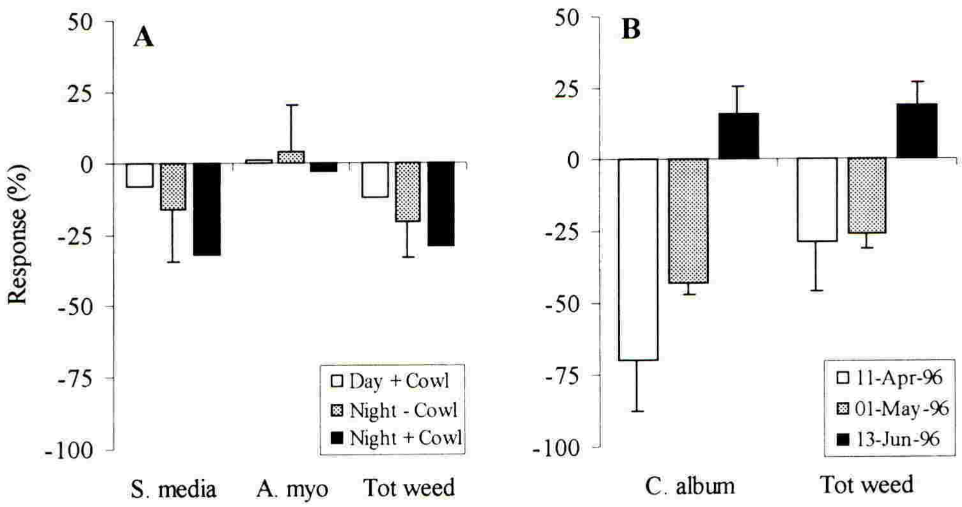

Figure 2. (**A**) Response (%) of weed density to cultivating and drilling in the daytime with lightproof cowl and at night with and without cowl compared with treatments in daytime without cowl when assessed 11-Nov-94 (A. myo = *Alopecurus myosuroides*). (**B**) Response (%) of weed density to cultivating and drilling at night in the spring compared with treatment in the daytime at three assessment dates. Error bars denote SED.

The reductions of weed seedling emergence, however, were transitory. The largest reductions were observed approximately three weeks after drilling. Subsequent assessments tended to show lesser or no differences in weed population between day and night treated plots (Figure 2B). This result was reflected in assessments of weed biomass conducted in May (data not presented) where there was generally no significant difference between plots cultivated and drilled in daylight or in darkness. There was no improvement in crop yield from cultivating and drilling at night (data not presented).

In isolation, therefore, cultivating and drilling in darkness is of limited practical use. Ascard (1994), however, suggested that a delayed weed emergence, as a result of cultivation in darkness, may lead to greater selectivity when using control methods of normally low selectivity, for example post-emergence harrowing. If weeds are less developed, due to delayed emergence, compared with the crop it will be possible to weed more aggressively without causing excessive crop damage. Therefore, if cultivation in darkness were used in combination with other weed control techniques, such as spring-tine harrowing, greater levels of weed control may be achieved than employing either technique independently.

Intercropping

Intercropping is the growing of two (or more) crops together on the same area of ground and often produces an advantage in terms of greater yield and less variation in yield than comparable areas of sole crops (Willey, 1979). Research conducted by Bulson *et al.* (1997) in an organic farming system aimed to quantify the benefits of intercropping winter wheat (*Triticum aestivum* L.) with field beans (*Vicia faba* L.) compared with sole cropping.

The results indicated that weed biomass in the intercrops was significantly reduced compared with the sole crops and that as the densities of wheat and beans increased weed biomass decreased (Table 2). Also, in terms of yield, Land Equivalent Ratio values of intercropping, based on a comparison with the optimum sole crop densities of wheat and beans, were significantly greater than 1.0 whenever wheat was sown at > 25% Recommended Density (RD) and beans were sown at > 50% RD. Thus intercropping offers benefits both in terms of increased yield and reduced levels of weed biomass, which, although not measured directly, may result in a reduction of weed seed return to the soil seedbank (Wilson *et al.*, 1993) thus benefiting subsequent crops in the rotation.

Table 2. The total shoot biomass of weeds (gm^{-2}) present in sole crops and intercrops composed of various combinations of wheat and bean densities (Bulson *et al.*, 1997).

Bean density (% of recommended density)	Wheat density (% of recommended density)					
	0	25	50	75	100	Mean
0	*	302	146	97	124	167
25	398	168	148	96	93	181
50	346	162	133	80	100	164
75	284	138	151	75	36	137
100	169	117	72	83	62	101
Mean	299	177	130	86	83	

SE between means of wheat density = ln 0.1337, SE between means of bean density = ln 0.1337, SE of interaction between wheat and bean density = lm 0.290, D.F. for error = 45(3).

Mechanical weed control

Mechanical weed control in organic cereal crops can be broadly split into two methods; spring-tine harrowing and inter-row hoeing (Rasmussen & Ascard, 1995). Spring-tine harrowing is by far the most common method of in-crop mechanical weed control in organic cereal crops, whilst inter-row hoeing is relatively uncommon in the UK. At present, however, there is little information on the optimum timing for mechanical weed control and its ability to control weeds and produce a crop yield benefit (Rasmussen, 1996).

A series of eight trials conducted on five sites aimed to evaluate spring-tine harrowing and inter-row hoeing in terms of their ability to control weeds and produce a yield benefit in organically grown winter wheat at a range of times and combination of times during the growing season. Further details of these experiments have been reported in EFRC (1997), Welsh *et al.* (1997) and Welsh (1998).

The two methods differed considerably, not only in their overall efficacy but also in their sensitivity to environmental factors such as the species composition of the weed flora, the growth stage of the weeds and soil type/conditions. This result was compatible with the findings of previous work conducted by Böhrnsen (1993) and Hammarström *et al.* (1993).

Reductions of weed density resulting from spring-tine harrowing ranged from 0 to 74% with a mean reduction of 31% (average across all sites and treatments). Its efficacy at any particular timing was greatly influenced by the species composition of the weed flora and weed growth stage. Tap-rooted weeds, e.g. field poppy (*Papaver rhoeas* L.) and mayweed (*Tripleurospermum inodorum* Schultz Bip.), were controlled most effectively at an early growth stage before they could develop a strong tap-root, whilst scrambling weeds, e.g. chickweed (*S. media)*, were controlled best at later growth stages when they could be 'raked' out of the crop. Crop damage was associated with most of the weeding treatments with reductions in crop density ranging from 0 to 22% compared with the unweeded control and it is this, in combination with generally poor levels of weed control, which resulted in the lack of any significant positive yield responses to this method of weeding.

In contrast, inter-row hoeing resulted in considerably greater reductions of weed density (0 to 93% compared with the unweeded control), with a mean reduction of 50% (average across all sites and treatments), although crop damage was still a limiting factor (mean reduction of 11% averaged across all sites and treatments). Where crop damage was minimal, significant positive yield responses were obtained which were also associated with significant increases in grain nitrogen concentration compared with the unweeded control. The efficacy of inter-row hoeing was less sensitive to weed species and weed growth and consequently offered more flexibility in terms of the timing of effective weed control operations. If the selectivity of inter-row hoeing could be improved by, for example, the use of automated guidance systems (e.g. Tillett *et al.*, 1999; Pullen & Cowell, 1995), then this should prove to be a highly effective method of weed control for organic cereal crops.

CONCLUSIONS

Crop rotation can have a significant effect on the weed population. The alternation of autumn/spring cropping along with the inclusion of break crops such as potatoes provides the best potential for weed control. Growing successive wheat crops is detrimental both in terms of yield and weed levels. Intercropping wheat with field beans offers a competitive advantage over sole cropping and can provide improvements in total crop yield / unit area. Cultivation in darkness can reduce weed emergence, although as a weed control technique in isolation it is likely to be of little practical value. Spring-tine harrowing can significantly reduce weed density but its efficacy is sensitive to the composition of the weed flora and growth stage of the weeds. Spring-tine harrowing did not result in a significant positive yield response at any of the sites. Inter-row hoeing resulted in considerably better levels of weed control and can produce significant positive yield responses.

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An evaluation of weed control strategies for large-scale organic potato production in the UK

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ABSTRACT

Weed suppression in the early stages of crop production is crucial if optimum yields are to be obtained in organic potato crops. Many of the weed control strategies currently used in small-scale organic farms are costly and/or labour intensive and may be unsuitable for use by the growing number of specialist, high acreage, organic potato producers in the UK. This review examines the range of pre and post-emergence weed prevention and control techniques available to organic potato growers throughout Europe. The relevance and cost-effectiveness of these weed control strategies is assessed in relation to UK conditions and growing systems. The potential for use of novel weed control measures is discussed with reference to current UK organic standards and production methods.

INTRODUCTION

Due to the increasing demand for organic potatoes, many existing UK organic potato producers are currently expanding their growing areas. Several conventional potato producers are converting either part, or all, of their production facilities to organic production. However, there are a number of agronomic problems, including weed control, that need to be considered in order to successfully scale-up organic potato production. Potatoes are often regarded as a cleaning crop within organic rotations. The need for a fine, deep seedbed at planting and for re-ridging after planting gives a number of opportunities to control weeds. In addition, the vigorous growth of the crop and the dense crop canopy once established aids suppression of most of the late emerging weeds. Weed control under organic management does not usually present serious problems for the smaller grower. However, an evaluation of the cost and efficacy of current organic weed control practices has to be made in order to make recommendations for cost-effective weed control strategies for the larger potato producer.

ADVERSE EFFECTS OF WEEDS

Weeds compete with the potato crop for light, nutrients and water, and tuber yields can be severely reduced depending on the availability of these three factors, which in turn can depend on the soil type and the density and competitive ability of the weeds present. An early series of trials showed that weeds reduced tuber yields by an average of 36 % if herbicides were not used (Neild & Proctor, 1962). However, yield reductions were shown to vary between 14 and 80 % depending on range of weeds, and the numbers of weeds present. Weed competition can affect tuber quality and weeds can interfere with mechanical harvesting by reducing the efficiency of soil separation and slowing the harvesting operation. Finally, certain weeds can act as alternate hosts for some potato pests and diseases. Aphid vectors of potato virus diseases and the causal agent of black scurf (*Rhizoctonia solani*) are particular problems (Callihan & Bellinder 1995).

WEED BIOLOGY

Planting date of the potato crop, soil type, weather conditions, the timing, type and frequency of cultivations and the other crops grown in the rotation all have an impact on the numbers and species within the weed flora (Thackral *et al.*, 1989). If the crop follows on from a grass/clover ley or a cereal crop, (as is normally the case in organic rotations), the weed flora will tend to consist mainly of cereal weeds. Problem weeds in potato crops include a range of perennial and annual weeds. The commonest perennial broad-leaved weeds in organic potato crops include creeping thistle (*Cirsium arvense*), perennial sowthistle (*Sonchus arvensis*), docks (*Rumex* spp.), field bindweed (*Convolvulus arvensis*) and volunteer potato (Lutman, 1992). The most frequently occurring annual weeds in potato crops include those which have an extended period of emergence, such as common chickweed (*Stellaria media*) or mayweeds (*Matricaria* spp.), and those which have an emergence peak which co-incides with the early stages of potato crop growth, such as knotgrass (*Polygonum aviculare*), redshank (*Polygonum persicaria*) and fat hen (*Chenopodium album*, Callihan & Bellinder, 1995). Some grass weeds do occur, but with the exception of couch grass (*Elymus repens*) and black bent (*Agrostis gigantia*), these are not seriously competitive and only tend to reduce yields when present in very high numbers (Lutman, 1992).

WEED CONTROL STRATEGIES USED ON ORGANIC HOLDINGS

Rotational strategies

Since potatoes often suffer from weeds to a lesser extent than other crops in organic rotations, and due to their potential as a cleaning crop, potatoes are usually planted before or after weed susceptible crops. If a serious perennial weed problem exists, the only means of control in an organic system involves a one year fallow, where repeated cultivations can be carried out in order to weaken remaining roots and stolons (Lutman, 1992). This practice may have deleterious effects on soil structure, (particularly if the soil is worked when wet). It may lead to environmental pollution in terms of nitrate leaching and may reduce earthworm numbers. The use of bare fallow is thus not recommended for organic systems.

Variety choice/planting density

Some potato varieties produce denser, more weed suppressive foliage than others, e.g. 'Cara' is a very vigorous variety, whereas 'Golden wonder' produces less foliage and establishes ground cover more slowly (Lutman, 1992). However, variety choice is invariably market led and weed suppressive ability is rarely taken into account when growers decide which varieties to grow. Planting density can be increased with the aim of increasing weed suppression, however the actual density of tubers planted must always be balanced by the increased seed cost and the implications for yield, and crop quality, (Lutman, 1992). It is, for example, well established that potato blight development is encouraged by high planting density (Callihan & Bellinder, 1995).

Cultivation practices

Cultivation practices currently form the basis of weed control in most organic potato crops and are successfully used routinely in many non-European countries. Work by Eberlein *et al.* (1997) showed that where low and medium weed densities were present, there was no yield loss in comparison to herbicide treated plots, following cultivation in good soil conditions. However, it has also been shown that cultivation can reduce yields by 5 - 20 % in comparison to herbicide treated plots (Bremner, 1966; Callihan & Bellinder, 1995). The above work demonstrated that the success of a cultivation operation to control weeds and minimise crop damage is heavily dependent on the skill of the machinery operator. It is also dependent on the type of machinery used, the soil type, soil moisture content at and following cultivation, the timing of cultivation relative to the age of the crop and the growth stage of the weeds present.

Most growers adopt the practice of chain harrowing and re-ridging the field at least once, and frequently twice between planting and emergence. If a second harrowing is considered necessary, it is usually done just as the potato sprouts are emerging. Later cultivations, followed by re-ridging can be carried out between the ridges if required. The majority of growers choose to cultivate when weeds are still small, i.e. before the annual broadleaves get past the two true leaf stage, or before the annual grasses get to the three leaf stage. This helps prevent re-rooting of weeds (Lutman, 1992). Many specialist growers are using rolling cultivators either in addition to, or usually in preference to the more standard chain harrow and ridgers. Rolling cultivators employ tines to remove weeds between the rows and rolling, star-shaped tines to cultivate the ridge sides. Ridging bodies are mounted behind the tines to rebuild the ridges after cultivation. These often result in better weed control and less crop damage than the less specialised chain harrow and re-ridge technique (D. Rankin, E S Black Ltd.; W. Rose, TIO Ltd., pers. comm.)

Thermal weeders

An increasing number of organic potato growers report that thermal weeding machines, provide a cost effective solution to weed problems prior to and at crop emergence (W. Rose, TIO Ltd; D. Rankin, E S Black Ltd., pers. comm.). Liquid or gas phase weeders have the advantage of being low technology and relatively simple to use, but their fuel costs are high (W. Rose, TIO Ltd., pers. comm.). Infra-red burners radiate the heat produced back to the weeds and do not flame them directly, thereby using less fuel. Thermal weeders tend to have limited efficacy against grass weeds, but their efficacy against most annual broad leaved weeds is good (Litterick, unpublished data). Thermal weed control may in the future be prohibited in organic standards, since the use of non-renewable is against organic farming principles.

Non-living mulches/plastics etc.

Non-living mulches made from fibre, re-cycled paper or plastic have been shown to give excellent control of weeds in organic potatoes in addition to maximising efficiency of water use in dry areas (Schonbeck, 1998). Their high cost (Table 1) will continue to preclude their use in all but the most high value crops such as seed and early salad potatoes.

Hand weeding

Hand weeding is rarely necessary in organic potato crops, since less labour intensive weed control techniques such as cultivation and flame weeding give satisfactory control under most circumstances. It is used on rare occasions where potato volunteer removal is crucial to the health of the crop, (e.g. prevention of potato blight and black scurf), or where there is a persistent perennial weed problem in localised areas within a field (D. Rankin, E S Black Ltd., pers. comm.). However, hand weeding is usually a last resort, due to the high costs involved, (Table 1) and the lack of labour availability in some areas of the UK.

Novel weed control strategies

Biological control - there are very few biological control agents available which are genuinely effective against specific weeds. For example, Ghorbani *et al.* (1999) have shown that *Ascochyta caulina* gives good control of fat hen. However, there are no weed biological control agents listed as permissible inputs for organic production. As a result of this, and the fact that there is no single weed species which causes severe problems in the potato crop, it is unlikely that biological control agents will form part of a routine strategy to control weeds in organic crops in the future.

Allelopathy/green manures - several workers have shown that the application of a green manure crop to the soil surface, or ploughed in can result in weed suppression in the following crop (Boydston & Hang, 1995; Krishnan *et al.*, 1998). The most common species used include brassicas such as oil seed rape and mustard, which all contain glucosinolates. These compounds are hydrolysed to isothiocyanates (ITC), thiocyanates and nitriles, many of which have been shown to inhibit plant growth or weed seed germination (Boydston & Hang, 1995). However, this technique tends not to be effective against perennial weeds with significant storage organs, (Boydston & Hang, 1995). The economics and efficacy of these techniques have not been reported on potatoes grown in the UK, and green manures are used to a limited extent on large scale potato production facilities. Providing soil conditions are suitable for cultivation and planting, and time allows, the use of green manures may prove an effective and economically viable weed control technique to be used alone, or more likely in combination with cultivation or flame weeding.

Night cultivation – work reported by Leake (1996), has shown that where light is excluded during soil preparation and drilling, significant reductions in germination of certain weed species can be achieved. Further work needs to be done to see whether this technique may have an application in potato production.

FINANCIAL ANALYSIS

A financial assessment of the main weed control options available to organic potato growers was made with reference to the equipment and machinery available in the Scottish borders in the 1999 growing season (Table 1). All costs associated with each technique are included in the estimates, (e.g. machinery and product hire/purchase costs, fuel, labour, insurance etc.). The prices were obtained for a single hectare on a 500 Ha unit. The efficacy of each weed control option was estimated through consultation with potato growers, agricultural consultants and contractors in the Scottish borders.

Table 1. Cost and effect of organic weed control options

Option	Cost per pass: 1 pass only[a] £/Ha	Spread over 2 passes £/Ha	Contract hire[b] £/Ha	Estimated potential effect: Pre-emerge	Post-emerge	Perennials	Grasses
Rolling cultivator	45	35	31	**[c]	**	*	**
Harrow and re-ridge	30	25	25	**		*	*
Single bed flamer[d]	109	84	100	***	*	**	
2 bed flamer[e]	127	93	100	***	*	**	
Paper mulch[f]	662	N.A.	662	***	***	***	***
Black plastic mulch[g]	1140	N.A.	1140	***	***	***	***
Hand weeding (8 people)	525	N.A.	N.A.		***	***	**
Rape green mulch[h]	70	N.A.	80	***	**	*	**

[a]based on the full ownership cost of all machinery written off over the accepted life span of each piece of equipment, plus fuel and labour.

[b]based on contract hire of all machinery and operators required

[c]* = partial control, ** = good control, *** = excellent control

[d]Drackedon GreenBurner®, Drackedon Engineering. Burn width = 1.8 m

[e]Drackedon GreenBurner®, Drackedon Engineering. Burn width = 3.6 m

[f]based on the average cost of Agralan® paper mulch (1.4 x 400 m rolls) applied to 1.8 m wide beds containing 3 rows of potatoes. Note that weed control efficacy only applies to the area under the mulch. Cultivation between beds may be necessary in addition to mulch due to the narrow product width.

[g]based on the average cost of a black plastic mulch (1.8 x 400 m rolls) applied to 1.8 m wide beds containing 3 rows of potatoes

[h]based on the average cost of discing and rolling field, sowing a rapeseed crop at 8 kg/Ha, and cultivating it in prior to planting (includes machinery costs, fuel and labour).

DISCUSSION

Cultivation practices are the cheapest means of weed control widely used in UK organic potato crops. Thermal weeding provides a viable, although more costly alternative to cultivation, and gives better weed control. Non-living mulches give excellent control, but are very costly.

It is likely that due to cost and efficacy considerations, organic potato growers will continue to rely on an integrated approach to weed control involving the use of cultivation practices and, in some cases, thermal weeding machinery, with occasional hand weeding where necessary. Future developments will probably include improved cultivation machinery, improved cultivation techniques specific to the potato crop and larger thermal weeding machinery suitable for more extensive operations. If further work shows that green manures provide a cost-effective means of weed control in the potato crop, without resulting in a yield penalty, then they may become an important part of the weed control strategy in areas where soil and climatic conditions allow. The high cost of non-living mulches and the likely high cost of future biological control agents will probably continue to preclude their use, even where organic standards permit them.

ACKNOWLEDGEMENTS

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Weed suppression by crops

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ABSTRACT

Crop plants may suppress weed development physically through superior vigour, allelopathically by the release of phytotoxins, or a combination of both. In experiments to evaluate the effect of different crops on weed number and biomass, most crops suppressed weed growth and percentage ground cover rather than reduced seedling numbers. Allelopathy may have been a factor in the few crops that did reduce weed seedling emergence. In studies over a ten-year period, weed emergence in the presence or absence of a crop was not consistently less when the crop was present. Cover-crops sown in September reduced weed biomass over-winter but did not suppress weed emergence. Whatever feature of weed development is reduced, and whether a physical or an allelopathic effect is responsible, the suppression of weeds by crops should be exploited to improve weed control in organic systems.

INTRODUCTION

The crop has an important role in weed control strategy and should not be dismissed as just a passive element. In the past, crop rotation was an integral part of weed control, particularly the use of cleaning and smother crops that prevent a build-up of weeds (MAFF, 1949). Crop plants can suppress weed development in the same way that weeds interfere with crop growth. The intensity of weed suppression depends principally on crop morphology and rate of growth but allelopathic ability also can be important (Putnam, 1986). Plant spacing, cultivar choice, seedbed preparations and other aspects of crop production will also influence the level of weed suppression (Christensen & Rasmussen, 1994; Grundy *et al.*, 1993). For example, the potato has a vigorous growth habit that smothers weeds but this is aided further by ridging cultivations that disrupt early weed development. In modern agriculture there is little flexibility to modify the cropping sequence solely for weed control purposes. The use of winter cover-crops is one way of adding a weed suppressing crop into the rotation at a time when the land might otherwise lie uncropped (Nelson *et al.*, 1991).

For all crops, good early establishment is important to achieve maximum weed suppression (de Lucas Bueno & Froud-Willliams, 1996). Where crop cover is poor, a lack of crop competition will allow the weeds to grow unhindered. Apart from contributing to yield loss in the present crop, greater weed growth will exacerbate future weed problems through increased seed production by the unchecked weeds (Bond *et al.*, 1998, Wilson *et al.*, 1995).

One aim of the present study was to evaluate the ability of different crops to suppress weed emergence and growth from natural weed populations in the absence of other control measures. The other objectives were to compare weed emergence in the presence and absence of a crop, and to assess the effectiveness of autumn-sown cover-crops in reducing weed emergence and growth over-winter.

METHOD AND MATERIALS

Crop evaluation

Field experiments were made to evaluate the ability of different crops to suppress naturally-occuring weeds in the absence of other weed control measures; only two of experiments are described here. Plots were drilled individually with the crops listed in Table 1 at appropriate densities in rows 30 cm apart with four rows to a plot. The plots were arranged in a randomised block design with eight replicate plots of each crop. Weed seedling number m^{-2} and percentage ground cover of weed and crop were recorded when the crops were well established. At harvest the fresh weight of the above-ground weed biomass was recorded.

Weed emergence

Weed seedling emergence was recorded in 94 crop-weed competition experiments with a range of drilled and transplanted crops made at HRI-W between 1989 and 1998 (Table 2). In each experiment, separate plots were set aside within each replicate block for recording weed emergence. The plots were either cropped like the rest of the experiment, or the crop was carefully removed shortly after emergence or after planting with the minimum of soil disturbance. A permanent 1 x 0.5 m area was marked out within each plot for recording purposes. Weed seedlings that emerged within the marked area were counted, identified and removed at weekly intervals from crop sowing or planting until crop harvest. Flowering weeds were removed at intervals from around the counting areas to prevent fresh weed seed contamination.

Autumn-sown cover-crops

In a study of the effect of autumn-sown cover-crops on weed development over-winter, field plots were drilled in September with grazing rye (*Secale cereale*), winter vetch (*Vicia sativa*), or phacelia (*Phacelia tanacetifolia*) at 286, 203 and 67 kg ha^{-1} respectively, or were left uncropped. This trial was carried out within a certified organic system at HDRA (Soil Association, 1998). The treatment plots were arranged in a randomised block design with eight replicates. Weed emergence was recorded in permanent 1 x 0.5 m quadrats marked out in each replicate plot. Weed seedlings that emerged were recorded and removed at weekly intervals from sowing until cover-crop incorporation in March. Weed biomass was recorded at 2 week intervals in duplicate plots of each cover-crop treatment set aside for destructive sampling.

RESULTS

Crop evaluation

Table 1. Effect of different crops on weed number, weed fresh weight and % weed ground cover

	Weeds m^{-2}	Weed fwt g m^{-2}	Weed % cover
	Experiment 1		
Pea	23	257	2
Broad bean	53	719	5
Cabbage	71	690	5
Turnip	36	93	3
Swede	66	895	9
Lettuce	59	336	6
Cress	11	111	0
Uncropped	77	3228	74
SED (49 df)	10.1	261.1	
	Experiment 2		
Wheat	146	1752	41
Barley	129	823	20
Dwarf bean	146	2260	44
Rocket	72	309	5
Salad onion	169	3552	70
Carrot	150	3823	71
Cress	45	201	1
Uncropped	188	3943	91
SED (49 df)	17.4	366.1	

There were great differences in weed biomass development between the different crops tested (Table 1). Garden cress (*Lepidium sativum*) and salad rocket (*Eruca vesicaria*) consistently reduced weed cover by more than 95%. Turnip (*Brassica rapa ssp. rapa*) and swede (*Brassica napus ssp. rapifera*) also suppressed most of the weeds present. However, when weed numbers were high, these crops were less effective at suppressing the inter-row weeds. Wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), pea (*Pisum sativum*) and broad bean (*Vicia faba*) suppressed weed development except when poor emergence or bird damage reduced crop stand. Cabbage (*Brassica oleracea var. capitata*), and dwarf bean (*Phaseolus vulgaris*) were able to suppress low numbers of weeds but were not consistent in their effectiveness. Lettuce (*Lactuca sativa*), carrot (*Daucus carota*), and salad onion (*Allium cepa*) were the least competitive crops and were virtually eliminated by the weeds.

Weed emergence

In the majority of experiments there appeared to be no significant effect of cropping on weed emergence (Table 2). None of the potato experiments showed any effect of cropping on weed numbers. With the other crops, weed numbers were reduced by the presence of the crop in a proportion of the experiments. Only with the weak competitors such as carrot and salad onion was there evidence of more weed seedlings on the cropped compared with the uncropped plots in a few experiments.

Table 2. The effect of crop presence on weed numbers in cropped and uncropped plots in weed competition experiments at HRI-W 1989-1998

Crop	Experiments with more weeds on the cropped plots	Experiments with fewer weeds on the cropped plots	Experiments with no effect of crop on weed number	Total experiments
Potato	0	0	6	6
Drilled salad onion	1	3	6	10
Drilled carrot	1	5	17	23
Drilled swede	0	4	8	12
Drilled turnip	0	6	9	15
Drilled radish	0	2	4	6
Transplanted onion	0	1	3	4
Transplanted cabbage	0	2	16	18
All crops	2	23	69	94

Winter cover-crops

The cover-crops all formed a dense ground cover by winter but this did not significantly reduce weed emergence in autumn (Figure 1). However, as in the crop evaluation study, weed biomass was reduced considerably in the presence of a crop (Figure 2). Despite the

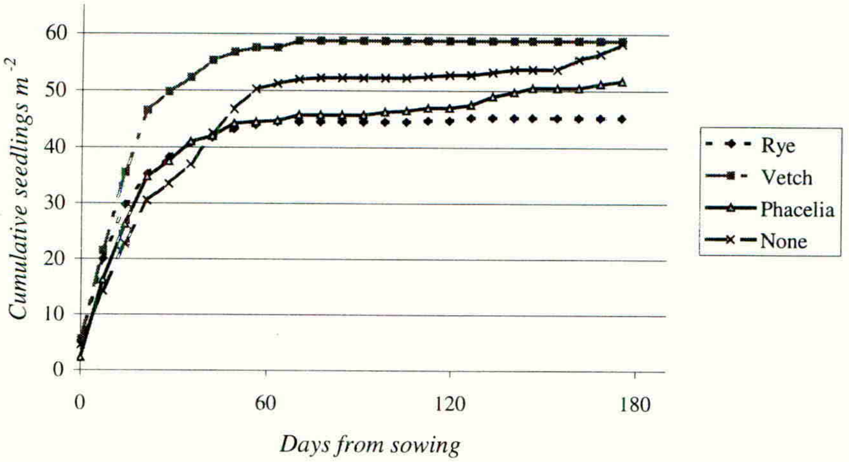

Figure 1. Cumulative weed seedling emergence m^{-2} recorded in overwintered cover-crops at weekly intervals from sowing in September until incorporation in March.

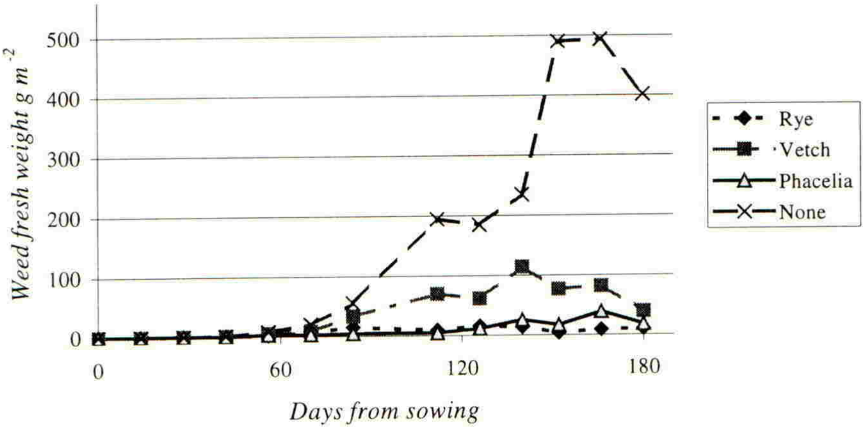

Figure 2. Weed fresh weight (g m^{-2}) recorded in overwintered cover-crops at 2 week intervals from sowing in September until incorporation in March.

phacelia suffering frost damage during the winter, the layer of dead foliage continued to suppress weed growth.

DISCUSSION

The majority of the crops studied reduced weed biomass production, with even the least competitive crops having some effect. The effect on weed biomass was mainly due to physical weed suppression by crops able to form a dense leaf canopy. Cruciferous crops, however, were particularly effective in preventing the establishment of dense stands of even the tall growing weed species like fat-hen (*Chenopodium album*). It was notable that where crop establishment was patchy, weed seedlings that emerged in the gaps were not effectively controlled by the developing crop canopy and weed biomass increased substantially. Similarly, at higher weed densities the inter-row weeds grew bigger that those under the denser leaf canopy within the crop row.

A reduction in the numbers of weed seedlings that emerged was less common in all of the studies described. The main flush of weed emergence occurred soon after crop sowing or planting when crop cover was sparse and was unable to suppress the weeds physically. However, some crops reduced the main flush of weed emergence providing evidence of an allelopathic effect. The response occurred mainly in the crops such as crucifers that are known or likely to have allelopathic ability. Garden cress had the most effect overall on weed suppression in terms of both weed biomass and seedling numbers.

Information about the physical or allelopathic ability of different crops to suppress weeds, as demonstrated in these studies, could be used to help complement other methods of weed control in organic cropping systems. Currently there is a dearth of information regarding the competitive ability of different crop varieties with respect to their weed suppressing traits. Although some work has been published with regard to small grain cereals (Seavers &

Wright, 1997; Cosser *et al.*, 1997), little information is available for vegetable crops. Weed suppressing attributes such as early vigour, leaf size or allelopathic ability could be successfully selected for in future breeding programmes (Lemerle *et al.*, 1996; Froud-Williams, 1997)

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Screening for weed competitiveness among selections of rice in West Africa

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ABSTRACT

Weed competition causes serious losses of rice yield in West Africa, particularly in the rainfed uplands and lowlands. The use of herbicides is limited and the majority of rice farmers have access to few resources. It is estimated that weeding accounts for between 28-40% of the total labour used in growing rice, and labour is the main constraint to the productivity of the systems.

Competitiveness with weeds is a selection criterion for rice cultivars suited to the rainfed areas. Conventional field experiments to examine the effects of weed competition on rice have the limitation that they require relatively large plot sizes and hence the number of cultivars is limited. To facilitate selection from a large number of cultivars, using smaller plot sizes, methods were reported which used sown competitors including *O. glaberrima*, maize, cowpeas, other rice cultivars and weeds to measure the competitiveness of test cultivars. Maize and the *O.glaberrima* were particularly competitive against the test lines, and there were good correlations between these and previous results.

INTRODUCTION

Almost 80% of the rice area in West Africa are in the uplands and rainfed lowlands. The increasing demand for land in the uplands has resulted in cropping intensification which has led to increased losses due to weed competition (Becker & Johnson, 1996). In the lowlands too, the effectiveness of weed management is a major factor influencing yields (Becker & Johnson, 1999). Rice is grown mainly by farmers with few available resources and in the rainfed areas, herbicides are only used in the minority of the areas. Crops are usually weeded at least once, but with other demands on farm labour, this is often delayed. Dalton *et al.* (1997) reported that, in the upland areas, 28% of the total labour used in rice production is accounted for by hand weeding, while in the rainfed lowlands it accounts for 40% of the total. Furthermore, in many systems labour availability is a major constraint to the productivity of the systems. Rice cultivars that are more competitive with weeds could be an important component of innovative strategies to develop technologies appropriate to the varied ecologies found in Africa (Buddenhagen, 1986), and this has become an important selection criterion for rice cultivars able to give higher and more stable yields (Johnson *et al.*, 1999).

Differing responses to weed competition among rice cultivars have been reported from Africa (Merlier & Deat, 1978, Fofana *et al.*, 1995). In subsequent studies, IG10 (*Oryza glaberrima* Steudel) suffered less from competition with weeds and suppressed weeds better than a traditional and improved *O. sativa* (Johnson et al., 1998). An important component of this competitiveness is IG10's ability to produce a greater leaf canopy that decreases the light available to competing species. This is achieved through a larger leaf biomass and a greater specific leaf area (SLA) than the *O. sativa* cultivars. Recent advances in plant breeding have produced *O. glaberrima* x *O. sativa* hybrids many of which share characteristics of both parents (Jones *et al.*, 1997), and improved screening methodologies to select weed competitive plant types from the wide range of progeny available. Previous field experiments to measure the effects of weed competition have involved relatively large plots (20 m^2) and six replications to overcome the heterogeneity resulting from weed growth (Johnson *et al.*, 1998). Such experiments do not lend themselves well to screening of a large number of rice lines. Crop plants, used as competitors, might be more practical to use as competitors than natural weed flora as the problems of variability in seed dormancy and establishment is reduced.

Two experiments are reported which had the objective of developing a rice screening methodology to determine differences between rice cultivars in their competitiveness with weeds. Experiment 1 was grown in 1996 at an upland site and Experiment 2 in 1998 in a lowland area.

METHODS AND MATERIALS

Experiment 1 was sited on a free-draining Alfisol (5° 06' W 7° 52' N), and grown during the main wet season. Overhead irrigation was used to supplement rainfall, to ensure the rice received a minimum of 200 mm of rainfall per month during the experiment. Fertiliser inputs were 20 kg/ha P (triple superphosphate) and 50 kg ha K (KCL) applied to the seedbed and 46 kg/ha N (urea) split equally between 28 and 56 days after emergence (DAE). The treatments consisted of 14 rice cultivars comprising *O. sativa*, *O. glaberrima* and interspecific hybrids, sown in single rows in plots 2.5 m long and 0.75 m wide. These single rows were bordered by competitors, as rows of either natural weed growth, cowpea, IG10 (*O. glaberrima*), a short duration rice (*O.* sativa), OS6 (long duration, *O.* sativa), maize, or same rice cultivar (monoculture). The plots were bordered by a row of a traditional rice variety, Moroberekan. After sowing, oxadiazon (Ronstar 25 EC, 0.75 kg a.i./ha) was applied to the experimental area, with the exception of the rows of maize, cowpea and weed which were shielded by polythene strips. The experiment was a randomised split plot design with the competitors as main plots and the 14 test cultivars as the sub-plots. All test cultivars and competitors were direct sown, except weed growth. Due to the intense shading of the rice, the maize was removed at 50 days after emergence

Experiment 2, was located nearby the former experiment, but in a lowland area that had been flooded and puddled. The surface water was drained prior to crop establishment, and then periodically flooded to simulate rainfed conditions. 20 rice cultivars were sown in single rows in plots 1.5 m long, with bordering rows consisting of the same rice cultivars (monoculture), natural weed growth, CG14 (*O. glaberrima*), Suakoko (*O.sativa*, traditional, indica type), Bouake 189 (*O. sativa*, improved, indica type) transplanted and direct sown. Only N fertilizer was applied, at 50 kg N ha^{-1}, and plots were treated with oxadiazon as above.

In both experiments, SLA was measured at 28 DAE. At maturity, rice plants were cut at ground level, oven-dried and weighed. The grain was separated from straw, and then weighed. Values for relative grain yield and relative biomass yield were calculated as yield in competition with a competitor as a percentage of yield when grown in monoculture.

RESULTS

Grain yields of rice in monoculture and the yields relative to these when rice was growing in competition with cowpea, maize, IG10, OS6 and weeds, are shown in Table 1. Biomass and relative biomass yields are not presented. Across the rice test cultivars, the grain yields relative to the monoculture plots were least where rice was grown in competition with the maize, indicating that this was the most competitive of the competitors, followed by weeds, IG10, OS6 and cowpea. Relative yield values greater than one indicate that the competitor was less competitive than the rice cultivar in monoculture. In competition there were three-fold differences in the relative yield values between cultivars. The greatest differences were to be found in competition with maize, where relative yield values varied from 0.22 with WAB56-104 to 1.31 with IG10. All cultivars, with the exception of WAB56-104, performed better when grown with cowpea than when in monoculture; which indicates the non-competitive habit of the cowpea. Only CG14 and IG10 performed better with maize than in monoculture, despite the fact that competition with maize only occurred for the first 50 DAE, at which time it was removed.

Table 1. Grain yield of twelve rice cultivars grown in monoculture and relative yields in competition with cowpea, maize, IG10, OS6 and weeds. Ivory Coast, 1996.

Rice cultivar	Grain yield kg/ha	Relative yields % Maize	weeds	IG10	OS6	cowpea
CG14	3802	110	98	84	115	127
WAB 56-104	3497	22	33	61	95	84
IDSA6	3488	66	68	66	79	130
WAB450-24-3-2-P18-HB	3304	75	65	97	97	165
WAB 56 50	3251	49	87	88	81	151
WAB450 1-BP-133-HB	3242	40	61	96	105	150
IG10	3096	131	128	112	151	244
ITA 257	2885	41	46	79	98	99
Bouaké 189	2776	82	71	52	107	161
Moroberekan	2753	93	104	88	89	158
WAB450 11-1-P40	2526	43	78	107	117	195
OS6	2416	99	139	113	107	171
Experimental means	3054	67	81	88	103	152
S.E between cultivars	± 459.5			± 20.5		
S.E " " competitors	-			± 4.8		

There was good correlation between the relative grain yields of the rice cultivars in competition with weeds and the relative yields in competition with maize ($r = 0.80^{***}$, $p \leq 0.001$), or IG10 ($r = 0.60^{*}$, $p \leq 0.05$). Those cultivars which had a higher SLA (data not shown) at 28 DAE also tended to have a higher relative biomass yield in competition with weeds ($r = 0.66^{**}$) and maize ($r = 0.87^{***}$), but this was not significant with IG10 ($r = 0.38$). Similar correlations were apparent between SLA at 28 DAE and relative grain yields with weeds ($r = 0.53^{*}$), with maize (0.82^{***}) and IG10 (0.15 ns).

Table 2. Grain yield of twelve rice cultivars in monoculture and relative yield under different levels of competition. Ivory Coast, 1998.

Rice cultivar	Grain yield kg/ha	Relative yields % Weeds	CG14	Suakoko
WAB450 1-B-P-183-HB	4905	107	42	29
WITA 4	4755	200	110	70
WITA6	4200	216	120	76
Suakoko	4121	219	167	84
Bouaké 189	4096	231	96	88
WAB450 16-2-BL2-DV2	4007	46	55	37
WABIR 12979	3779	191	100	85
CG14	2795	208	80	71
Gambiaka	2716	218	151	55
Azucena	2280	244	133	78
WAB450 1-B-P-20-HB	2099	98	104	45
WAB450-9-2-6-1-1	1873	215	81	45
Experimental means	2865	165	91	
S.E between cultivars	± 459.5		± 20.5	
S.E " " competitors	-		± 4.8	

In experiment 2, the weed growth was very poor as sowing had been delayed and the subsequent weed growth killed prior to sowing, effectively a "stale seed-bed" treatment. In monoculture there was wide variation in the grain yield among the test cultivars. In competition with Suakoko there were three fold differences in the yield stability, with the highest yielding cultivar also giving the lowest relative yield in competition with Suakoko. A number of the cultivars gave higher yields in competition with CG14 than in monoculture. Relative biomass at harvest of the cultivars when grown in competition with CG14 ($r = 0.625$, $P = 0.003$) and Suakoko ($r = 0.565$, $P = 0.009$) was significantly correlated with SLA of the same cultivars.

In 1995 and 1996, experiments were conducted which compared distinct rice cultivars under different levels of weed management. These results relating to the three cultivars grown in both years are reported by Johnson *et al.* (1998), but results relating to the growth of these and three additional cultivars are used to validate the results of Experiments 1. Correlations between the relative biomass yields after competition with weed growth and only a single hand weeding (farmers' practice) and between the relative biomass yields in Experiment 1 gave values of $r = 0.90$ (maize), $r = 0.91$ (weeds) and $r = 0.64$ (IG10, $n = 6$), and respective values for relative grain yields of 0.94, 0.89 and 0.27.

DISCUSSION

In both experiments the sown competitors differed substantially in their effect on the test rice cultivars. Cowpea was a relatively weak competitor and in experiment 2, the natural weed growth was very sparse. Under these circumstances of low competition, almost all cultivars increased their grain yield by almost 50%, and many in the latter experiment doubled their yield. This "plasticity" could be of considerable advantage under the varied conditions of plant population density, which are commonly found on farmers' fields. IG10, which has exceptional vegetative vigour, more than doubled its grain yield when in competition with cowpea compared to when in monoculture. The majority of the test cultivars produced similar grain yields to the monoculture when grown with OS6 a long duration rice cultivar, with the notable exception of IG10 which had a grain yield 50% above that when grown in monoculture. In contrast the yields of the test cultivars were generally very depressed when grown with either maize or IG10. The ability of IG10 and CG14 to maintain high yields in competition with maize is perhaps due to their ability to produce tillers after the competition effects of the maize was removed. This had been reported by Koffi (1980), who considered that the ability characteristic of some *O. glaberrima* to recover after late weeding on farmers' fields to be of substantial advantage. The use of IG10 as a competitor, however, imposes strong competition throughout the growth cycle of medium duration cultivars. This sustained and intense competition is perhaps why there was a relatively poor correlation between the performance of rice cultivars when grown in competition with weeds on larger plots in 1995 & 1996 and their performance in the screening trial. The rice cultivar that gave the best relative yield with IG10 was OS6, which had a longer duration than the other cultivars. The usefulness of IG10 as a sown competitor might be limited in very favourable growing conditions, due to susceptibility of this cultivar to lodging which makes harvesting difficult and results in lost grain.

There was significant correlation between SLA and the competitive ability of the cultivars in the two experiments. Higher SLA values enable plants to produce a greater leaf area for a given biomass partitioned to leaves, and has been highlighted as having an important role in imparting superior weed competitive ability to rice plants (Dingkuhn *et al.*, 1999; Johnson *et al.*, 1998). The greater the leaf canopy a plant is able to develop during the vegetative stages of development, the greater the light interception and the less light that is available for competing species. Given the suggested importance of SLA, which enables a plant to establish a greater leaf area for a given biomass, a large number of cultivars could be screened for high values of SLA to select cultivars for further testing under field conditions.

Competition from weeds tends to be very variable under the majority of circumstances due to the large number of species involved, successive generations, the extent of competition for light, nutrients and water. Such variability is likely to compromise predictions of the performance of rice cultivars under field conditions, using a screening methodology based on a very limited range of circumstances. The results of these experiments, however, clearly show wide differences in the performance of cultivars when grown in competition. There is good evidence to suggest that the maize or IG10, sown as competitors to rice, could be used to predict the performance of different rice cultivars in competition with weeds under upland conditions. While under lowland conditions, Suakoko and CG14 generally suppressed the growth of the test cultivars, but due to the sparse growth of weeds it was not possible to compare the results in this experiment. A screening methodology based on sown competitors such as maize, IG10, CG14 and Suakoko could be used to undertake an initial screening of rice cultivars for their competitive ability with weeds. This would overcome, at least in part, two of the limitations of conventional field experiments with weeds, in that plots could be relatively small enabling a larger number of cultivars to be screened, and that the use of sown competitors would greatly reduce the inherent variability in natural weed populations. In the above experiments, the land had been cleared from natural vegetation for a number of years and had been in regular cultivation. Fertiliser was therefore applied to raise soil fertility to levels comparable with land newly cleared from fallow and to be more representative of farm conditions. The screening methodologies however could be adapted to screen cultivars for their competitiveness with weeds in organic systems, by modifying the inputs used. Furthermore, the methodology could be modified for use in different ecologies or with other crops by using different cultivars or alternative species as competitors.

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Organic weed control – getting it right in time

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ABSTRACT

Weed control is often a major problem in organic horticultural systems; a critical aspect of non-chemical weed control programmes is the timing of operations. The concept of optimum weeding periods based on crop-weed competition experiments is outlined. Field studies with radish demonstrate how rapid crop development can avoid the need for weeding. The defined weeding times for a range of temperate horticultural crops have been compiled from published and unpublished sources. The incorporation of timing into an organic weed control strategy is discussed. Future developments in weed control are highlighted, with special reference to computer-aided decision support systems.

INTRODUCTION

In organic field vegetable production the control of weeds is often a major problem, limiting both yield and quality. The development of improved weed control strategies for these systems is therefore considered a priority area for research in organic agriculture (UKROFS, 1998).

It is often assumed that keeping crops free of weeds from sowing through until harvest is necessary to prevent yield losses. But, weed competition studies, including ones at Horticulture Research International (HRI) under the conventional system, and at Henry Doubleday Research Association (HDRA) under the organic system, have demonstrated that a short weed-free period or even a single weeding may be all that is needed to prevent crop losses. Yield will not be affected if the weeds are removed before the onset of competition and the crop kept weed-free until weed emergence decreases and the crop becomes more competitive. If weeding is delayed, however, then yield will be reduced. With drilled bulb onions, for example, the yield penalty can be as much as 4% for each day that weeding is delayed beyond the critical point (Hewson & Roberts, 1971).

Studies with a wide range of crops have determined the period when weed control measures will be most effective. But the information is not readily available to growers. In addition, optimum weeding periods can only be applied in practice if suitable implements are available that will be effective against weeds at that time. The aim of this paper is to describe the background to defining optimum weeding periods, to provide information on the weeding periods for different crops, to discuss the application of weeding periods in practice with the available weeding implements, and to highlight future developments.

OPTIMUM WEEDING PERIODS

Optimum weeding periods are determined in competition experiments where cropped plots are left weedy for different periods before being weeded and then kept weed-free, or plots are kept weed-free for similar periods and before weed is allowed to develop. Plotting the curves of the crop yields at harvest from the two sets of treatment plots indicates the period when the crop needs to be weed-free (Figure 1). A crop may need to be weed-free for a short 'critical period' (Figure 1a), or a single weeding at a precise time (Figure 1b), or a single weeding within a 'weeding window' (Figure 1c) may be sufficient. The optimum weeding times are not fixed, and greater flexibility can be achieved by giving the crop an advantage over the weeds, for example, through the use of module-raised transplants, or by putting the weeds at a disadvantage using cultural measures such as stale-seedbeds. This widens the weeding window and makes the timing of weed removal less critical.

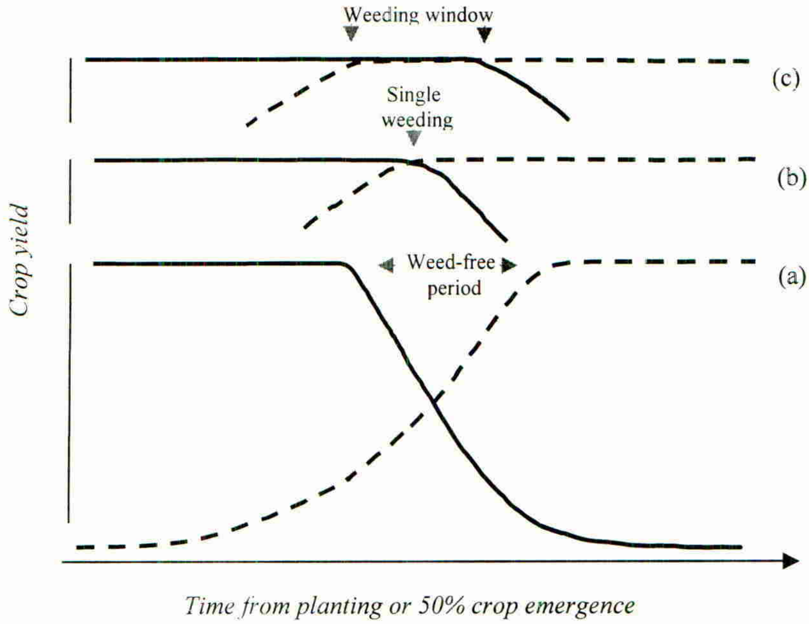

Figure 1. Effect on crop yield of leaving the crop weedy for different periods before weeding (———) or keeping it weed-free for different periods and then allowing the weeds to develop (– – –).

Rate of emergence and growth are important factors in plant competition, a crop that emerges quickly and matures rapidly may not need weeding at all. At HRI, radish was sown at monthly intervals from March to July 1998 into freshly prepared seedbeds, in eight rows 150 mm apart in a 1.83 m wide bed. Treatment plots were 3 m long and included weed-free and unweeded plots and plots kept weed-free or left weedy for 2, 3, 4 or 5 weeks after 50% crop emergence. At each weeding time, the weeds were carefully removed by hand to avoid soil disturbance. The radish emerged earlier and grew faster than the naturally-occurring weeds. Time to 50% crop emergence varied from 14 days in March to 5 days in July. The period from sowing until harvest ranged from 57 days for radish sown in March to 34 days for the July sowing. Weed density varied from 45 to 135 weeds m^{-2} in the different experiments. Fat hen (*C. album*) was the dominant species in the earlier sowings, with chickweed (*Stellaria media*) and various mayweed species (*Matricaria* spp.) the main weeds in later sowings.

At harvest, radish number and weight were recorded from 2-m lengths of the inner four crop rows. There was no difference in yield between the weed-free and any of the other weeding treatments including the unweeded in any of the experiments. The yield curves of total fresh weight of radish m^{-2} at harvest of the June sowing are shown in Figure 2. Radish root and leaf weights, and plant numbers were similarly unaffected by weeding treatment. In addition, few weeds had reached the flowering stage and none had set seed by the time of crop harvest. A short-term crop like radish therefore has the potential to act as a substitute for fallowing in depleting the weed seedbank.

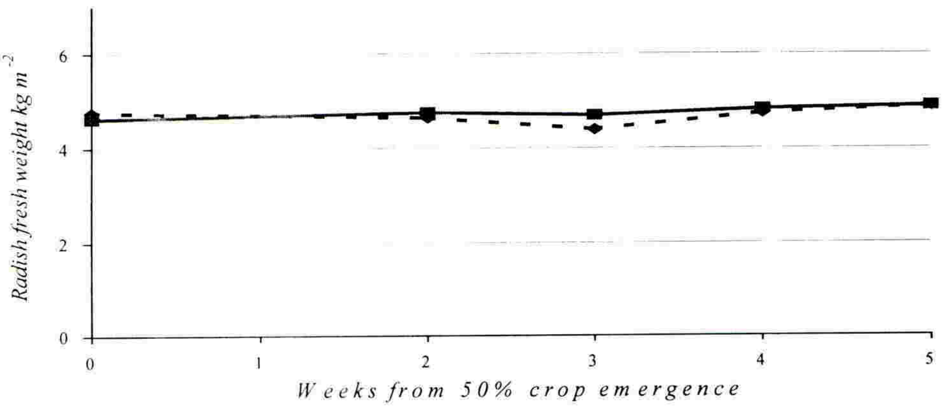

Figure 2. Effect on radish yield of leaving the crop weedy for 0, 2, 3, 4 or 5 wk before weeding (———) or keeping it weed-free for those periods and then allowing the weeds to develop (— — —).

THE WEEDING PERIODS FOR DIFFERENT CROPS

While there have been many studies of weed competition in different horticultural crops, only a minority of these have been made in a way that allows the optimum weeding period for those crops to be determined. Defined optimum weeding periods, from published and unpublished sources, are listed for horticultural crops grown under European conditions (Table 1).

Crop production methods can give the crop an advantage over the weeds. Drilled bulb onions needed to be weed-free for a critical period of up to 2 wk at 6 wk after 50% crop emergence. Transplanted bulb onions required only a single carefully timed weeding to prevent yield loss. Additional measures to reduce weed numbers such as stale seedbeds or pre-emergence flaming can increase the flexibility in the timing of weeding operations.

Differences in crop growth and morphology also contribute to reducing weed control needs. Swede and turnip may look similar but differ in their relative speed of emergence and hence the rates of developing a good leaf canopy. The faster development of turnip provides an advantage over swede in suppressing weed development. Weeding once at 2 to 4 weeks after 50% crop emergence was the most consistently effective in preventing yield loss in both crops. But, when weed numbers were low, weeding could be delayed for a further 4 weeks in turnip without significant crop losses occurring (Bond, unpublished). So keeping weed numbers down is important but to gain the full benefit, the crop itself needs to be able to take advantage of any reduction.

Table 1. Optimum weeding periods for horticultural crops grown under European conditions from published and unpublished sources

Crop	Production method	Optimum weeding period	Source reference
Bean (broad)	drilled	At 3 wk after 50% emergence	Hewson *et al.*, 1973
Beet (red)	drilled	At 4 wk after 50% emergence	Hewson & Roberts, 1973
Beet (sugar)	drilled	At 4 – 6 wk after 50% emergence	Scott *et al.*, 1979
Cabbage (summer)	drilled	At 3 wk after 50% emergence	Roberts *et al.*, 1976
	transplanted	At 3-8 wk after planting	Unpublished
Carrot	drilled	At 4 wk after 50% emergence	Bevan *et al.*, 1993
Lettuce (summer)	drilled	At 3 wk after 50% emergence	Roberts *et al.*, 1977
Onion (bulb)	drilled	From 6 to 8 wk after 50% emergence	Hewson & Roberts, 1971
Onion (bulb)	transplanted	At 4 - 6 wk after planting	Bond *et al.*, 1998
Onion (salad)	drilled	At 5 wk after 50% emergence	Bevan *et al.*, 1993
		At 4 – 5 wk after 50% emergence	Bond *et al.*, 1998
Potato (Main)	planted	At 2 – 8 wk after planting	Unpublished
Radish	drilled	None	This paper
Raspberry	planted	At cane emergence in May	Lawson & Wiseman, 1976
Swede	drilled	At 6 wk after sowing	Forbes, 1985
	drilled	At 2 – 4 wk after 50% emergence	Unpublished
Turnip	drilled	At 2 – 4 wk after 50% emergence	Unpublished

Potatoes are probably the most competitive vegetable crop and have a wide weeding window. In recent experiments at HRI, a single weeding made between 2 and 8 weeks after 50% crop emergence was all that was needed to avoid crop losses (Bond, unpublished). Even tall growing weeds like fat hen that emerged after the single weeding were unable to reduce tuber yield. However, yield losses of up to 21% occurred in the unweeded or late-weeded crop.

THE APPLICATION OF WEEDING PERIODS IN PRACTICE

Crop and weed stage and pattern of seedling emergence in relation to the timing of weeding operations will have an important effect on weeding efficiency depending on method used. Pullen & Cowell (1997), quantified the performance of six different mechanical weeding mechanisms in controlling inter-row weeds at two different growth stages and at three different tractor speeds in arable crops. Some of the mechanical treatments in that trial achieved equal or better control than the herbicide treatment, the sweep hoe weeder was particularly promising. This knowledge can be utilised to determine the optimum timing of control with the most effective implements and work rates in the crops tested.

The timing and frequency of harrowing is important both for the effect on the weeds and on the crop (Rasmussen & Svenningsen, 1995). The biomass of *Brassica napus* was only reduced by autumn harrowing because by the spring it had developed a deep taproot. Similarly, Welsh *et al.*, (1997), found that corn poppy (*Papaver rhoeas*) and shepherd's purse (*Capsella bursa-pastoris*) which also develop tap roots, were more effectively controlled in autumn than in spring. The shallow rooted weeds, chickweed (*Stellaria media*) and cleavers (*Galium aparine*), however, were better controlled in spring when there was more foliage to catch on the tines.

In relatively short-term, spring-sown vegetable crops, weeding times are less flexible than in arable crops. A knowledge of defined optimum weeding times will only be of benefit if they can be applied in practice. Appropriate weeding equipment must be available but it is not always known what is the most effective implement to use at a particular weeding time, and how this will fit into a whole strategy of weed management. A collaborative PhD study between HDRA, HRI and Coventry University is addressing these issues in a study of weed control strategies in organic onions and carrots. Both crops are widely grown organically but are notoriously difficult to keep free of weed competition due to slow emergence and a lack of a dense leaf canopy. Optimum weeding times, previously defined in small-scale hand-weeded experiments are being tested in an organic rotation with field-scale trials and machinery. A whole strategy approach is being taken, evaluating combinations of cultural, mechanical and thermal weed control methods to determine the optimum weeding programme for each crop. The economics of each strategy will be determined to make advice as relevant as possible to growers.

THE FUTURE

Experimental studies provide an indication of optimum weeding times but to be of real benefit to growers, weeding intervals need to be predicted in advance of crop establishment. Many factors interact to determine the precise weeding period. Computer modelling allows the effects of different factors to be simulated and tested. A plant competition model developed at HRI simulates the growth of the crop and the weeds. In its simplest form the model can be used to predict the optimum weeding period for a chosen crop and weed combination (Aikman *et al.*, 1995). The model can simulate the effect on crop yield of one or more weed emergence events with different densities in each flush. Repeated model simulations will predict the effect on the weed-free period of varying both the weed and the crop density.

The reliability of the competition model's predictions depends on having a realistic estimate of weed emergence. A model relating emergence to depth of burial for a range of important weed species has been developed at HRI (Grundy *et al.*, 1999). In combination with a model that simulates the movement of seeds during cultivation (MOSAICS), also developed at HRI, this model can be used to predict the likely emergence of weeds from a known weed seedbank. Models for weed emergence, competition and control will form the basis of an expert system for advising on weed control strategies in organic systems.

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Precision inter-row weeding in winter wheat

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ABSTRACT

A novel inter-row steerage hoe based on computer vision guidance is described and its row following performance is found to be reliable with an RMS error of 16 mm. Trials to compare the relative performance of the experimental hoe and harrowing using a spring tine weeder are described. Both techniques reduced weed dry weight compared to an untreated control though there was no significant effect on yield. A further complementary experiment to investigate the effect of row width is also described. Results indicate that yield is not affected by row width up to the 22 cm used by the steerage hoe.

INTRODUCTION

Organic farms have always included cultivation as part of the weed control strategy, but have relied heavily on long rotations to keep weed populations under control (Lampkin, 1990). Recent interest in stockless organic system reduces flexibility in this respect and places more emphasis on control strategies such as cultivation.

The farmer can use two alternative cultivation techniques for weed control post emergence, harrowing and inter-row hoeing. Harrows uniformly treat both crop and inter-crop spaces relying on the crop being more robust than the weed. Selectivity between crop and weed therefore requires careful timing and provides limited opportunities for treatment. The implement which typically consists of a number of closely spaced thin spring steel tines has the advantage of ease of operation at relatively low cost.

An alternative and potentially complementary form of mechanical weed control uses a more aggressive cultivator which achieves selectivity through guidance between crop rows. This has the advantage of dealing with a wider range of weed species even after they have become well established (Rademacher, 1962). A limited amount of control within the row can also be achieved by burial from soil thrown out from between rows (Jones *et al.*, 1996). The main disadvantage of the technique, which this work sets out to address, is the difficulty in achieving adequately accurate inter-row guidance to avoid crop damage.

This paper describes an experimental inter-row steerage hoe which uses computer vision and sophisticated tracking techniques to guide cultivators between crop rows. Results are given in terms of the geometrical accuracy achieved as well as agronomic effectiveness relative to an untreated control and harrowing. A complementary experiment relating to choice of row widths is also described.

EXPERIMENTAL EQUIPMENT

Experimental steerage hoe

The rear mounted experimental hoe illustrated in Figure 1 is based on a 4 m wide Garford Farm Machinery implement consisting of two frames. The front frame is connected to the tractor via the 3-point linkage with check chains tight. Its height is controlled by two flanged wheels which also serve to resist lateral movement. The rear frame is linked to the front via a parallel linkage allowing it ± 20 cm of sideways movement controlled by hydraulic cylinders. Single 13 cm wide spring tine mounted A-blades are arranged at the 22 cm inter-row spacing along the moving frame. The 44 cm wide tractor wheelings are each cultivated by two A-blades.

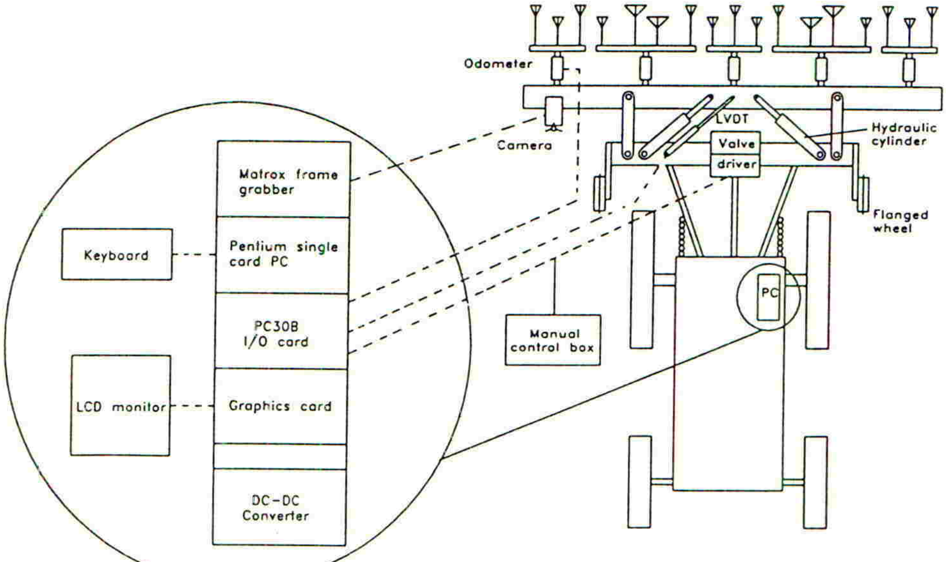

Figure 1 Schematic of the experimental steerage hoe

A video camera is mounted on the moving frame inclined down at 45° such that it views five crop rows to one side of the tractor as illustrated in Figure 2. Images are passed at 25 Hz to a 200 MHZ Pentium PC and analysed to extract the lateral offset and heading angle of the camera with respect to all five crop rows. The analysis techniques employed (Tillett & Hague, 1999) are robust to moderate levels of missing crop and weed growth. The heading and offset information is passed to a Kalman filter based algorithm that tracks camera position over time based on the vision observations and a model of tractor/hoe kinematics. The advantages of such a tracking algorithm over use of raw image data are: the location of crop rows in the image can be predicted from prior information, reducing search time for image features; spurious vision observations can be identified and rejected; the correct central row can be identified; a measure of confidence is available to the operator.

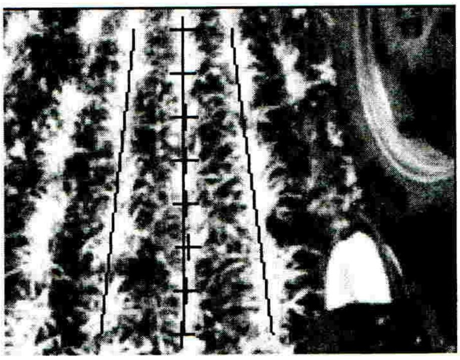

Figure 2

View from the video camera

The offset derived from the tracking algorithm is used to determine whether the hydraulic side shift mechanism should shift left, shift right or stop.

Harrow

The harrow used in these trials was a standard 4 m wide Einböch finger tine weeder.

EXPERIMENTAL METHODS AND RESULTS

Hoe guidance accuracy

To record hoe path, one of the hoe tines was removed, and replaced by a nozzle which dispensed paint. The performance of the system was assessed by measuring the location of the paint trace relative to the crop rows. To facilitate measurement, a template marked at intervals equal to the 22 cm row spacing was used; these marks were aligned with crop rows. A second scale was used to read the offset of the paint trace from the central position to the nearest 5 mm. Before the trial commenced, manual adjustment was made to null any constant bias of the hoe tines. A pass of approximately 50 m length was performed at 6 kph, and the hoe offset measured at 1 m intervals following the procedure described above. The crop growth stage was 14,22 and the lighting bright direct sun.

Analysis of the results given in Figure 3 shows a residual bias of 2.9 mm and an RMS error of 16 mm.

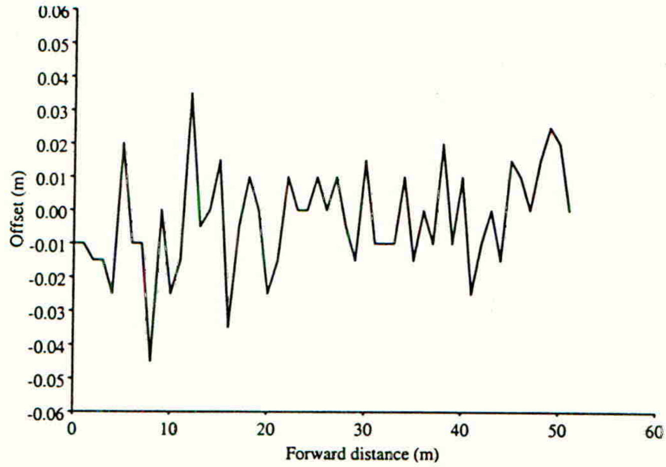

Figure 3 Lateral position of steerage hoe relative to crop rows

Effect of hoe and harrowing on weeds and crop yield

Winter wheat (cv. Brigadier) was sown in widely spaced rows (22 cm) on 21 October 1997 at a seedrate of 400 seeds / m^2. An earlier study (Blair *et al.*, 1997) had indicated little influence of row width between 12.5 - 25 cm on yield. This trial was carried out within a standard conventional system (not within a certified organic system) and the crop was managed according to best local practice to optimise yield. Plots were weeded with either a hoe or harrow on 8 May 1998.

Samples were taken from 4 of the 6 randomised blocks for biomass on 19 June 1998 when the crop was at growth stage 65. Dry weight of crop and weed was assessed. Further samples were taken for yield component analysis immediately prior to harvest which took place on 11 August 1998. Fertile tiller numbers were also recorded at this time. Plots were harvested using a plot combine, and yields corrected to 15% moisture.

Results from the June samples given in Table 1 showed that both types of weeder had reduced weed (cleavers) biomass. Crop dry weights were slightly reduced in the non weeded plots.

Table 1. Crop and weed dry weights 19 June 1998.

Treatment	Crop dry weight g/m^2	Weed dry weight g/m^2
No weeding	1012	61.5
Hoe weed	1228	27.3
Tine weed	1154	7.9
SEM (42df)	87.7 ($p<0.01$)	13.70 ($p<0.001$)

Hand harvested samples taken prior to harvest showed no significant difference between individual components of yield between treatments. Tine weeding tended to reduce fertile tillers whereas the untreated plots tended to have smaller grains. Combine yields tended to be lower than those of the hand harvest due to the hand sampling not fully taking into account the poorer areas of the plot such as wheelings. 'No weeding' gave a significantly lower specific weight than either of the weeding treatments.

Table 2. Hand yield and combine harvest data

Treatment	Hand yield	Combine yield	Specific weight
None	10.72	8.99	74.63
Hoe	11.06	9.28	77.82
Tine	10.47	9.29	77.60
SEM (28 df)		0.135 (ns)	0.587 ($p<0.001$)
SEM (10 df)	0.415 (ns)		

Effect of row width on yield

Winter wheat (cv. Brigadier) was sown at 4 different row spacings (12.5 cm, 15 cm, 18 cm and 22 cm) on 21 October 1997. Seedrate was maintained at 400 seeds/m^2 across all row spacings. The crop was managed according to best local practice to optimise yield.

Samples of crop were taken for yield component analysis immediately prior to harvest which took place on 11 August 1998. Fertile tiller numbers were also recorded. Plots were harvested using a plot combine, and yields corrected to 15% moisture. There were 4 replicates of each treatment arranged in randomised blocks.

Hand harvested yield components showed that the widest spaced rows tended to have more fertile tillers and more grains per ear which translated into higher yields. However, combine yields were very similar across all 4 row widths. The differences are probably attributable to the method of sampling for the yield component samples.

Table 3. Yield components

Treatment	Fertile tillers	Grains per ear	1000 grain weight	Harvest Index	Hand yield	Combine yield
22 cm	471.0	42.6	44.95	0.48	10.61	10.56
18 cm	424.2	42.0	45.02	0.49	9.40	10.54
15 cm	464.5	40.2	44.33	0.48	9.76	10.49
12.5 cm	457.3	40.7	42.38	0.49	9.33	10.68
SEM (9 df)	14.99	2.08	1.080	0.023	0.757	
SEM (9 df)						0.213

CONCLUSIONS

- The steerage hoe automatic guidance system proved reliable and adequately accurate under the conditions tested.
- Both the steerage hoe and harrow significantly reduced weed dry weight, though there was no significant difference in yield compared to untreated plots.
- Row width did not significantly affect yield over the range examined, confirming earlier results.
- The wider range of crop and weed growth stages at which inter-row hoeing can be conducted over harrowing provides operational advantages to offset increased capital cost. Future work will examine the economic situation in more detail.

ACKNOWLEDGEMENTS

We thank MAFF for funding this work and Garford Farm Machinery and Keith Rennie Machinery for providing equipment.

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The potential of *Ascochyta caulina* as a biological control agent for *Chenopodium album* in organic production

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ABSTRACT

Application of *Ascochyta caulina* to *Chenopodium album* plants resulted in high levels of infection and leaf necrosis at high relative humidity. Biological control of *C. album* by *A. caulina* was more effective when the spores were applied in nutrient rich media (V-8 vegetable juice). Prolonged high humidity (r.h.> 95% for 20 hours after inoculation) and plant growth stage (plants must be younger than 4 leaf stage) at time of spore application are critical for successful biological control. High nitrogen levels in the plant were shown to favour high levels of infection in *C. album*.

INTRODUCTION

Weed management is a critical component of any arable farming system. During the past 50 years, conventional agriculture has enjoyed the privilege of selective weed control through the use of synthetic chemicals (Froud-Williams, 1991). However, growing public concern about the persistence and toxicity of herbicides has necessitated a reconsideration of their use (Froud-Williams, 1991), and an increasing number of farmers are converting to organic production systems, where all synthetic pesticides are prohibited. Alternative weed control strategies need to be developed, one of which, biological control of weeds is attracting increasing interest.

Chenopodium album (fat-hen) is a weed in many arable crops. It is ranked the most important weed in ten major crop production systems in Europe because of its abundance and competitiveness, fertility, the longevity of its seeds in the soil, and the resistance developed to atrazine-based herbicides (Kempenaar *et al.*, 1996). *Ascochyta caulina* is considered a potential mycoherbicide against fat-hen (Kempenaar, 1995). Under natural conditions it causes necrotic lesions on leaves and stems of *Chenopodium* and *Atriplex* weed species (Kempenaar *et al.*, 1996). Artificial application of *A. caulina* spores to fat-hen may result in necrosis and mortality of the weed depending on factors such as the concentration of spores applied, formulation of the spore suspension, leaf wetness and temperature after spore application, plant developmental stage at the time of spore application and plant nutrient status. We have conducted a series of experiments in order to determine critical conditions (microclimate, plant-related and fungus-related) which determine the success of the most virulent known strain of *Ascochyta caulina* as a mycoherbicide for fat-hen. Here we provide a brief review of some of the work.

MATERIALS AND METHODS

Plant production; C. *album* was grown from seed in group of 3 in 9 cm diameter pots in sandy loam soil (except in experiment 5) in a greenhouse at 15-25 °C with 68% mean r.h. Eight hours of light were provided daily at mean photon flux density of 215 μ mol $m^{-2} s^{-1}$.

Pots were watered as required.

Inoculum production and application; A. *caulina* inoculum (W 90-1 isolate supplied by Dr. P. Scheepens, AB-DLO Wageningen, Netherlands) was produced on oatmeal agar in Petri dishes (9 cm diameter), each containing approximately 25 ml of medium. *A. caulina* plates were incubated for 2 weeks at 20 °C under fluorescent light at an intensity of 75-80 $\mu mol\ m^{-2} s^{-1}$. At the time of spore application, spores were collected from cultures in 0.01% Tween 80 (Sigma Chemical Co. Ltd, UK) solution and spore suspension filtered through cheesecloth. Nutrients (to a final concentration of 3.5 g/l Czapek-Dox Broth and 0.4 g/l yeast extract) were added to the spore suspension prior to spraying. The concentrations of spore suspension were estimated using a haemocytometer and adjusted to $1x10^6$ spores ml^{-1} or $1x10^7$ spores ml^{-1} solution. *C. album* seedlings were sprayed until run-off (apart from experiment 4) at the four true leaf stage using a hand sprayer.

Spore viability; to ensure that the spores used were viable, spore germination in each trial was measured by plating or spraying spore suspension on water agar slides, which were then incubated for 24 h at high r.h. (>95%) at 20-25 °C. The number of germinated and non germinated spores were counted under a light microscope.

Experiments

Experiment 1. Effect of length of time interval between spore application and the imposition of a >95% r.h. regime (20 h) on the activity of *A. caulina* against *C. album*. After spore application, the plants were placed in a greenhouse for periods of 0, 2, 4, 6, 8 or 10 h, then transferred to a phytotron cabinet at high r.h. (>95%) for 20 h. At the end of this period plants were placed in the original greenhouse for the duration of experiment.

Experiment 2. Effect of r.h. periods (>95%) and different environmental conditions on the activity of *A. caulina* against *C. album*. Inoculated plants were placed in a dark phytotron cabinet at 20 °C for high humidity (95%) periods of 0, 6, 12, 16 and 24 h. Plants were then placed in greenhouses with different environmental conditions (as given in Figure 2).

Experiment 3. Percentage *in vitro* germination of A. *caulina* spores in different nutrient solutions. Six different formulations were studied for their effect on spore germination. These formulations were: a) sterile distilled water, b) sterile distilled water with 0.05 % Tween 80 (v/v) surfactant, c) V-8 vegetable juice (Campbell Ltd), d) V-8 with 0.05 % Tween 80 (v/v) and e) *Chenopodium* extract at concentration of 64 g/l (produced by boiling 64g fresh wt *Chenopodium* plant material in distilled water for one hour and filtered through filter paper (15.0 cm Whatman 1)) and f) *Chenopodium* extract at concentration 32 g/l. 0.5 ml of each formulation (containing $1x10^7$ spores ml^{-1}) was spread over the surface of 1% (w/v) water agar plates in 9 cm Petri-dishes in triplicate and incubated (continuous light 75-80 $\mu mol\ m^{-2}s^{-1}$ at 20 °C) for 24 hours. Percentage germination was assessed under a light microscope after 4, 6, 12 and 24 hours. To determine % spore germination, 200 spores were observed per Petri-dish under a light microscope. A spore was considered germinated when the germ tube was longer than the width of the spore.

Experiment 4. Effect of plant growth stage on the pathogenicity of *A. caulina* against *C. album*. The seedlings were inoculated at six different development stages as described in Figure 4. Sprayed plants were placed in a dark growth cabinet at 20 °C and r.h. >95% for 24 h and then placed in a greenhouse. The degree of necrotic lesion on the treated plants was scored as an assessment of the proportion of necrotic leaf after 1 week.

Experiment 5; Effect of tissue nitrogen on disease development in *C. album* infected with *A caulina* applied at $1x10^7$ spores ml^{-1}. *C. album* plants were grown in group of 3 in 9 cm diameter pots containing washed sand. A 50% strength Long Ashton nutrient solution (Hewitt, 1966) was modified to contain different nitrogen concentrations (0, 2.5, 5, 10, 15, 20, 25 and 30 ml/ 4"pot) and applied to *C. album* plants. Plants from the different treatments were then sprayed at the four-leaf stage with 400 l/ha spore suspension of the *Ascochyta* isolate W90-1.

RESULTS AND DISCUSSION

Results of experiment 1 indicated that the extent of subsequent disease development is clearly dependent on the humidity during both the fungal spore germination period and the subsequent infection period. An increase in the time interval between spore application and high humidity (95%) imposition resulted in a significant reduction of biocontrol activity against *C. album* plants (Figure 1) and less than 25% necrosis was observed if leaves were dry for more than 4 hours after spraying with spores. In experiment 2 a minimum high humidity (>95%) period of 16 h directly after spore application, but also r.h. of more than 48% after the high humidity period were required for more than 50% necrosis to occur (Figure 2). Disease development peaked 10 hours after the majority of spores germinated. This probably indicates that the fungus was forming appressoria and haustoria during this period. Since post high-relative humidity incubation affected disease development, it is possible to conclude that low relative humidity retards both germination and appressorial / haustorial formation. Nutrient availability was a significant factor on % spore germination (Experiment 3, Figure 3). The richer and more accessible the media is (in terms of nutrients and surfactant composition), the higher the % spore germination. No significant increase occurred after 12 hours (data not shown). Studies of spore germination on detached leaves of *C. album* which were inoculated with the previously mentioned spore formulations showed that spore germination followed a similar pattern to the *in vitro* study (data not shown).

Plant age at spraying proved to be a critical factor on disease development (Experiment 4). Younger plants of *C. album* were more affected by the biocontrol agent *A. caulina* (Figure 4). Older than 12 days (four-leaf stage) at spraying showed less than 50% necrosis. The significant decline in disease development in plants sprayed beyond the 4 leaf stage may be due to changes in leaf physical properties, e.g. development of cuticle and waxes and/or leaf chemical properties e.g. changes in nutrient status, changes in phytoalexins etc.

In experiment 5 there was a positive correlation between disease development and tissue nitrogen concentration. With increasing nitrogen in the leaf tissues, disease score were significantly increased and 100% mortality was occurred at 2.4% nitrogen in the leaf

(Figure 5). Given that *C. album* growing in a range of crops (including maize, cabbage and sugar beet) typically has tissue nitrogen concentration of about 4% dry weight (data not shown), N supplies for the fungus in field situations are unlikely to be limiting.

Results obtained in this work suggest that *A.caulina* has potential as a biological control agent against *C. album*. The key limiting factor appears to be r.h. or moisture around the spores during germination and penetration. Further work is required to evaluate optimum formulations for agricultural use to determine the persistence of the fungus and its efficacy under field conditions in the UK.

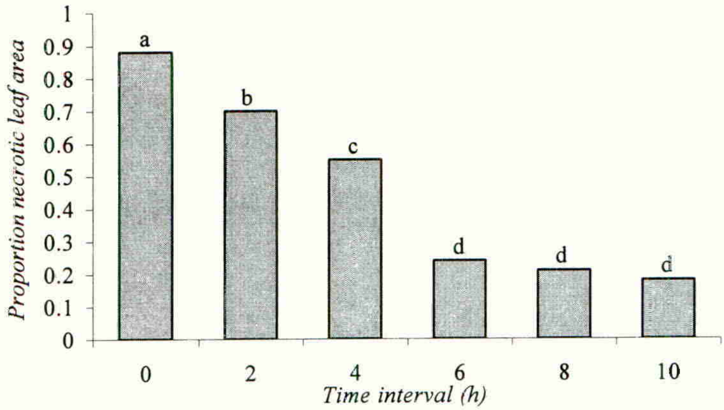

Figure 1. Effect of length of time interval between spore application and the imposition of a >95% relative humidity regime (20 h) on the activity of *A. caulina* against *C. album* plants. Analysis of variance showed a significant difference between treatments (n=8). Bars with the same letter are not significantly different according to Tukey's (Honestly Significant Difference) Test ($P<0.05$).

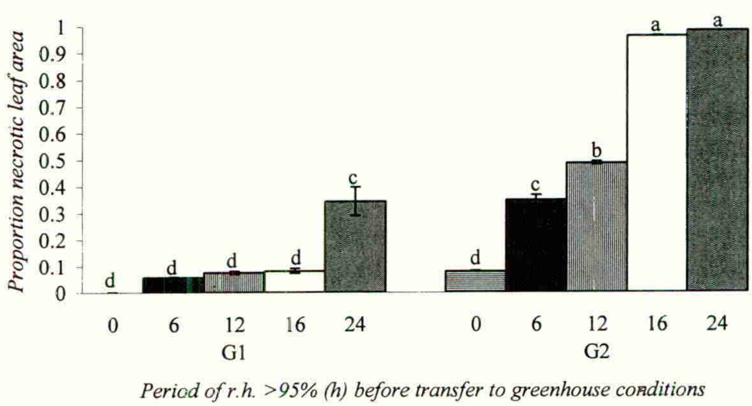

Figure 2. Effect of relative humidity periods *(>95%)* and different environmental conditions on the activity of *A. caulina* against *C. album* plants. Analysis of variance showed significant difference between

treatments. Bars with the same letter are not significantly different according to Tukey's (Honestly Significant Difference) test *($p<0.05$)*. Error bars present standard error of the means (n=8).
Description of parameters; 6, 12, 16 and 24 are periods of r.h. (h) >95% which have been imposed upon *C. album* plants after spore application. G1; greenhouse with 25.6 °C, 48% r.h. and 260 $\mu molm^{-2}s^{-1}$ light (daytime) on average during the experiment. G2; greenhouse with 19.4 °C, 72% r.h. and 215 $\mu molm^{-2}s^{-1}$ light (daytime) on average during the experiments.

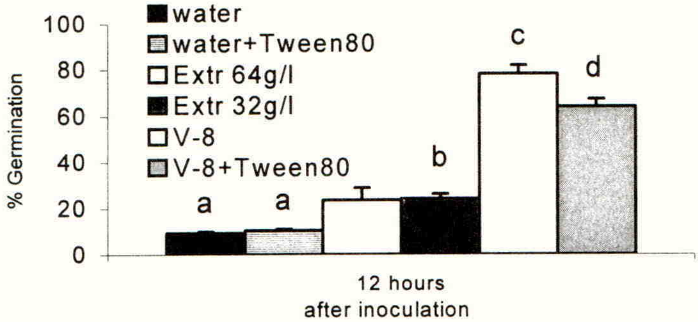

Figure 3. Percentage *in vitro* germination of *A. caulina* spores in different nutrient solutions 12 hours after inoculation. Analysis of variance showed significant difference between treatments. Bars with the same letter are not significantly different according to Tukey's (Honestly Significant Difference) test *($p<0.05$)*. Error bars present standard error of the means (n=3).

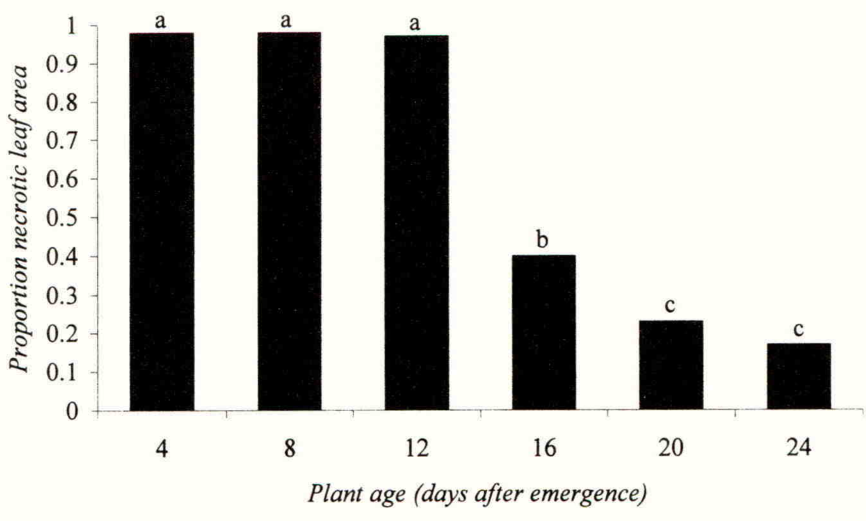

Figure 4. Effect of plant age on the pathogenicity of *Ascochyta caulina* against *C.album*. Bars labeled with the same letters are not significantly different according to Tukey's (Honestly Significant Difference) test ($p<0.05$) (n=8).
Plant growth stage at the time of spore application; Seedling stage (day 4 after sowing), two leaf stage (day 8), four leaf stage (day 12), six leaf stage (day 16), eight leaf stage (day 20) and ten leaf stage (day 24).

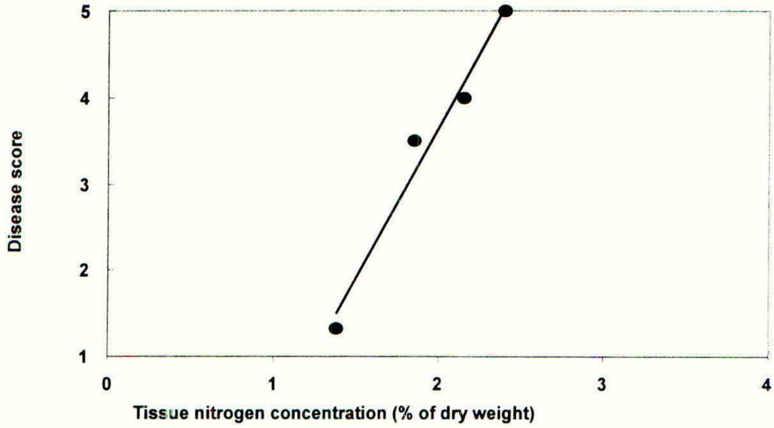

Figure 5. Effects of tissue nitrogen on disease development in C. album infected with A caulina applied at 1×10^{7} spores ml^{-1}. Treated plants were scored for the disease development (0:non-infection, 1:1-25% necrosis, 2: 26-50% necrosis, 3:51-75% necrosis, 4: 76-99% necrosis, 5:dead plant)

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